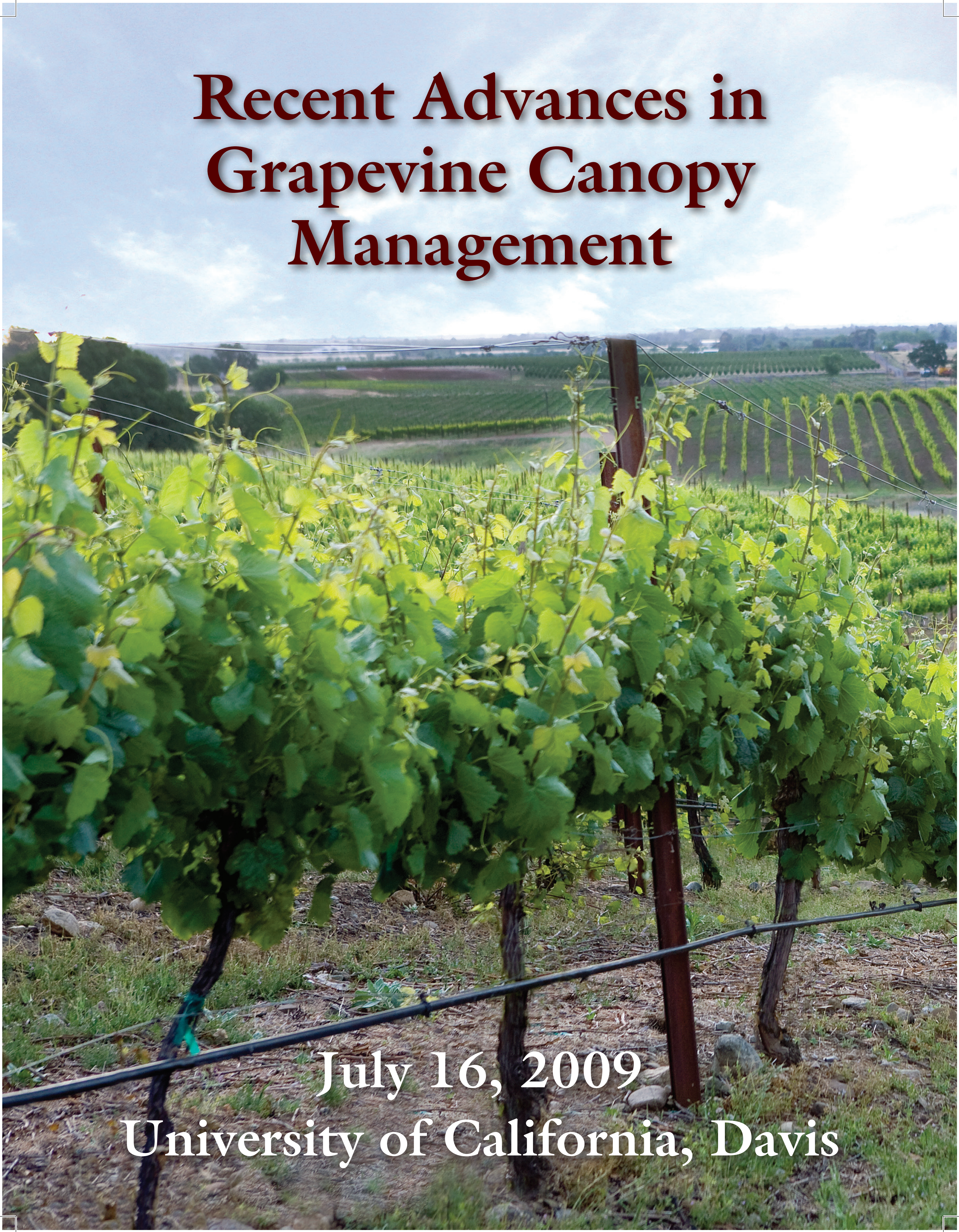
Recent Advances in Grapevine Canopy Management



July 16, 2009

University of California, Davis

Recent Advances in Grapevine Canopy Management

Dedicated to
Emeritus Professor W. Mark Kliewer

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PREFACE

In August of 1986, Professor Mark Kliewer of the University of California, Davis, organized the first international symposium on grapevine canopy management held in California. The symposium, held in conjunction with the XXII International Horticultural Congress at UC Davis, was entitled “Grapevine canopy and vigor management practices for improvement of vine microclimate and grape and wine quality”. The program included speakers from Australia, France, Israel, Italy, New Zealand, Switzerland and the USA. Over 500 scientists and industry members attended the Symposium, attesting to the burgeoning interest in the subject. The information presented defined the state of knowledge regarding the impacts of grapevine canopy management practices on vine productivity and fruit quality at the time, and triggered two decades of rapid advances in research and industry innovation. For California, the symposium marked the beginning of the transition to modern vineyard production and canopy management systems. Clearly, the face of California viticulture has changed dramatically since 1986.

Professor Kliewer, a member of the Department of Viticulture and Enology at UC Davis for over 30 years, was a pioneer in grapevine canopy management research in California. His work helped shape the modern grape production systems currently used in California, and led to significant improvements in both productivity and fruit quality. He also educated a generation of viticulturists, and trained over 50 graduate students. In tribute to his many contributions to the grape and wine industries of California and the world, we dedicate this symposium in his honor.

Although many subsequent meetings on grapevine canopy management have been held during the past two decades, we felt that a comprehensive review of the advancements in the field since 1986 was needed. Fittingly, the symposium is being held in conjunction with the 16th GiESCO Congress held at UC Davis. GiESCO (Group of International Experts of Vitivinicultural Systems for CoOperation), was first organized by the French viticulturist Alain Carbonneau. This group initially focused on grapevine training and trellising systems research, and its members have contributed significantly to our knowledge in this area.

We wish to thank the scientists participating in this event. They are among the very best of those currently working in canopy management and viticulture research. We also wish to thank the GiESCO Organizing and Scientific Committees for their assistance and support. Lastly, financial support provided by the E&J Gallo Winery is gratefully acknowledged.

Nick Dokoozlian and Jim Wolpert
Symposium Organizers
July 2009

DEDICATION

Dedicated to Emeritus Professor W. Mark Kliewer

Dr Mark Kliewer instructing students during a laboratory in the Tyree Vineyard, UC Davis, in 1988.

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FOUNDATIONS OF CANOPY MANAGEMENT: THE CONTRIBUTIONS OF DR. MARK KLIEWER

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Abstract: Dr. W.M. Kliewer has contributed substantially to current principles of grapevine canopy management. He conducted incisive work on the effects of light and temperature on the synthesis and catabolism of sugars, anthocyanins, organic acids and amino acids. His body of work on nitrogen utilization in grapevines elucidated the role light plays in the synthesis of amino acids and their accumulation in berries. From his evaluations of trellis designs and canopy manipulation techniques he demonstrated the importance of managing leaf area density especially in productive vines to attain mature, high-quality fruit for wine making

Dr. W. Mark Kliewer (Figure 1) joined the Department of Viticulture and Enology at the University of Calfornia at Davis in 1963 at the onset of a renaissance in grapevine architectural design. In New York, Dr. Nelson Shaulis and his colleagues were completing their celebrated work on the benefits of light penetration into vine canopies with a demonstration of Geneva Double Curtain training (Shaulis et al. 1966). Meanwhile in Australia researchers had begun to systematically elucidate the influences of light, temperature and vine balance on vine physiology and productivity (see, for example, Baldwin 1964, Buttrose 1966, May and Antcliff 1963, Kriedemann 1968). Kliewer, a biochemist, embarked on a program focussed primarily on the compositional quality of grape berries as affected by temperature and light and by the leaf canopy as a source of shade, sugar and amino acids. He worked collaboratively on these topics early with his Australian colleagues (Buttrose et al. 1971, Kliewer and Antcliff 1970, Kriedeman et al. 1970) and on light microclimate effects later with Dr. Richard Smart (Kliewer and Smart 1989) but some of his most important research was conducted with local colleagues, visiting researchers and his 57 graduate students on a range of vine canopy management issues that particularly served California's burgeoning premium wine industry.

LIGHT AND TEMPERATURE EFFECTS

Kliewer's earliest work on grape was focussed on the temperature and light dependent synthesis and catabolism of organic and amino acids, sugars and anthocyanins in vines and berries (Buttrose et al. 1971, Kliewer 1964, 1966, 1967a, 1968a, 1973, Kliewer and Lider 1970, Kliewer and Nassar 1966, Kliewer and Schultz 1964). The relevance of this work to canopy management was evident in an early study by Kliewer and Lider (1968) showing the significant effects of sun exposure and of shade cast by the canopy and within clusters on the temperature and composition of berries (Table 1, Figure 2). Later, Lakso and Kliewer (1975a, b, 1978) would provide key insights into the temperature dependence of malic acid accumulation and degradation in grape berries by determining the relative activities of phosphoenolpyruvate carboxylase and malic enzyme in response to temperature which favour malic acid accumulation at moderate temperatures (20-25°C) and degradation at above 38°C.

Several studies of light and temperature effects on berry color and phenolics were conducted under controlled environments. Accumulation of anthocyanins in berries was found to be repressed by exposure to high temperatures (30-35°C) (Buttrose et al. 1971, Kliewer 1970c, 1977, Kliewer and Torres 1972). Light effects on berry color development were inconsistent among varieties and temperature exposures, but under moderate "field" temperatures (20-25°C) anthocyanins were generally enhanced by light and increasing light exposure (Kliewer 1970c, 1977, Wicks and Kliewer 1983). Dokoozlian and Kliewer (1996) found that the accumulation of anthocyanin and other phenolics in berries is dependent on light exposure both pre- and post-veraison. They hypothesized that key enzymes in the anthocyanin synthesis pathway are established or activated prior to veraison in response to light such as shown for phenylalanine ammonia lyase (PAL) by Roubelakis-Angelakis and Kliewer (1986). These findings revealed the importance of timing canopy manipulations to increase the light exposure of young fruit, but also the need to maintain some shading to prevent excess heating of fruit clusters.

By the late 1980s the evidence was clear that the development, physiology, fruit yield and fruit quality of a grapevine are all governed principally by the canopy light environment (see reviews by Kliewer 1982, Smart 1985). Given the light filtering effects of leaves on both the intensity and quality of light within the canopy, Kliewer and Smart (1989) studied the possible role of phytochrome in light effects on fruit composition. Under low-light conditions they found the activities of PAL, nitrate reductase, and invertase in berries were stimulated with supplemental red light. Dokoozlian and Kliewer (1995a) characterized

Fi gure 1. Dr. Mark Kliewer enjoying a glass of sparkling at his Oregon vineyard.

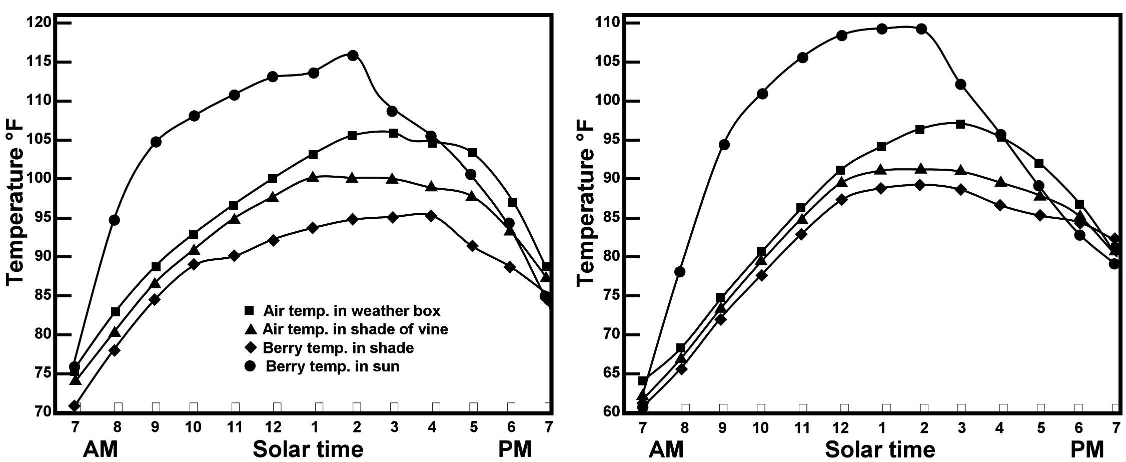

Figure 2. Temperature of Thompson Seedless berries in the sun and shade, and air temperature in a weather box and in canopy shade, measured hourly on hot (left) and moderate-temperature (right) days. Redrawn from Kliewer and Lider (1968).

Table 1. Influence of cluster exposure to the sun on the basic composition of mature Thompson Seedless berries. Sun exposed clusters were borne on canes trained for maximum exposure. Shaded clusters developed in the canopy interior and received little direct radiation. Berries were selected randomly from each cluster. Data are from Kliewer and Lider (1968).

		Berry juice components					
Exposure	**Berry mass (g)**	**Soluble solids (°Brix)**	**Glucose (g/L)**	**Fructose (g/L)**	**pH**	**Tartaric acid (g/L)**	**Malic acid (g/L)**
Sun	1.14	24.2	11.5	14.5	3.79	6.5	0.5
Shade	1.05	23.1	10.9	12.9	3.63	6.4	1.2

the spatial variation and seasonal changes in the intensity and quality of light within grapevine canopies and found that the reductions in photosynthetic light and the ratio of red to far-red light within canopies are directly related to leaf area density. For Cabernet Sauvignon on a narrow (two-wire) vertical trellis, they found maximum foliage density was reached early in fruit development, showing the need to apply manipulations early to maintain optimum light levels in the canopy. Dokoozlian and Kliewer (1995b) determined a threshold leaf area density of 4 m^2/m^2 above which little light penetrated to the fruit zone, and found that some simply measured indices of canopy density [i.e., point quadrat leaf layer number (Smart 1988), atmometer evaporative potential (Livingston 1936), and pruning mass (Shaulis et al. 1966)] are good predictors of leaf area density and light in the fruit zone.

NITROGEN UTILIZATION

The early work on amino acids was continued with a body of work on grapevine nitrogen including its role in canopy performance and the light dependence of its utilization within the vine. Analyses of amino acids in berries and vines over growing cycles revealed the prominent role of arginine and proline in the seasonal storage and mobilization of N to support the growth of shoots and young berries (Kliewer 1967b, 1968b, 1969, 1970a, Nassar and Kliewer 1966). A dependence of berry amino acid levels on leaf area relative to fruit mass per vine was found by Kliewer and Ough (1970). Later studies focused on the extent to which nitrogen limits the growth and functional performance of canopies in supporting fruit development (Ewart and Kliewer 1977, Kliewer et al. 1991, 1994). Canopy light interactions with N distribution and utilization were also explored. Perez and Kliewer (1982) showed that nitrate reductase activity in leaves is enhanced by light exposure. Bowen and Kliewer (1990) found that the distribution of N among leaves was correlated with light intensity as affected by canopy leaf layers, and the N content of basal leaves in particular was correlated with bud fruitfulness and fruit yield of individual shoots. Canopy division was demonstrated to improve the responses of fruit yield and canopy growth to N fertilizer (Kliewer et al. 1991). A critical finding by Krueger and Kliewer (1995) linking canopy light to arginine supply within the vine was that sunlight exposure enhances the synthesis of arginine in leaves.

CANOPY MANAGEMENT

Kliewer conducted several studies aimed at quantifying the leaf area needed to support fruit development to maturity. In early work, timed and age-selective defoliation treatments were used to determine carbon partitioning priorities in the vine and the active leaf area required to support the stages of berry growth and sugar accumulation (Kliewer 1970b, Kliewer and Fuller 1973). Kliewer and Antcliff (1970) conducted one of the first studies to differentiate the influences of leaves as sugar or shade sources by selectively covering or removing young or old leaves at different positions in the canopy. A significant finding was that berry growth and soluble solids accumulation depended more on young apical leaves than older basal leaves. Covering rather than removing leaves increased berry acidity and reduced soluble solids. Kliewer and Weaver (1971) adjusted crop levels in Tokay by pruning and cluster thinning and found that 1 to 1.4 m^2 of leaf area was required to attain maximum berry mass, maturity and color. Kliewer and Dokoozlian (2001) analyzed data acquired from several studies in which combinations of leaf area density, crop load, canopy length and canopy number per vine were manipulated. Without canopy division, the leaf area required to ripen the fruit of several *V. vinifera* grape varieties ranged between 0.8 and 1.4 m^2 per kg of fruit. With division of the canopy to increase the leaf surface area exposed to sunlight, only 0.5 to 0.8 m^2 of leaf area per kg of fruit was required to ripen the crop. In Cabernet Sauvignon, 50% more leaf area was required by single canopies than divided canopies to achieve berry soluble solids of 22°Brix (Figure 3). The ratio of crop mass to pruning mass, a commonly used vine balance index, was found to be closely related (negatively) to the ratio of leaf area to crop mass.

Throughout his career Kliewer was devoted to the practical side of his science and contributed to a number of studies that developed and evaluated new trellis systems and canopy manipulation techniques for California conditions. Early studies demonstrated that increasing the canopy width or dividing the canopy to intercept more sunlight increased yields without affecting fruit quality (Kasimatis et al. 1975, 1982). Studies of foliage reduction applied to vigorous vines showed that removal of basal leaves improves fruit composition but only in vines with low light levels in the fruit zone (Bledsoe et al. 1988, Kliewer et al. 1988). Hedging which removes distal leaves can have opposite effects (Kliewer and Bledsoe 1987). Training shoots horizontally or downward was demonstrated to devigorate growth (Kliewer et al. 1989). In an evaluation of six popular trellis systems and three in-row vine spacings for production of Cabernet Sauvignon in California's Napa Valley, the trellises supporting numerous shoots per vine distributed between separate parallel canopies with low leaf densities produced high yields and desirable fruit quality (Kliewer et al. 2000). Closer (to 1 m) in-row vine spacing initially produced higher yields, mainly through higher shoot densities, but this benefit diminished over the three years of the study. These findings demonstrated to the California industry the importance of canopy management to the yield and quality performance of vineyards.

CONCLUSIONS

Kliewer has contributed substantial insight, creativity and knowledge to the field of grapevine canopy management. His methodical approach to elucidating environmental influences on grapevine physiology provided many key elements of our current understanding of successful vine architecture. A main strength of his work has been its provision of basic knowledge on vine physiology and berry biochemistry upon which creative

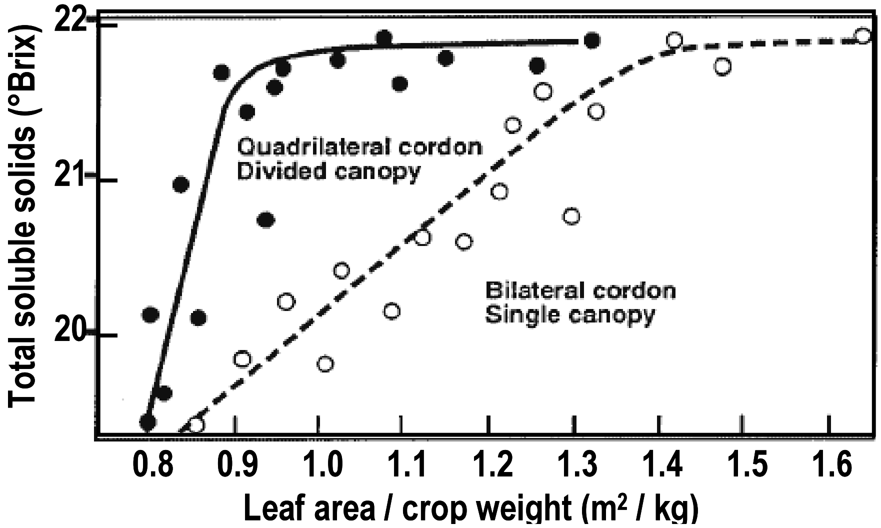

Figure 3. Regressions of total soluble solids in Cabernet Sauvignon berry juice at harvest on the leaf area per unit crop weight of vines trained to either single canopy or divided canopy systems. From Kliewer and Dokoozlian (2005).

canopy designs and management practices have been based. Equally important to the field and industry has been the training and guidance given with grace to his students who have themselves contributed to science and the success of the wine industry in California and beyond.

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THE ECO-PHYSIOLOGY OF GRAPEVINE CANOPY SYSTEMS -LEARNING FROM MODELS-

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Abstract: The interactions of plant canopies with the environment are very complex. In an agricultural (viticultural) context, canopy management practices additionally interfere with and modify these relationships. Over the last three decades several modeling approaches have been undertaken to get an integrated view on grapevine canopy functioning, one of the first being the estimation of sunlight interception by vineyards differing in their dimensions (Smart 1973). Here we report on several approaches to model carbon assimilation and water use for grapevine canopies based in part on mechanistic and empirical relationships linking single leaf responses to environmental variables such as soil water availability (through pre-dawn water potential and the fraction of free transpirable soil water, FTSW), temperature, photon flux density (PFD), and relative humidity (via stomatal coupling). There are different ways to couple stomatal functioning to photosynthesis in these models. Through the use of the approach of Ball et al. (1987), one can include variety dependent changes in the stomatal sensitivity factor during drought stress. To describe canopy structure is more complex. The simple geometric model of Riou et al. (1989) can be used as a base. In its more elaborate form leaves can be allocated to distinct canopy zones and can be classified according to age (using the plastochron concept), and light environment (sunlit or shaded). Leaf area development in most models is temperature driven and coupled to changes in canopy dimensions. A more sophisticated attempt has recently been made by Louarn et al. (2008) describing the three dimensional distribution of plant organs in a grapevine canopy in order to study the physiology and micro-climate effects caused by structural differences. We will show several examples on what we can learn from these models and how they may be used in an applied sense, for instance in the prediction of the effects of climate evolution grapevine water relations.

Keywords: model, whole-vine gas exchange, canopy structure, water deficit

The geometrical structure of a plant canopy determines its interaction with fluxes of energy. Canopy architecture and density are intimately related to crop productivity since the distribution of leaf and non-leaf surfaces influences light interception and subsequent carbon assimilation and water loss. This has been widely recognized for fruit and grape production (i.e. Wagenmakers 1991, Dokoozlian and Kliewer 1995). Since the large spatial and temporal variations in the radiation regime in different locations of a canopy are difficult to measure, simulation models have become the main tool to integrate the activities of individual leaves and their responses to the natural environment (i.e. water supply) and to evaluate the performance of various plant canopy forms. In most models a scale-up approach from the leaves to the canopy is used (i.e. Caldwell et al. 1986, Harley and Baldocchi 1995) with more or less complex descriptions of canopy form and leaf area distribution (i.e. Wang and Jarvis 1990). Since grapes are grown in a multitude of different canopy systems across the world, they represent an ideal tool to address the problem of modeling whole vineyard gas-exchange as influenced by canopy structure. In one attempt, the distribution of surfaces (leaves, shoots, fruit) in space has been modeled for two different grapevine canopies (Schultz 1995) using a two-dimensional beta function (Wang and Jarvis 1990). However, the data set required to develop such a model is very complex and difficult to obtain and a simpler approach using a geometrical model may be more adequate (Riou et al. 1989). One other possibility to integrate physiological responses on a single leaf level into canopy or even stand scale responses are coupled structural-functional models, which have been developed for annual species (maize, Fournier and Andrieu 1999), trees (peach, Allen et al. 2005) and recently grapevines (Grenache and Syrah, Louarn et al. 2008). These models can integrate structural components of a canopy, such as shape, orientation and location of plant organs which influence light interception and thus canopy energy balance with functional properties such as stomatal aperture, photosynthetic capacity and photomorphogenesis or other metabolic processes. Because vineyard canopy structure, functioning and management are important in the formation of yield and quality (i.e. Smart 1985, Reynolds and Wardle 1989, Gladstone and Dokoozlian 2003), these type of models may serve in the future to deduce management decisions with respect to yield and quality production and go well beyond simple descriptions of canopy architecture (leaf area density distribution) and light harvesting (Schultz 1995).

MATERIAL AND METHODS

Radiation model and canopy structure

In the first case, we adapted the canopy radiation and structure model of Riou et al. (1989) to model light interception of- and light distribution within the canopy and to link a water balance model to it (Lebon et al. 2003). The model assumes that the geometrical shape of the canopy resembles a hedgerow, thus the trans-section is rectangular. The 2 vertical canopy sides have a certain porosity (or gap fraction) (Po, %) which allows light not intercepted by the foliage to pass through the canopy, where it may be intercepted by a neighboring row or the soil, depending on solar angle. The horizontal part of the canopy is non-porous by definition. Changes in canopy dimensions and leaf area within the geometrical envelope, i.e. canopy height (H, m), canopy width (L, m), and canopy porosity are modeled as a function of accumulated heat sum (> 10 C). Direct and diffuse light intercepted by 8 canopy zones, 3 on each of the hedgerow sides (apical, central, basal), 1 on top of the canopy and 1 inside the canopy are calculated separately.

Water relations of grapevine canopies

The model was combined with a water module (Lebon *et al*. 2003). Basically, the model consists of a representation of the soil-plant-atmosphere system composed of simply defined subsystems. The soil is considered as single finite reservoir with an amount of total transpirable soil water (TTSW) or its fraction (FTSW) over the soil profile which is estimated as the amount of water (mm) between the soil moisture content at field capacity and the minimum soil moisture observed at any soil depth in a dry year (Ritchie 1981). The atmosphere is characterised by its climatic components. Transpiration by the vines and evaporation from the soil are treated separately. All the water fluxes or quantities are expressed in mm. The total amount of transpirable soil water, TTSW, is experimentally determined (see above) and denotes the starting point for the model when the soil is at field capacity. For more details see Lebon et al. 2003). The FTSW was shown to be directly related to pre-dawn water potential (Ψ_{PD}) irrespective of the TTSW of a vineyard site (Lebon *et al*. 2003).

Gas-exchange

We have followed two different approaches for modeling single leaf photosynthesis. One was based on an empirical model using a set of response functions to environmental variables (Tenhunen et al. 1989, Lakso et al. 2005), the other was based on the biochemical approach of Farquhar et al. (1980) (Schultz 2003). Parameterization of the second has not yet been completed for conditions including effects of water deficit on photosynthesis but includes responses to (1) phenological stage (6 phases are distinct) (2) leaf age (3) light intensity (4) leaf temperature. Water deficit is currently modeled through the relationship of maximum quantum saturated rate of photosynthesis (A_{max}) (under ambient CO_2 concentration) to pre-dawn leaf water potential (ψ_{PD}). Dark respiration is modeled using previously published Q_{10} values as dependent on plastochron index and phenological stage and in relation to ψ_{PD}.

Coupling photosynthesis and stomatal conductance

Photosynthesis is linked to stomatal conductance (g) using the approach of Ball et al. (1987), where g is related to the product of A and (hs/Ca), where hs=relative humidity and Ca=is the CO_2 partial pressure. The slope of this relationship was termed the stomatal sensitivity factor, *k*, which changes with soil water deficit and which allows us to distinguish varietal responses to drought.

Model validation

We have validated the model using different approaches with different varieties in different viticultural regions of Europe. One approach was to measure single leaf A and g throughout the day in different canopy zones of different canopy systems under changing plant water status keeping the leaves in their natural position. The second approach was comparing the calculated transpiration rates by the model for the whole canopy with data from sap flow gauges (Granier type); and the third approach was comparing calculated whole vine net assimilation rates with measurements conducted with a whole plant gas-exchange system. The required input data for the model are global radiation, air temperature, relative humidity, wind speed and ψ_{PD}.

RESULTS AND DISCUSSION

One of the validation data sets is shown for the 8 canopy zones in Fig. 1. Measured and simulated stomatal conductance in this case were compared for a hedgerow system using the variety Syrah during a water stress experiment (ψ_{PD}=-0.51 MPa) in southern France. Measured and simulated values were in good agreement (Fig. 1). Photosynthesis and stomatal conductance were slightly underestimated on the West side in the morning but the strong afternoon depression in both photosynthesis and stomatal conductance on the East side were simulated accurately (Figs. 1 B, E, H). However, in order to ultimately evaluate model performance, we compared model calculations with whole plant measurements of gas-exchange in the field using an automated polyethylene chamber system (Poni et al. 1997). The experiment was part of a study comparing two different canopy systems with the variety Chardonnay in Bologna, Italy. One of the systems studied resembled the hedgerow, vertical shoot positioned system used in many European vineyards, the other was a minimal pruning system, which develops very large canopies with hanging shoots. Figure 2 shows some results for a diurnal time course of net CO_2 exchange rate (NCER) of the two systems during a clear day in September which are similar to those described elsewhere (Lakso et al. 1996). With the exception of some discrepancies between measured and simulated NCER values early in the morning, agreement was excellent. The complex canopy structure of the minimal pruning system probably contributed to these differences, and more complex approaches to describing leaf area distribution may improve performance of the model (Wang and Jarvis 1990).

What can we learn from models?

Using the above described model set up, it is possible to evaluate different structural and vineyard dimension parameters in their effect on whole canopy performance. This is a useful tool, if one wants to estimate the possible effects of an evolving climate on canopy water consumption for instance. Figure 3 shows a simulation where water consumption is estimated for North-South (NS) oriented as compared to East-West (EW) oriented vineyard rows in Bordeaux, France. For most of the season NS orientation has a larger water consumption than EW orientation, but late in the season this trend is reversed (Fig. 3). This type of analyses can be extended to evaluate certain canopy systems and even management practices with respect to their impact on canopy performance under changing environmental conditions.

Recently, Louarn et al. (2008) have used a combination of approaches to construct virtual canopies of two varieties, Grenache and Syrah, with four common spur-pruned canopy systems (Gobelet, bilateral free cordon system, and 2 bilateral cordon system with vertical shoot orientation differing in the number of catch wires). They employed a limited number of parameters to describe the volume occupied by a shoot (turbid-medium-like envelope) and combined this with results from random samplings for the position of individual shoot organs (leaves as discrete geometric polygons) within this volume to generate individual shoots with individual leaf positions and orientations. Coupled to a set of descriptors of plant architecture, bud location and shoot orientation and angle, complex 3-D canopies were regenerated (Fig. 4). A particular advantage of this more statistical approach as compared to earlier 3-D descriptions of grapevine canopies (Mabrouk et al. 1997) was the improved integration of inter-plant variability and the implementation of varietal specific parameters (Louarn et al. 2008).

This type of model allows for a more accurate simulation of light interception and can be coupled to the mechanistic gas-exchange model of Farquhar et al. (1980) (Louarn et al. 2005) which has been fully parameterized for grapevines (Schultz 2003) (Fig. 4E). If research development continues in the future this type of approach will allow the simulation of the response

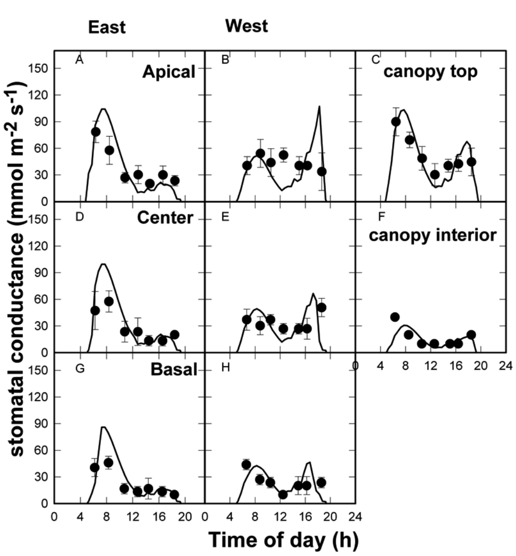

Fig. 1. Measured (symbols) and simulated (lines) stomatal conductance for 8 zones of a Syrah canopy on August 3 at Roujan, France. The ψ_{PD} was –0.51 MPa. Leaves were kept in their natural position.

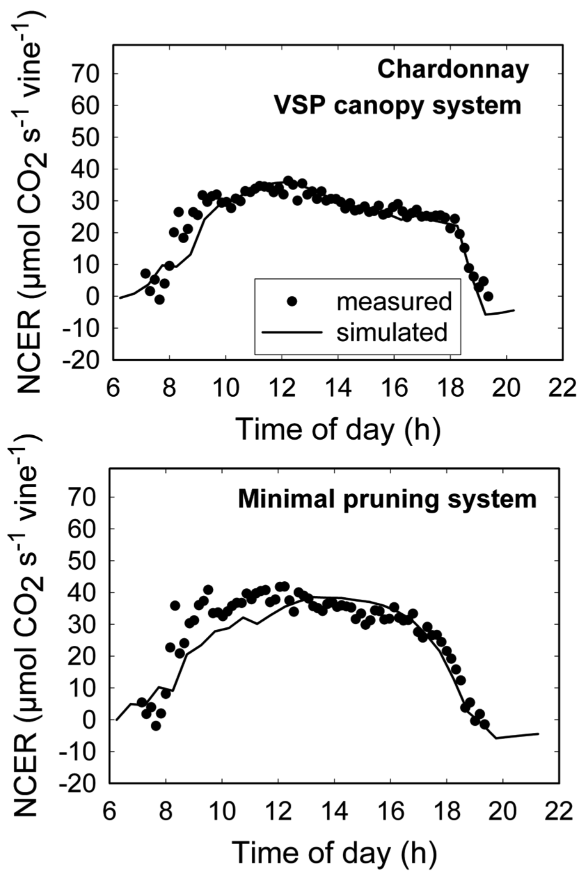

Fig. 2. Simulated (lines) and measured (symbols) whole-vine net CO_2-exchange rate for 2 canopy systems on a clear day in September in Bologna, Italy. Measurements were conducted with a whole-plant polyethylene chamber system at 10minute intervals in the field.

of entire vineyards to changes in environmental conditions such as water deficit or salt stress and may be able to give some answers to the impact of climate change and the mitigation possibilities in terms of canopy structure and management.

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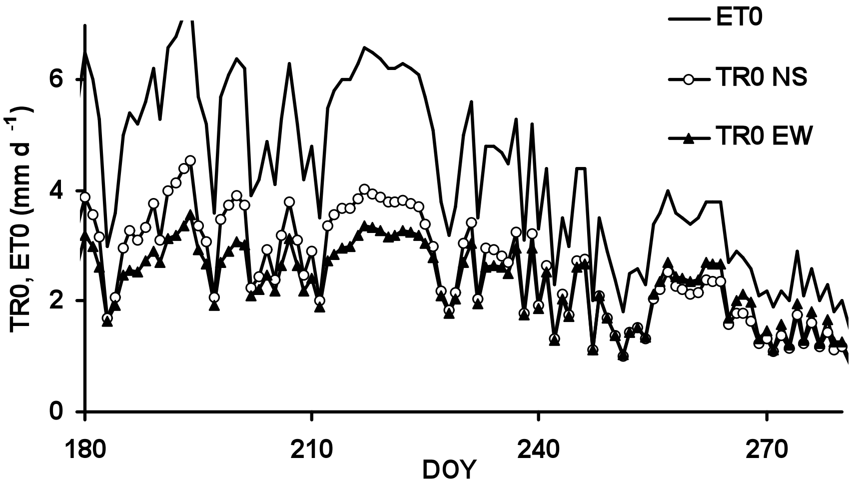

Fig. 3. Simulated vineyard transpiration (TR0) of different row orientations (NS, open symbols; EW closed symbols) as compared to potential evapo-transpiration (ET0) throughout most of the growing season (day of year, DOY).

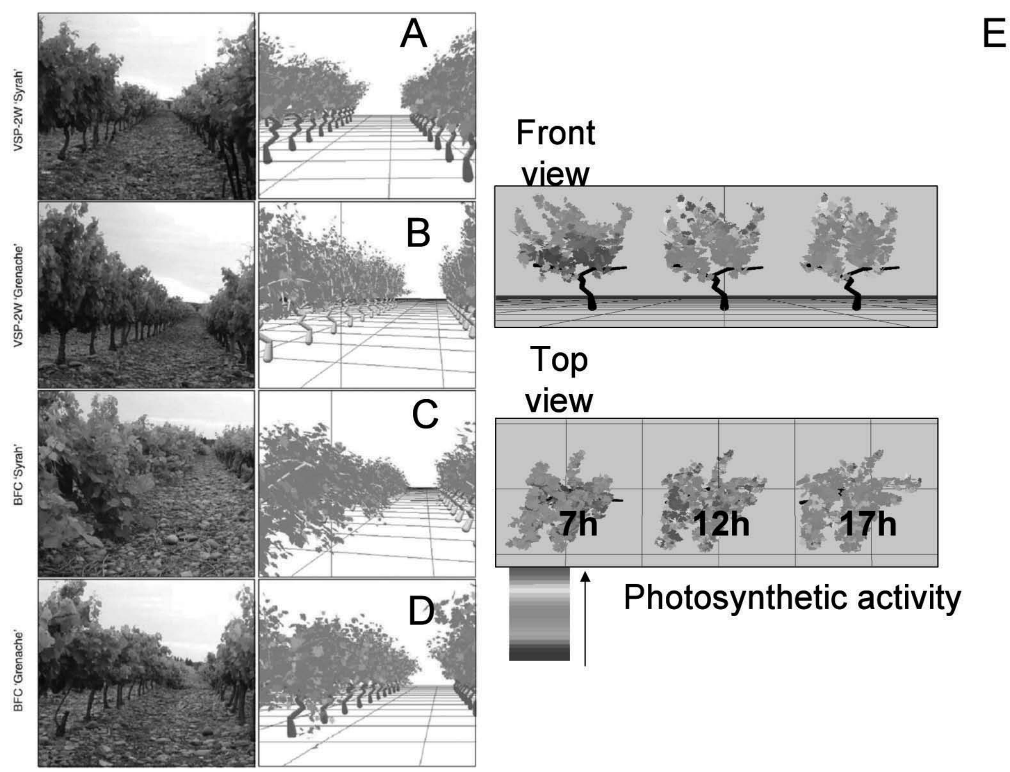

Fig. 4. Comparison of photographs taken in a real vineyard (veraison) with the corresponding simulations for two-wire (VSP-2W) (A, B) and one-wire (BFC) (C, D) training systems for the varieties Syrah (A, C) and Grenache (B, D). (E) shows an example for the coupling of a structural to a functional model on light interception and gas-exchange (E) (after Louarn et al. 2005 and 2008).

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INFLUENCE OF CANOPY MANAGEMENT SYSTEMS ON VINE PRODUCTIVITY AND FRUIT COMPOSITION

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Abstract: Canopy management systems are continually evolving in response to changes in vineyard management practices, adoption of alternative varieties, clones and rootstocks, and to economic and other industry considerations, e.g. modulation of yield and fruit composition between seasons. Adoption of low input systems for mechanization of dried grape and wine production following the introduction of mechanical harvesting in the early 1970's has led to a re-evaluation of approaches to canopy management, particularly in a low input context in Australia. Research conducted in the last 100 years has underpinned developments in canopy management and development of low input management systems. Compared to traditional systems of cane pruning with vertical shoot positioning in cool regions and spur pruning in warmer regions improvements in yield, fruit and wine composition with lighter pruning have been found. The productive capacity of lighter pruning systems, managed on tall trellises is increased by the early development of large open, canopies which provides a greater photosynthetic capacity, as leaf gas exchange and photosynthesis are largely unaffected by pruning system. Lighter pruning systems also have a larger vine mass and retain more stored carbohydrates during dormancy, which support early shoot growth in spring. Mechanical fruit thinning after fruit set can be used to manipulate fruit to leaf ratios, meet yield targets, promote early ripening and improve fruit and wine composition.

Canopy management principles and practices have been established with the aim of optimizing sunlight interception, photosynthetic capacity and fruit microclimate to improve yield and wine quality, particularly in vigorous, shaded vineyards (Smart et al. 1990). Approaches to canopy management are continually evolving in response to changes in other vineyard management practices (e.g. approaches to irrigation, drainage and soil management); adoption of alternative varieties, clones and rootstocks and economic sustainability. Mechanization of harvest and pruning has been adopted in Australian vineyards without compromising product quality to reduce the costs of wine and dried grape production (Clingeleffer 2000). This has provided a catalyst to refine approaches to canopy management, in a low input context. For wine production, significant benefits have been described from integrated approaches to control shoot vigor through the use of light pruning, deficit irrigation techniques, competitive sward management and adoption of low-medium vigor rootstocks (Clingeleffer 2009a,b). These approaches promote development of open canopies carrying small bunches with small berries and produce wines with enhanced quality attributes. Benefits from mechanical crop thinning to manipulate fruit to leaf ratios, modulate yield levels and promote early fruit maturity, colour and flavor development have also been reported (Clingeleffer 2009a,b). For dried grapes, highly productive systems have been developed utilizing tall trellises and cordon based, hanging cane approaches to canopy management. These provide a large canopy surface which optimizes photosynthetic capacity of high vigor, grafted vines with separation of fruiting and renewal zones to optimize fruitfulness and facilitate mechanization of the drying and pruning processes (Clingeleffer 1994, 1998, 2002).

This paper will provide an overview of research, conducted over the last century, which has underpinned the development of modern approaches to vine and canopy management, particularly in a low input context for both dried and winegrape production.

MATERIALS AND METHODS

The evolution of canopy management practices and underpinning research conducted over the last 100 years will be described for Sultana, the main dried grape variety used in Australia. Key research contributions undertaken for Sultana at the CSIRO Merbein site, located in the warm irrigated region in the Murray Valley will be documented. Similarly, key research contributions underpinning the developments in vine and canopy management in modern, mechanized low input winegrape vineyards will be described. Three examples which highlight the impact of varying canopy management practices on fruit and wine composition, in a low input context, will be presented. They include:-

A comparison of four pruning regimes (i.e. hand spur pruning, tight and loose mechanical hedging with cuts applied to give a pruned width of 0.4m and 0.6m respectively and minimal pruning) applied to Cabernet Sauvignon grown in a warm irrigated region (Petrie et al. 2003).

A comparison of three pruning systems (i.e. traditional 6-cane system with vertical shoot positioning, hanging canes and minimal pruning established on a high, 1.8 m cordon) applied to Cabernet Sauvignon grown in Mornington, Victoria, a cool climate region (Clingeleffer 1993).

Application of post-set mechanical crop thinning to manipulate the fruit to leaf ratio of Shiraz, grafted on Ramsey rootstock, and grown in a warm irrigated region (Clingeleffer et al. 2002).

RESULTS AND DISCUSSION

Evolution of canopy management for Australian Sultanas

Sultana grapevines (syn. Thompson Seedless) were first grown in Australia in the 1890's. The variety is unfruitful in the basal buds and requires cane pruning. The early settlers tried a number of pruning systems that gave 'good' yields (i.e. espalier, rod and spur and sylvoz, Henshilwood 1950). Adoption of the Sylvoz system was recommended for its simplicity, strong development of replacement canes and prevention of excessive growth at the end of the cane, all key principles of canopy management (Perkins 1985). However, the industry adopted a 'standard' three wire vertical trellis system with wires 0.7, 0.9 and 1.3 meters above the ground to which six canes were tightly twisted on to the lower wires (Lyon 1924). In the past century changes to vine and canopy management practices evolved, largely in response to increasing vine vigor. This was attributed to improved soil, irrigation and drainage management, adoption of improved clones and rootstocks and economic demands for improved production and cost efficiencies and lower costs, including mechanization of the drying process (Clingeleffer 1981, 1994). Over that period there has been a three-fold increase in productivity without compromising quality. The concept of trellis drying was first introduced by May and Kerridge (1966) to facilitate mechanization of the drying process. It involves drying of the fruit *in-situ* on the trellis after severance of fruit bearing canes, application of the drying emulsion and machine harvesting of the dried product. Trellis drying is now used by more than 70% of the Australian industry. Approaches to canopy management largely involve facilitation of trellis drying processes. Developments in canopy management of Sultana over the last century and the significant research contributions underpinning these changes are provided below.

Pruning to vigor and lighter pruning: Lyon (1930) found a correlation between growth and yield of Sultanas. He introduced the concept of pruning to vigor rather than the use of fixed cane numbers. The concept was further developed by Lyons and Walters (1941) who recognized the importance of pruning to maximize the crop and promote satisfactory development of the bearing unit and carbohydrate reserves for following seasons. Delayed ripening and reduced growth of renewal wood were identified as symptoms of over cropping. Lyon (1937) suggested that water stress may have contributed to the delayed ripening and poor growth described as over-cropping symptoms.

Over the last century there was a trend to lighter pruning as vine vigor, and hence vine capacity, increased (Clingeleffer 1981). This was facilitated by the use of larger trellises to accommodate the increase in shoot number, canopy size and crop load (see below). Cane numbers ranged from 6 (Lyon 1924), 8 (Lyon and Walters 1941), 10 (Antcliff et al. 1956), 12 (Antcliff 1965) and 14 (May et al. 1973). More than 20 canes may be retained on modern, cordon based, tall trellis systems (Clingeleffer 2002). An asymptotic yield response to lighter pruning was also established by Antcliff et al. (1956) and May et al. 1973. Studies with un-pruned Sultana vines (Lyon 1934, Clingeleffer 1981) led to the introduction of minimal pruning (Clingeleffer 1984a). Studies with minimal pruning of Sultana support the asymptotic response to pruning level. They show that pruning limits the potential crop and indicate that symptoms attributed to over-cropping were more likely due to water stress and low vine vigor and hence insufficient capacity to mature larger crops (reference?). Un-pruned Sultana vines maintained good productivity over a 40 year period (1967-2008) (reference?).

Trellis design: Lyon (1938) recognized a need to improve trellis design to alleviate problems of bunch crowding, uneven maturity and rain damage which accompanied increased vine size, yield and vegetative growth as vineyard management practices became less limiting. He recommended the use of a 0.3 m T-trellis which was later shown to improve yields by 12-20%, improve shoot distribution, develop uniform bunches, reduce wastage and improve drying ratios (Lyon 1939, Lyon and Walters 1941). Shaulis and May (1971) achieved a further 50% gain in productivity with a wide 0.9 m T-trellis, which developed a divided canopy leading to better budburst, more fruitful shoots and larger bunches, a result of more berries per bunch. May et al. (1973) achieved a 100% improvement in productivity with a combination of wide 0.9 m T-trellis, grafting on a high vigor rootstock (Ramsey) and lighter pruning (14 canes) over own rooted Sultanas with 8 canes trained on a narrow, 0.3 m T- trellis. There productivity gain was achieved without significant effects on juice total soluble solids or titratable acidity levels.

May (1960, 1966) reported that vertically trained shoots were superior to horizontally trained shoots when used as fruiting canes due to increased fruitfulness, development of larger primordia and increased vigor. May and Scholefield (1972) and Scholefield et al. (1977a) were able to improve productivity of narrow 0.3 m T-trellis with foliage wires which allowed replacement shoots to grow 2 m above the fruiting zone.

Since the introduction of trellis drying, research and commercial experiences have shown that it is ideally suited to vigorous high yielding vines to ensure retention of photosynthetic capacity (i.e. 50% leaf area) when the fruit bearing canes are cut (Scholefield et al. 1977a). Trellis drying can reduce yields in low vigor situations (May and Scholefield 1972, Scholefield et al. 1977a). Excessive defoliation as a result of cane cutting produced bunches with fewer flowers in spring (Scholefield et al. 1977b). Changes to canopy management and trellis design were made to facilitate trellis drying. Initially these were targeted at improving performance on T-trellis systems by installation of foliage wires, either vertically above the T-trellis or in a V or U formation to encourage vertical shoot growth of replacement canes and retention of a larger canopy after cane cutting and to allow access to the fruiting zone for application of drying emulsion (Clingeleffer 1981).

A number of cane pruning systems were compared to the standard T-trellis systems and evaluated for their potential to facilitate trellis drying and reduce cane pruning costs. May (1965a) showed that tight twisting of replacement canes onto trellis wires was unnecessary to sustain yield and that loose wrapping could reduce pruning costs. Systems trialed included various arched cane systems with simple forms of attachment which promoted vertical growth of replacement shoots away from the fruiting zone, produced an excellent spread of smaller bunches with reduced fruit clumping where adjacent vines met and carried a smaller proportion of bunches on shorter, terminal shoots (Clingeleffer 1981, May et al. 1978). A simple split system of training where all the canes were attached on one wire of a 0.9 m T-trellis with spurs on the other side of the crown was also introduced to facilitate mechanical cane cutting (May et al. 1978). The use of a simple hanging cane system based on a high, 1.8 m bilateral cordon was introduced by Clingeleffer (1981) to reduce pruning costs, provide an excellent spread of bunches in a single vertical plane, to promote separation of replacement shoots from the fruiting zone, and to improve cane fruitfulness and yield. Hanging cane systems where canes are attached to one or two wires below the cordon are still in wide use. Clingeleffer and May (1981) introduced the swing-arm trellis to extend the concepts of separating the fruit and cane replacement shoots. The swing-arm trellis had wires to support fruiting canes arising from a central bilateral cordon placed in a horizontal plane while replacement shoot growth occurred in the vertical plane. At pruning, the trellis was rotated 90 degrees so that the vertically climbing replacement canes were then positioned in the horizontal plane. The swing-arm system had higher yields due too more bunches resulting from increasing node numbers, better budburst and increased fruitfulness, i.e. responses attributed to development of better exposed climbing canes.

Modern tall trellis systems, now adopted on a wide scale by industry utilize the swing arm principle in combination with a high (1.8 m) bilateral cordon with hanging canes attached to trellis wires below (Clingeleffer 1998, 2002). These systems facilitate light pruning, upward vertical growth of replacement shoots and reduce shoot crowding leading to improved fruitfulness and productivity, application of drying emulsion, pest and disease control, mechanical cane cutting to commence the drying process and simplify removal of spent canes and pruning.

Bud fruitfulness and environmental factors: Barnard 1932 identified bud fruitfulness as an important factor contributing to yield variability between seasons, leading to the introduction of microscopic bud examination to estimate yield potential and adjust pruning level (Barnard and Thomas 1938, Thomas and Barnard 1938, Antcliff and Webster 1955). However, as a result of pruning studies conducted by Antcliff et al. (1955, 1956), it was suggested that detailed pruning recommendations based on forecast potential were not justified as there was no advantage in limiting production in high fruitfulness years. May (1961) developed a simple approach to assess fruiting potential across the district and suggested that there were benefits to adjust pruning levels in years of low fruitfulness. Lyon and Walters (1941) recognized the importance of selecting 'quality' canes at pruning. Antcliff et al. (1958) were able to further quantify the significance of cane morphology as they showed that the most fruitful canes were well ripened with a uniform brown appearance, of good diameter, without long internodes and had some lateral growth.

Enhanced understanding of the impact of environmental factors on crop development provided a link between seasonal variability in bud fertility and performance on trellises which reduced shoot crowding, and improved light interception and photosynthetic capacity (Clingeleffer 1981). Links between bud fruitfulness and climatic conditions were identified by Antcliff and Webster (1955). Baldwin (1964) reported a 20 day 'sensitive period' from mid November to early December, during which bright sunshine and maximum temperature were most significant in the determination of bud fruitfulness. May and Antcliff (1963) showed that shading the canopy during the period of initiation in November and December had a significant impact on bud fruitfulness and on yield in the following season. Bud fruitfulness and primordia size has been linked to carbohydrate levels in buds and dormant canes (Antcliff and Webster, 1955, Sommer et al., 2000). May (1965b) found that light intensity had an effect on bud fruitfulness and that the response was linked to shading of the bud rather than the subtending leaf. May et al (1976) compared the performance of shaded and well exposed canes on the same vine and found a direct link between the aerial environment in which a cane developed and its fruitfulness and yield, although berry weight and sugar accumulation were unaffected. The relationships between light interception, fruitfulness and yield for Sultana vines trained on a range of modern trellis systems were described by Sommer et al. (2000, 2001).

May and Antcliff (1963) demonstrated a direct effect of shading on crop development. Treatments with reduced light intensity had smaller bunches and smaller berries, although sugar accumulation was unaffected. Kliewer and Antcliff (1970) showed that defoliation treatments reduced berry weight and soluble solids but increased acidity, particularly in the early stages of ripening and that removal of apical leaves had a greater impact than removal of basal leaves. They established that 10 square centimeters of leaf per gram of fruit was required to adequately mature the crop, a value confirmed for minimal pruned Sultanas (Clingeleffer 1984). Sommer et al. (1995) compared the performance of cane and minimal pruned vines. They found that minimal pruned Sultanas had a capacity to carry and mature larger crops because they produced many more shoots and developed a larger canopy which filled earlier than cane pruned vines.

Enhanced understanding of leaf and canopy function: Kriedemann (1968) showed that photosynthesis of Sultana leaves was a function of light intensity, temperature and leaf age. His results highlighted the importance to photosynthesis of partial and intermittent illumination, sunflecks and shade within a dense canopy. The optimum temperature for photosynthesis was between 25-30 °C. Maximum photosynthesis of young leaves was achieved when they attained full size and decreased as they reached senescence. Kreidemann et al. (1970) confirmed that peak photosynthetic activity occurred when leaves were fully expanded, about 40 days after unfolding and that irrespective of leaf age, sucrose was the major CO_2 fixation product. Kreidemann and Smart (1971) found that photosynthesis declined rapidly, due to stomatal closure under water stress (i.e. leaf water potentials below -5 b or 0.5 MPa) and fell to zero between -12 b (1.2 MPa) and -15 b (1.5 MPa). They also showed that leaf photosynthesis, when light limited, followed a cosine response to changes in the angle of incident light and were able to demonstrate the importance of diffuse solar radiation in sustaining high levels of photosynthesis at low intensities of incident radiation. Kreidemann et al. (1973) were able to characterize the occurrence and photosynthetic utilization of sunflecks by leaves located within the canopy. Photosynthesis was sufficient to more than offset respiration losses from the shaded leaves. Similarly, Kriedemann and Buttrose (1971) showed that photosynthesis by young, green shoots could more than offset respiratory losses during their development.

Canopy management principles as they relate to low input winegrape production

Widespread adoption of mechanical pruning either by hedging (May and Clingeleffer 1997) and minimal pruning (Clingeleffer 1984b) followed the introduction of mechanical harvesters in the 1970's. Research studies have shown that there is considerable potential to manipulate, within a low input context, the development of both the canopy and crop (Clingeleffer 2009a,b). Important research contributions to this field are provided below.

Limitations of trellis design and row spacing: Inadequate trellis design limits the productivity of vigorous wine grapes. May et al. (1976) showed that yields of Crouchen on a 1.2 m T trellis, which developed an unmanaged divided canopy, were 25-30% higher than on a 0.3 m T-trellis. Similar results were reported for Shiraz by Hedberg and Raison (1982). They also found that closer row spacings (e.g. 2.25 m cf 3.0 m) could be adopted to increase total leaf area and hence photosynthetic capacity and yield per hectare. Clingeleffer (1983) and Sommer and Clingeleffer (1995) described significant productivity gains in narrow row plantings (i.e. spacings of 2.25 cf 3.0 m) across a number of key wine varieties, particularly when minimal pruned on single wire trellises. Wide trellis systems were widely used in the Australian industry in the 1970's but have now been replaced because of the cost of maintenance and difficulties with mechanical pruning and harvesting of the cordon based systems.

Type of fruiting unit: May et al. (1976), Woodham et al. (1983), Clingeleffer and Sommer (1995) reported that cane pruning reduced yields of wine varieties. This was attributed to debilitating effects associated with the removal of one- and two-year- wood at pruning on vine size and capacity (Woodham et al. 1983, Rühl and Clingeleffer 1993). For Cabernet Franc, yield, pruning weight, bunch number, bunch weight and berry weight were reduced by 26%, 25%, 7%, 18% and 10% respectively by cane pruning compared to spur pruning (Clingeleffer and Sommer 1995). Spur pruning of Cabernet Franc removed about 8% of the vine's total stored carbohydrate, 10 % of reducing sugars and 31% of sucrose (Rühl and Clingeleffer 1993). It could be expected that these values would be about double with cane pruning.

For Cabernet Sauvignon, Clingeleffer (1989, 1993) varied the length of fruiting units on the same vine (i.e. 2-node spurs to 14-node canes) to avoid confounding effects of crop load and carryover effects of treatments applied in the previous season. Juice composition was largely unaffected by a 5-fold difference in cropping level, suggesting that detailed pruning to similar length fruiting units is unnecessary. Important responses were earlier budburst on shorter bearers and at distal nodes with stimulation of budburst and shoot growth near to pruning cuts; a positive linear relationship between yield and nodes per bearer as a result of increased bunch and shoot numbers and a linear decrease in bunch weight and yield per node as node number per bearer increased. There was no significant difference in yield between the 2-, 3- and 4-node bearers due to a sharp decline in budburst. Detailed studies of budburst and fruitfulness along the bearers demonstrated the within vine control of budburst and showed the strong influence of node number on percentage budburst and the influence of the pruning cut on budburst. Maximum fruitfulness was found between nodes 7 and 10 on longer bearers, as reported for a range of winegrape varieties by May and Cellier (1973).

Pruning level: May et al. (1976) showed for Crouchen that yield responses to increasing node number, tended to be asymptotic, as reported above for Sultana, as increasing the node number from 32 to 48 nodes per vine produced a 15% increase in yield but a further increase in yield was not achieved with 64 nodes per vine. To determine the main adaptive processes to lighter pruning, Clingeleffer (1993a) manipulated pruning level of Cabernet Sauvignon by increasing the node number retained on 24 bearers, with pruning levels ranging from 48-336 nodes per vine. Treatments ranged from 2-node spurs to 14-bud canes. The lighter pruning treatments resulted in significant yield increases (2-fold) without influencing fruit composition and spectral properties, except for a slight delay in maturity (maximum 0.8 °Brix). There was a positive linear relationship between yield and nodes per bearer because of increased shoot and bunch numbers. The main adaptive processes controlling production with increasing nodes per vine were the development of more bunches (83-277 bunches per vine), smaller bunches (80.4-42.4g) and reduced budburst (1.24-0.61 shoots/node). Yields were similar for the 2-, 3- and 4-node treatments, due to a sharp decline in budburst with the less severe treatments, which is agreement with commercial and experimental studies with mechanical hedging, where yield was similar to hand pruning (May and Clingeleffer 1977). Lightly pruned vines were more efficient, as improved productivity was associated with a reduction in both one-year-wood and total wood removed at pruning. The large differences in the ratio of yield to one-year-wood, ranging from 3.6 to 32.2 indicate that it is not a good predictor of the vines potential for crop production as has also been observed in minimal pruning studies with Cabernet

Franc (Clingeleffer and Krake 1992). In that study the minimal pruned, compared to spur pruned vines had many more shoots (276 cf 122 shoots per vine), shorter shoots (14.9 cf 60.3 cm) with fewer nodes (5.5 cf 12.4 nodes/shoot) and shorter internode length (2.7 cf 4.9). The results show that severe pruning limits the productive capacity of the vine, leading to strong shoot growth which must be managed and removed at pruning. The vine has the capacity to self regulate through reduction in budburst and development of smaller bunches and reduced shoot growth.

Canopy development: Sommer and Clingeleffer (1993) compared the performance of non- irrigated Cabernet Sauvignon pruned to 6 canes with mechanical hedging and minimal pruning in a vineyard receiving supplementary irrigation in the cooler, Coonawarra region. Yields of the 6-cane, hedge and minimal pruned treatments were 3.7, 5.5 and 18.9 t/ha respectively. The non-irrigated treatment had lower total soluble solids (20 ^{o}Brix) compared to 22.1 ^{o}Brix and 21.8 ^{o}Brix with the hedged and minimal pruned treatments respectively, despite having a similar leaf to fruit ratio to the minimal pruned vines (ie. 16.9 and 16.1 cm^2/gm). This difference was associated with stress and reduced photosynthetic capacity of the non-irrigated vines around veraison. Hedging stimulated shoot growth leading to the highest leaf to fruit ratio of 29.8 cm^2/gm. The production capacity of each treatment was related to canopy size with the 6-cane, hedge and minimal pruned treatments having maximum leaf areas in the order of 4, 11 and 22 m^2/vine, respectively. As with Sultana, total leaf on minimal pruned vines developed more rapidly early in the season and attained maximum leaf area earlier. Canopy growth ceased earlier than the other treatments, presumably due to competition between the shoots and the developing crop and development of laterals with more severe pruning treatments. Similar results were also reported for Cabernet Sauvignon on own roots or grafted on the high vigor Ramsey rootstock, which included comparisons of cane and minimal pruning treatments in each case (Sommer et al. 1993). On own roots, yields were increased by minimal pruning from 15.0 to 25.5 t/ha and on Ramsey rootstock from 33.1 to 49.9t/ha. Maximum leaf area was increased by minimal pruning from 6.5 to 16 m^2/vine for own roots and from 13.5 to 28 m^2/vine for Ramsey vines. Furthermore, studies by Rühl and Clingeleffer (1992) and Sommer and Clingeleffer (1996) with Cabernet Franc and Cabernet Sauvignon have demonstrated the significance of the greater mass of older wood on minimal pruned vines for the storage of carbohydrates to support the early shoot growth in spring, as differences in carbohydrate concentrations between the pruning systems were relatively small in the various plant parts (ie. roots, trunks, cordons and one- and two-year-wood).

Canopy management of winegrapes, in a low input context.

Research over 40 years has shown benefits from adoption of lighter pruning systems. These include development of vines with small, well exposed bunches with small berries, spread over a large canopy surface leading to good disease control and improved berry composition, provided adequate sugar levels are reached (Clingeleffer 2000, Clingeleffer et al. 2000). Compared to severe forms of pruning, minimal pruned vines generally produce juice with better organic acid composition, expressed as a superior tartrate to malate ratio, better wine colour and higher phenolics (Clingeleffer 1993, Clingeleffer 2000). Benefits from the development of an integrated approach involving vine vigor control by light pruning, deficit irrigation techniques and competitive sward management and adoption of low-medium vigor rootstocks together with manipulation of the leaf to fruit ratio by crop thinning have been reported by Clingeleffer (2009b). Further examples have been chosen for inclusion in more detail below.

Light hedging and minimal pruning (warm climate): The benefits of light pruning when applied to Cabernet Sauvignon grown in a warm climate, were demonstrated by Petrie et al. (2003). The 4 pruning systems (hand spur, tight and loose mechanical hedging and minimal) produced distinctly different canopy architectures. While yield was not affected by the treatments, as pruning severity decreased, bunch numbers increased (74 to 243), bunch weight decreased (68.8 to 23.7g) and berry weight decreased (1.03 to 0.76 g). The fruit was harvested on the same day with total soluble solids for the spur and mechanical hedging treatments between 23.0 and 23.6 ^{0}Brix, while maturity was delayed with minimal pruning (21.9 ^{0}Brix). Spur pruning decreased berry anthocyanins compared with the other treatments (ie. 0.55, 0.67, 0.84 and 0.68 mg/g for the spur, 0.4 and 0.6 m hedging treatments and minimal pruning, respectively). The lighter hedging (0.6 m) had significantly higher levels of anthocyanins than the 0.4 m wide treatment. Despite the lower maturity, colour levels in the fruit of minimal pruned vines were similar to the 0.4 m hedge treatment and higher than the spur pruned vines. The results confirm earlier studies where manipulation of canopy architecture using light pruning produced more open canopies and improved fruit and wine composition (Clingeleffer 2000, 2009a,b and Clingeleffer et al. 2000). They also demonstrate how a subtle difference in mechanical pruning can cause a substantial difference in fruit quality.

Hanging canes and minimal pruning (cool climate): The performance of Cabernet Sauvignon with managed and unmanaged canopies was compared in studies with traditional, high input cane pruning using 6 canes and vertical shoot positioning and two low input systems, hanging canes and minimal pruning established on high, 1.8m high cordons (Clingeleffer 1993b). Hanging canes and minimal pruning both produced higher yields (19.4 and 18.9 t/ha, respectively), smaller berries (0.74 g) but delayed maturity (i.e. total soluble solids of 20.4 and 21.3 ^{0}Brix, respectively) compared to cane pruning which had a yield of 12.7 t/ha, a berry weight of 0.95 g and total soluble solids of 21.8 ^{o}Brix. Fruit from both the hanging cane and minimal pruning treatments had higher tartrate to malate ratios and produced wines with higher colour density (i.e. 20.1 and 19.1 a.u. respectively cf to 15.3 a.u. for cane pruning), higher total anthocyanins (1030 and 962 mg/L respectively cf to 850 mg/L for cane pruning) and higher total phenolics (68 and 64 a.u. respectively cf to 54 a.u. for cane pruning). Wines from the higher yielding, lighter pruned treatments were also preferred in sensory assessments. The cane pruned treatment produced high shoot vigor which required vertical training and leaf removal at the bunch zone. The results suggest that alternative strategies of management should be considered to reduce production costs in cool climates where varieties with low fruitfulness require cane pruning and the canopy is managed with vertical shoot positioning. Favourable vine architecture can be achieved through the use of tall trellises and lighter pruning techniques. The results are consistent with those of Kliewer et al. (1989) who found that vertical training of shoots stimulated growth rate and lateral development leading to high shoot weights whereas downward training of shoots had the reverse effect. Furthermore, Lavee and Zehavi (1994) found that vertical shoot positioning of mechanically pruned Cabernet Sauvignon and Chardonnay reduced light interception, yield and overall efficiency, indicated by lower ratios of yield to pruning weight. Opportunities to develop low input pruning systems based on hanging canes and swing arm principle as described above for Sultanas should be explored.

Post-set crop control by mechanical thinning: Manipulation of fruit to leaf ratios by crop adjustment after fruit set of minimal pruned Cabernet Sauvignon and Shiraz, either by mechanical thinning using mechanical harvesters or skirting, has been successfully applied in both cool and warm regions (Clingeleffer 2009a,b, Petrie et al. 2003). In one such study with Shiraz grafted on Ramsey rootstock and grown in a warm irrigated region, mechanical crop thinning was applied in early December, 3 weeks after the completion of fruit set (Clingeleffer et al. 2002). Fruit of the mechanically thinned treatment ripened faster than the control and was harvested for winemaking three weeks earlier (i.e. 8th March cf to 23rd March) at similar maturity levels (ie. 22 ^{o}Brix). Mechanical thinning reduced the yield by 36% (i.e. from 35 to 23 tha^{-1}) due to the combined effects of bunch removal, lower berry numbers per bunch and development of smaller berries. Compared to the control, mechanical thinning produced fruit with a significantly lower pH (3.80 cf 4.22), higher titratable acidity (5.20 cf 3.72 g/L) and higher anthocyanins (1.10 cf 0.82 mg/g). Wines from the thinned treatment had improved spectral qualities (i.e. increases in colour density of 36%, ionised anthocyanins of 34%, total anthocyanins of 48% and phenolics of 46%) and received higher sensory scores. Such results show that manipulation of fruit to leaf ratios by post-set crop control techniques may be a powerful tool to manipulate fruit and wine composition when integrated with low input management practices. A range of mechanical and chemical techniques for control of cropping levels by removal of shoots, berries, inflorescences and bunches are being reported in the literature. For example, a simple, tractor mounted radial head mechanical thinning device been successfully used for post-set crop control of mechanically hedged Cabernet Sauvignon and targeted crop removal from minimal pruned Cabernet Sauvignon. Gibberellic acid treatments have been successfully applied to minimal pruned Riesling vines in Germany to reduce crop load and subsequent fruitfulness and retain quality benefits associated with reduced bunch rot and enhanced flavour and aroma characteristics (Weyand and Schultz, 2006).

CONCLUSIONS

Approaches to canopy management of wine and dried grapes have evolved as improved planting material has been adopted and changes have been made to vineyard management practices leading to increased vine vigor and capacity, and as mechanization has been introduced to reduce production costs. For wine production, techniques to reduce vine vigor and enhance fruit and wine composition (Clingeleffer 2000a,b) offer considerable potential to minimize interventions required to manipulate the canopy in traditional systems (e.g. vertical shoot positioning, summer trimming, shoot and leaf removal) and reduce trellis costs and hence, total production costs.

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VINE BALANCE: WHAT IS IT AND HOW DOES IT CHANGE OVER THE SEASON?

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Abstract: Vine balance is a commonly used term in viticulture that expresses the concept of an appropriate balance of vegetative to reproductive growth of the vine. A properly balanced vine has adequate vine growth to provide appropriate vine capacity to ripen the crop, develop fruitful buds for the following year, and develop appropriate reserves. The crop is appropriate to allow the needed vine growth, but not excessive growth and yet take advantage of a good balance of yield and quality. Balanced vines will not require excessive canopy management. The concept of "crop load" is closely related. Although these concepts are qualitatively quite clear to most, the quantitative expression of vine balance or crop load is more difficult. Most expressions are indirect (such as yield to pruning weight ratio), and do not address dynamics of growth balances during the season. A dynamic simulation model of carbohydrate production can help provide seasonal patterns of vegetative and reproductive growth requirements in relation to canopy carbon supply. How those patterns relate to fruit and wine aroma and flavor metabolites is still poorly understood, but recent research on seasonal dynamics of methoxypyrazine synthesis and degradation may provide some directions for future research.

The concept of vine balance, often discussed and felt to be a key goal of grape growing, refers to the relative balance of vegetative to reproductive growth. The term crop load is conceptually similar but is more restricted to the balance of vine capacity/supply to crop demand while not directly considering vegetative demands. The effects of vine balance or crop load on wine quality is hotly debated in the literature and tasting room, but more and more it appears that best wine quality is not obtained from vines that are greatly out of balance, either overcropped or excessively undercropped.

Vine balance and crop load are defined in various ways that are discussed in excellent reviews on vine balance by Dry, 2005 and Archer and Hunter, 2005. These reviews summarize the current understanding very well, so we will primarily emphasize a few points on current approaches, but will focus on the seasonal dynamics of vine balance and crop load and discuss approaches to integrating vine balance with grape and wine flavors and aromas.

Vine balance has generally been expressed as yield per pruning weight or leaf area per gram of fruit. Although generally useful and relatively practical, such indices are indirect, and thus limited by their underlying assumptions. Pruning weight is assumed to estimate vine capacity. Pruning weight is an indirect expression and as such is based on assumptions that may not always hold (e.g. unpruned vines will have zero pruning weight, yet may have a large vine capacity). Vine capacity is more directly related to vine light interception, and varies greatly depending on spacing, training system, canopy display and trellis fill. For example, divided canopies such as the Lyre system might have similar leaf areas and pruning weights to undivided canopies, but considerably more light interception. Additionally, the pruning weight to light interception relationship is not linear; changes in pruning weight at low pruning weights will have greater effects than at high pruning weights where additional growth primarily causes more shade rather than increased light interception. Crop level also may affect vine pruning weights. Expressing capacity as pruning weight also assumes healthy leaves with full function, though leaf function may vary greatly with mineral nutrition or water deficits. Finally, there is only one value given per year, thus any seasonal dynamics are ignored.

Leaf area per gram of fruit attempts to be more physiologically direct as it reflects the actual leaf area obtained. Physiological studies show that basic berry size and composition (Brix, TA, etc.) are a function of exposed, healthy leaf to fruit ratio. It is assumed, reasonably, that exposed leaf area reflects light interception, but in the field it is more difficult to estimate the exposed leaf area and average leaf function due to the complexity of the grape canopy. Alain Carbonneau (1995) provided more detail in estimating vine capacity by the estimation of exposed surface areas of varying trellis systems which allows seasonal estimates of vine capacity.

Another limitation of such methods is that they do not directly address which physiological processes are involved. It is unlikely that only one process is involved, though carbohydrate production and allocation appears to be one of the most fundamental as it provides both the energy and the building blocks for growth and metabolism. Certainly, mineral nutrition and water relations are intimately involved, and all of these are affected by canopy management of leaves and cluster microclimate.

To fully integrate many complex processes in a dynamic environment will require dynamic models. Initially, carbon production and utilization is the best-understood process and has been successfully modeled in many plants. Therefore a simplified carbon balance model has been developed to begin to evaluate the seasonal dynamics of the carbon component of vine capacity and demand for carbon (Lakso and Poni, 2005; Lakso, 2006; Lakso et al., 2008).

SEASONAL DYNAMICS OF VINE BALANCE AND CROP LOAD

A simplified dynamic carbon balance model, developed initially for apple trees, was adapted for grapevines using an auto-programming software, STELLA®, that requires few programming skills. The model, called VitiSim, uses a daily time step to simulate seasonal leaf area development, vine light interception, canopy photosynthesis, canopy respiration, total dry matter accumulation, and dry matter distribution to competing vine organs. From these we can: (a) develop seasonal curves of the growth, vine capacity, demands of varying organs and balances between the supply and demands; (b) evaluate the effects of daily weather or long-term climate as well as different stress and cultural factors on these patterns; and (c) try to determine if and when critical periods of carbon supply and demand occur, especially in relation to fruit development and ripening.

Seasonal Demand Dynamics. In mature vines we and others have found that the vast majority of net seasonal dry matter assimilated goes into current growth (leaves, shoot stems and crop). Thus shoot and crop demands have the greatest impacts. In this example, we present model simulations of large heavily-cropping Concord juice grape vines (spaced 2.4 x 2.7 m) with industry standard 100 shoots/vine (crops about 22 tons/ha) and minimally-pruned vines with 350 shoots per vine (crops about 27 tons/ha).

As expected, seasonal patterns of supply and demand show different patterns. The demands of shoot growth for carbon typically shows a single peak around or after bloom, with the peak occurring earlier in vines with higher node numbers and later in vines with fewer shoots that grow longer into the season (Fig. 1). The demand pattern for the crop is the typical double peak with a peak a few weeks after bloom during the later cell division, followed by a decline during the lag period (Fig. 2). After veraison the second peak occurs very rapidly, then declines with ripening. It should be noted that shoot numbers affect the timing of peak demand, however, different crop levels have little effect on crop demand timing, just total demand. Root growth has been found to be extremely variable in seasonal pattern likely reflecting a weak sink strength (Comas et al., 2005).

Seasonal Carbon Supply and Supply:Demand Balances. The seasonal pattern of supply is relatively simple, peaking between bloom and veraison and varying primarily with total light interception. Since light interception depends on leaf area, higher shoot numbers will lead to a more rapid canopy development and an earlier peak in canopy photosynthesis (Fig. 3). The differences of pruning level on the individual demand and supply curves do not appear very striking. However, when the combined demand of the crop and the shoot canopy are subtracted from the net CO_2 available from canopy photosynthesis (Fig. 4), there are several clear differences in the seasonal balance. Compared to the 110-shoot vine, the minimally-pruned vine requires more reserves initially due to the greater number of shoots beginning growth, but then the rapid canopy completion and the early decline in shoot demand leads to a much more positive carbon balance in the immediate post-bloom period. This is the period of fruit set, flower bud development, and early root growth. Post-veraison, the minimally-pruned vine has a strong carbon deficit as the supply is similar but the crop demand is much higher.

These patterns may explain why we have seen very stable high yields over many years with minimally-pruned vines (if other stresses are limited), yet they struggle to reach acceptable

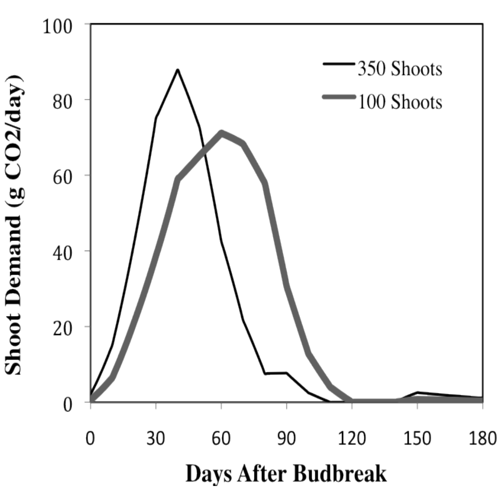

Fig. 1. VitiSim simulations of the demand for shoot growth of Concord vines with 100 shoots or 350 shoots/vine and long-term Geneva NY weather.

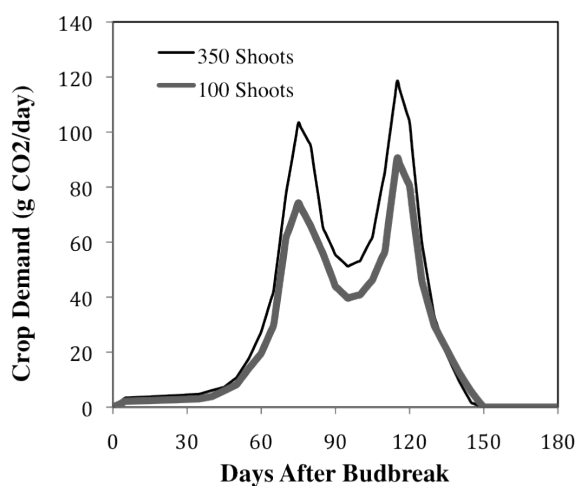

Fig. 2. VitiSim simulations of the demand for crop growth of Concord vines with 100 shoots or 350 shoots/vine and long-term Geneva NY weather

sugar levels in the crop. A practical response to this has been developed by our colleagues, the late Bob Pool and currently Terry Bates, by using high node numbers, then mechanically thinning the crop at 75-80 days after budbreak to re-establish the vine crop load. Also it may explain why we did not find any reduction in fine root growth and found slightly earlier root growth with minimally-pruned vines, even with 20-25% higher crop levels (Comas et al., 2005).

Although Concord vines may not represent the magnitude of the values of shoot numbers and crop in other systems, we believe the general patterns and the effects of pruning level shown here will be similar in most species and varieties. Hopefully a better understanding of the seasonal dynamics of carbon balance and vine growth will help deepen our understanding of vine balance.

VINE GROWTH, BALANCE AND FLAVORS

A primary interest in vine balance or crop load is the relationship to grape and wine aromas and flavors. In New York we have extremely variable weather from year to year, making premium wine production a challenge. For the Cabernet family of red varieties, we often have problems with excessive green characters in the wines in cool and especially wet years. This is also aggravated by shaded clusters in heavy canopies, vigorous growth, and short growing seasons. With colleague Justine Vanden Heuvel, viticulturist, we have been examining factors that affect concentrations of methoxypyrazines, the common bell pepper aroma that is important to green characters in Cabernets, though not the whole story.

Vine vigor and balance has been seen to be important to methoxypyrazine (MP) levels (Bogart and Bisson, 2006). The most striking results have shown that minimally-pruned vines have much lower concentrations of isobutyl methoxypyrazine (IBMP, the most important form) during the season than normally pruned vines (Allen and Lacey 1993). It has also been observed and documented that exposed clusters generally have 20-40% lower concentrations of IBMP, and that these differences appear early in the growing season (Ryona, et al., 2008). Also, Ryona et al. (2008) found that final harvest concentrations of IBMP (on the same day) was highly correlated to the pre-veraison maximum values. Environmental conditions, either weather or irrigation, that lead to more vigorous growth, especially later into the season appear to induce higher IBMP concentrations (Roujee de Boubee et al., 200; Sala et al., 2005, Chapman et al., 2004). Finally, Chapman et al. (2004) in a crop load study found that (1) pruning heavily to low bud numbers reduced crop but led to higher IBMP, and (2) that thinning at veraison to a range of lower crops had essentially no effect. Although growth data was not presented, it is likely that heavier pruning led to increased vigor. All together, the observations and research suggest that fruit from vines with excessive vegetative vigor generally has greater MP's and more green flavors.

Experiments on MP's in Cabernet Franc. To differentiate the effects of cluster exposure from vigor we have conducted experiments over two seasons to determine seasonal patterns of IBMP in Cabernet Franc comparing exposed versus shaded clusters within the same vines (Ryona et al., 2008) as well as inducing shoot vigor differences with shoot numbers (then cluster thinned to the lightest crop) and comparing exposed clusters only. Fully exposed clusters were chosen to minimize any effects of shoot numbers or vigor on cluster microclimate.

Seasonal IBMP concentrations in fruit showed the same pattern in 2007 and 2008 with the great majority of synthesis occurring in the period of 30-50 days after bloom (Fig. 5). However, much higher concentrations developed in 2008 (a wet year of high shoot growth during the IBMP synthesis period) than in 2007 (a dry hot year of reduced shoot growth just prior to the IBMP synthesis).

When comparing effects of shoot numbers and natural vari-

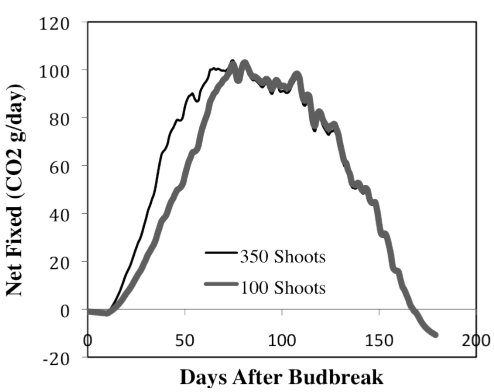

Fig. 3. VitiSim simulations of the canopy net CO2 fixation of Concord vines with 100 shoots or 350 shoots/vine and long-term Geneva NY weather.

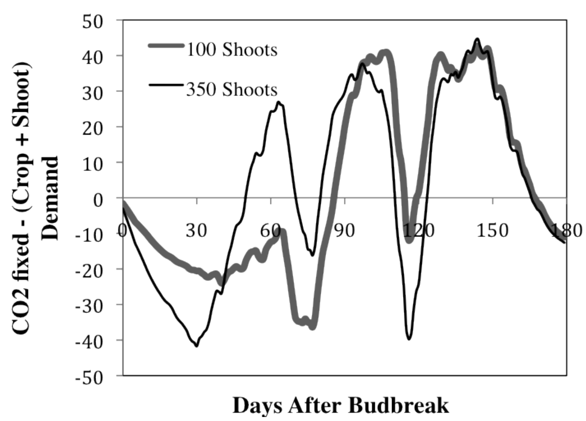

Fig. 4. . VitiSim simulations of the balance of canopy net CO2 fixation minus the combined demand of crop and shoot growth of Concord vines with 100 shoots or 350 shoots/vine.

ation in shoot vigor on IBMP in fully exposed clusters, a clear correlation of maximum IBMP levels and mean shoot growth rates during the main IBMP synthesis period was found (Fig. 6).

To achieve vine balance, the vine must:

(1) have adequate leaf area to be able to appropriately ripen a normal crop and to support adequate development for roots, reserves and bud development for next year, and

(2) not have excessive leaf area that will cause dense canopies and poor canopy microclimates and in the Cabernet varieties possibly induce high levels of IBMP.

A simple calculation was done for the relationship of Cabernet Franc shoot length to provide adequate leaf area to ripen the crop represented by 1, 2 or 3 clusters/shoot (Fig. 7). This shows that shoot lengths of 100 cm may be adequate for a 7 t/ha crop, but heavier crops shoot lengths of 140-180 cm would be required.

The length of a shoot not only affects leaf area produced, but also affects how long the shoot will continue to grow. We monitored Cabernet Franc shoot growth on many vines and found that if shoots grew to the required lengths of about 150 cm to provide adequate leaf area, they also terminated growth just before or at the beginning of the IBMP synthesis period (Fig. 8). Vines with longer shoots that grew to over 2 m produced excess leaf area, grew vigorously during the IBMP synthesis period and produced fruit with higher levels of IBMP.

Thus it appears that a balanced vine in this case would grow shoots until they were about 150 cm long, terminate before IBMP synthesis and have adequate leaf area to support 10-12 t/ha crops. For Cabernet types, this may in part explain why minimally-pruned or high node-number vines as common in Australia can produce quite ripe flavor profiles with heavy crops: the high node numbers produce early full canopies to be able to ripen a large crop, but also the large number of shoots terminate growth early. Conversely, in other areas that use heavier pruning and restrict crop, stimulation of shoot growth too much may lead to vigorous shoot growth during the IBMP synthesis period, giving small crops of green fruit as Chapman (2004) showed.

Visits with many top producers as well as experimental results suggest that in general shoot lengths of approximately 150 cm will be optimal as it will fill the trellis to give full vine capacity to support the ripening of a full crop, avoid excessive canopy density, reduce the need for multiple topping and expensive canopy management, terminate growth relatively early to allow good development of both the crop, the roots and the perennial structure with its reserves.

Reaching this goal is not always easy. With a low potential site and soil, nutrients and water can be added incrementally to reach the desired balance. But with high potential sites, especially in wetter climates or years, controlling growth is a challenge. Many growers in arid zones effectively utilize some form of deficit irrigation in the bloom-veraison period to regulate shoot growth and reach the goals outlined. In humid zones this option is limited. From the physiological perspective taken in this effort, it would be preferable to move to higher bud counts to develop a full canopy quickly and reduce final shoot lengths, then after set and some berry development, cluster thin to the appropriate crop level that can be fully ripened along with the development of reserves and good vegetative maturity (periderm development – an indicator found to be well correlated to wine score in Shiraz – Rolley, 2004).

It should be noted that our work refers to Cabernet Franc. White wine cultivars may differ in their responses and often appear to be optimal with less stress and more vine vigor. Also Pinot Noir may be a special case for red wines that may have different optima.

CONCLUSIONS

In conclusion, vine balance, and the related crop load, are not static concepts over the growing season as is implied by simplified indices. Dynamic carbon balance modeling can pro-

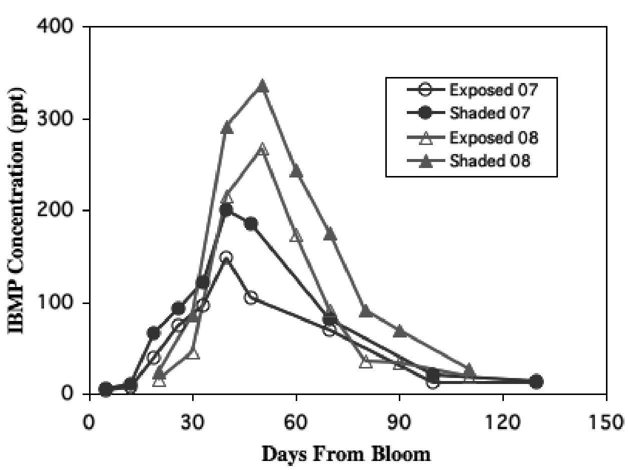

Fig. 5. Seasonal pattern of berry IBMP concentration in exposed and shaded clusters of Cabernet Franc in NY.

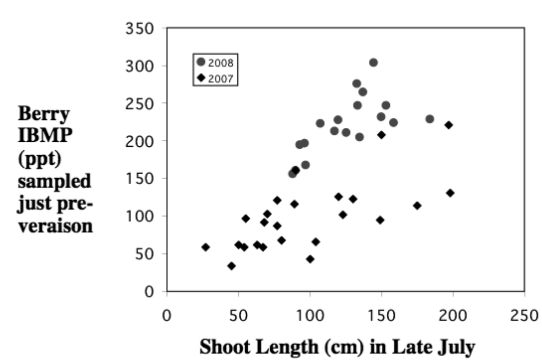

Fig. 6. Relationship of pre-veraison maximum berry IBMP and mean vine shoot length during the main period of IBMP synthesis.

vide useful seasonal integration of current knowledge that may provide a more in-depth understanding of these important, yet complex relationships. An example of the correlations of shoot growth and methoxypyrazine synthesis in Cabernet Franc suggests relationships between vine growth and grape and wine aroma and flavor development which is a critical area for future research.

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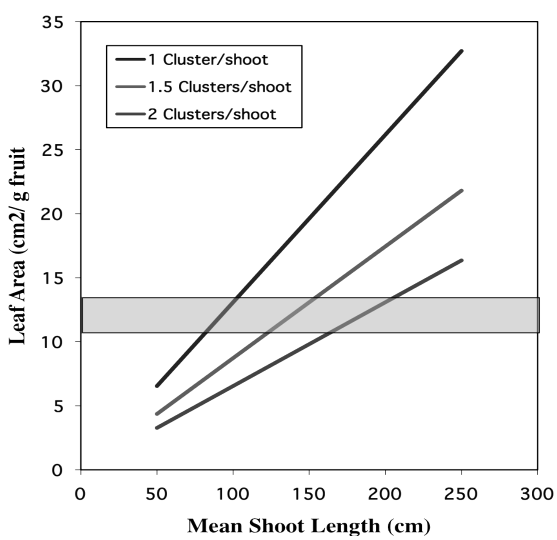

Fig. 7. Calculation of Cabernet Franc leaf area per fruit for shoots of different lengths with 1, 2 or 3 clusters (approximating yields of 7, 10 and 14 tons/ha) based on experimental data on shoots and cluster weights. Assumes adequate leaf exposure. Gray bar indicates adequate LA/g fruit of about 10-12 cm2.

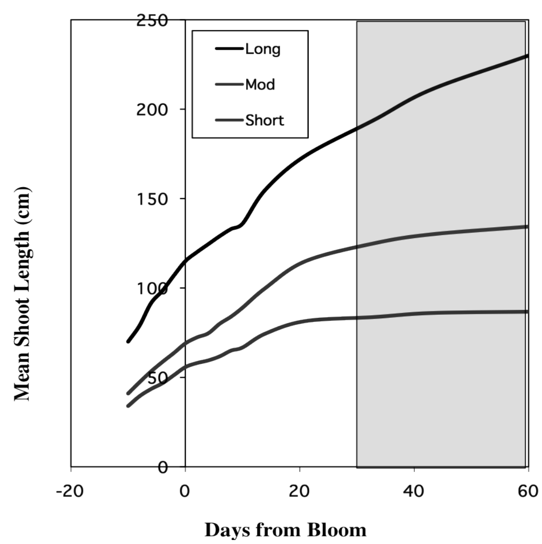

Fig. 8. Growth curves of short, moderate and long (final lengths of 90, 140 and 230 cm respectively) Cabernet Franc shoots and the period of pre-veraison synthesis of IBMP (gray zone). Note the short and moderate length shoots slow growth just before IBMP synthesis begins.

EVOLUTION OF CANOPY MANAGEMENT: FROM HISTORY TO SCIENTIFIC MODELING

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Abstract: The diversity of the grapevine architectures is described and classified. Its explanation relies on the evolution of canopy management in the world which is presented from history to recent developments. The influence of canopy management on microclimate and plant physiology is summarized, while pointing out the evolution of biological concepts in Viticulture. Modeling is a final tool allowing to synthetize knowledge and observations, and to simulate grapevine responses to canopy manipulation. Examples are given such as the biological triptych 'Exposed Leaf Area – Production – Vigour', and canopy reconstruction.

Keywords: grapevine, canopy management, training system, history, ecophysiology, modelling, vegetation, microclimate, production, berry maturation, wine quality, mechanization, new technologies, costs of production, environment, Terroir.

Canopy management has been an efficient challenge either for the progress in Ecophysiology (or Environmental Physiology) including Microclimatology, Architecture, whole plant Physiology, or for the progress in cultivation technics such as pruning, trellising, mechanization. It is interesting, at first, to make a survey, as exhaustive as possible at the world scale, of the *biodiversity of architectures*, covering the range of natural, historical, current and new forms. This represents the basis for the proposed study which deals with the historical evolution of canopy management and the main steps of the associated research.

I – DESCRIPTION OF THE MAIN FORMS OF CANOPY ARCHITECTURES AND THE ORIGIN

A dictionary of the architectures and the training systems of the grapevine was produced by Carbonneau and Cargnello (2003) in the context of the GESCO (Groupe d'Etude des Systèmes de COnduite de la vigne / Study Group of Training Systems of the grapevine; since 2007, G*i*ESCO: Groupe *international* d'Experts en Systèmes vitivinicoles et CoOpération / Group of *international* Experts in vitivinicultural Systems and CoOperation).

This dictionary includes in particular a description, a codification and a drawing of 50 basic forms or architectures which represents the biodiversity in the world and the background of the study. Figure 1 illustrates that. Such a huge variability in canopy shapes has its roots in the history of Viticulture.

At this point, it is useful to remind that the grapevine was domesticated by man, very probably at the neolithic period in TransCaucasia which is located between the black sea and the Caspien sea, and corresponds approximatively to the present Georgia. The wild grape was *Vitis vinifera silvestris*, dioïc – the female (or some hermaphrodite) plants bearing very small berries –, which was naturally selected in association with forest trees in this zone the climate of which is a combination of mountain, continental and mediterranean types. The man domesticated the grapevine as he did for other plants and animals, probably by selecting progressively the most attractive hybrids inside progenies from natural crossings. The frequency of such crossings was probably largely increased by the nearness of the layerings, cuttings, seedlings, which were sampled in the adjacent forest and introduced in a space close to the house (*domus* in latin is the semantic root of domestication). Thus appeared *Vitis vinifera sativa*, hermaphrodite, selected for larger and more attractive bunches and berries. Personnally, I call this scenario, the *'neolithic gardens'*, in reference to the *'indian gardens'* having similar functions and been observed by the European colons in New York or great lakes region (R.M. Pool, 1974, private communication).

It is logical to assume that man, from the very beginning of the Viticulture, trained this liana called the grapevine, with many similarities with the forms he observed naturally in the forest. That means probably that the most ancient canopy management was to train vines in trees or on branchs cut from trees as posts for support. On the same time, man probably observed that a rough pruning, as perhaps some animal did for eating fresh leaves and fruits, helped him on the next season to harvest more easily less bunches, but larger ones and bearing more juicy and attractive berries. Then Viticulture went outside this first historical zone, the origin centre, to progressively spread over the world, to the East and to the West, leading man to continue the genetic selection and to adapt cultivation technics to the various environments, particularly drier ones.

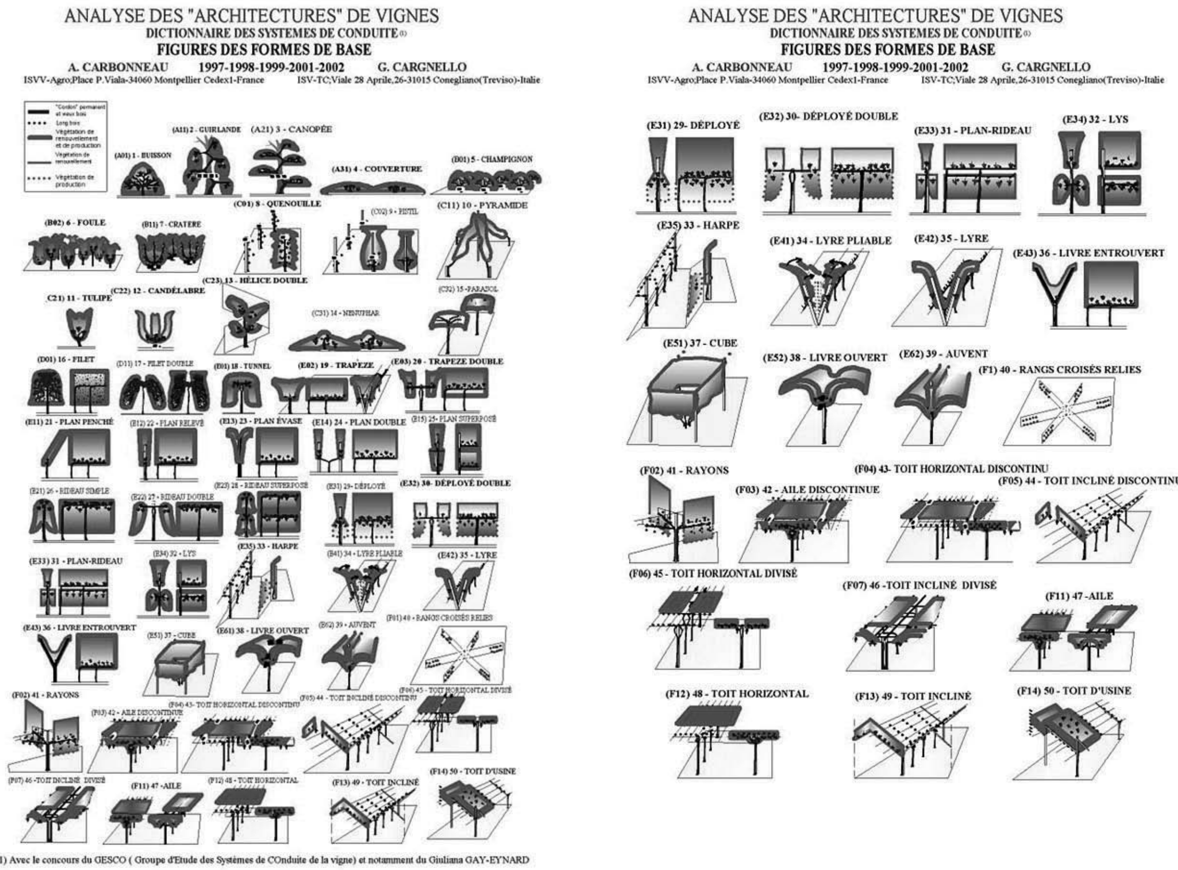


Figure 1: Schemes of the 50 worldwide basic forms or architectures.

II – EVOLUTION OF CANOPY MANAGEMENT FROM THE ORIGIN TO RECENT HISTORY

Viticulture followed all the paths used or created by man. Fresh or dried grape berries, wines, mixed beverages, were exchanged as goods among others. Figure 2 from Fregoni (1991) shows the main pathways described by the specialists of History.

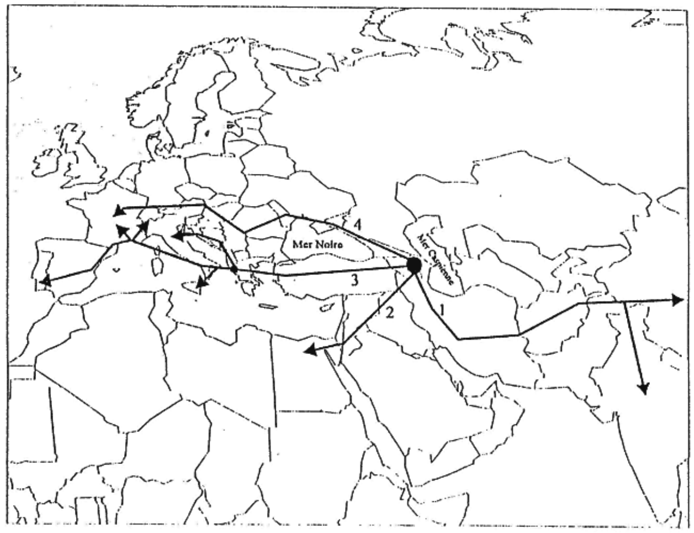
The good knowledge of Etruscan history allows us to assume that the ancestor model of canopy management, coming from the origin centre, was this one used by the Etruscan, the grapevine associated with the tree, or sustained by high and strong sticks. Such forms can be seen nowadays in the North East and Centre of Italy (figure 3), and are the parents of most of traditional technics of trellising such as the Raggi Bellussi in the Veneto (figure 4). This family is called the *‘Etruscan Viticulture’*.

Very soon in the history, the grapevine was cultivated in other environments, under mediterranean or sub-desertic climates, in the middle-East, in Egypt, around the Mediterranean basin establishing some ‘secondary’ origin centres particularly in Greece, in the Balkans, in Southern Italy and Sicily. Man adapted the vine to dry situations, and nowadays we can find some very old vineyards very probably similar to the historical ones: vines in small bush or vase (figure 5), vines on the ground (figure 6), vines in big vase and very large spacing in very dry situations (figure 7); those vines led to the group of Gobelet training systems (figure 8). This family is called the *‘Greek Viticulture’*.

We learned a lot from the Roman experience (Columelle, Virgile, Pline ‘l’ancien’/ Pline the Older). According to Pline ‘l’ancien’ (*Storia Naturale*), the Romans from the South to the North of Italy cultivated 6 main types of vine architectures, as a gathering of the Greek and the Etruscan models (figure 9). This could be called the *‘Roman classicism’* because of the high level of the technics and the precision of their description.

NB. During the conquest of the Gaul by the Romans, it seems that few of the viticultural practices described by Pline were teached to the Gallic. Most of the training systems were ‘Gobelet-type’ even in very vigorous situations, in the plain of Languedoc or near Bordeaux for instance, where this is a bad technical choice. Why the Etruscan models were not developped in the Gaul? The reason is probably due to the fact that the Roman legions were composed at that time mainly by mercenaries originated from Greece and Middle-East.

Unfortunately, most of the Roman knowledge and experience was lost after the Gallo-Roman period, which was for a big part due to the Barbarian invasions. In the Middle-Age in



Extension de la culture de la vigne dans le Bassin Méditerranéen jusqu'au début de notre ère, d'après Fregoni (1991)

Figure 2: Map of the main historical pathways of the expansion of Viticulture.

Figure 3: Tiers of long cordons held between trees, in the Po valley (North-East of Italy).

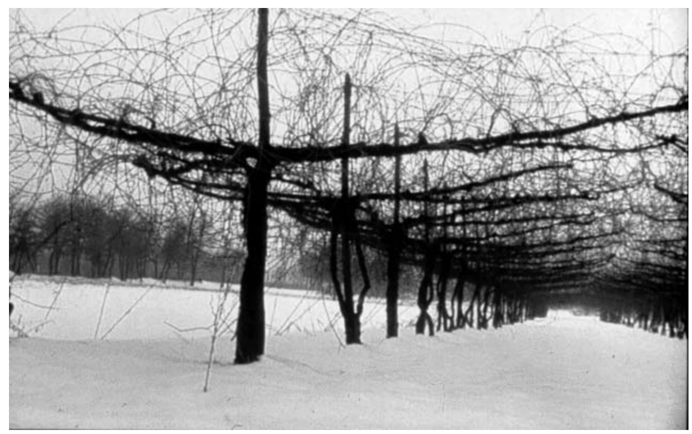


Figure 4: Raggi Bellussi, monumental 'roof architecture', coming from the tradition to train vines in trees, in the Veneto (North-East of Italy).

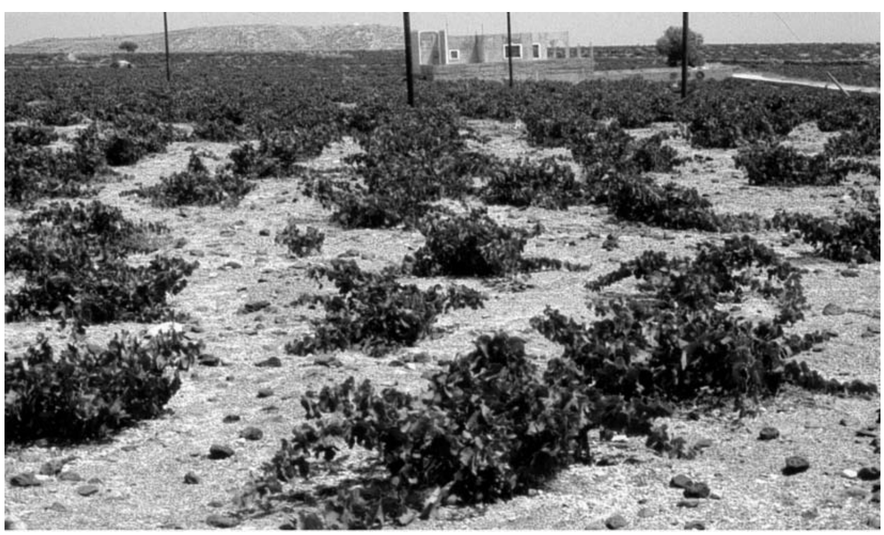


Figure 5: Small bush vines close to the ground in Santorin island, ancestor of the 'Gobelet' family.

Figure 6: Vines with cordons growing on the ground, usual practice in old vineyards in the Middle-East or in Southern Europe (here on sandy soil).

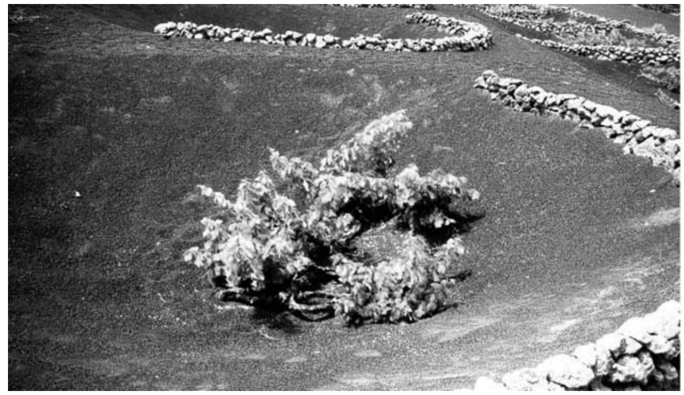


Figure 7: Big Vase, planted very large, in a very dry situation, here in Lanzarote island (Spain) where water is only coming from air humidity condensation collected at the bottom of the cuvettes.

Figure 8: Classical Vase or 'Gobelet', well structurated, planted at medium density, on gravelly soil in Châteauneuf du Pape (France).

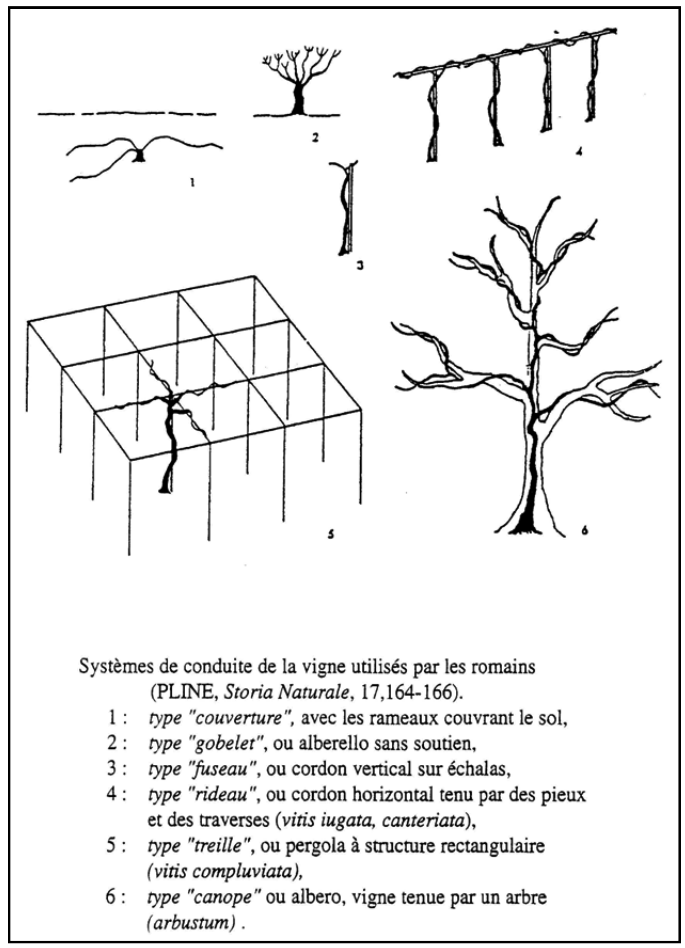


Figure 9: Scheme of the 6 main training systems used during the classical Roman time, according to Pline the Older.

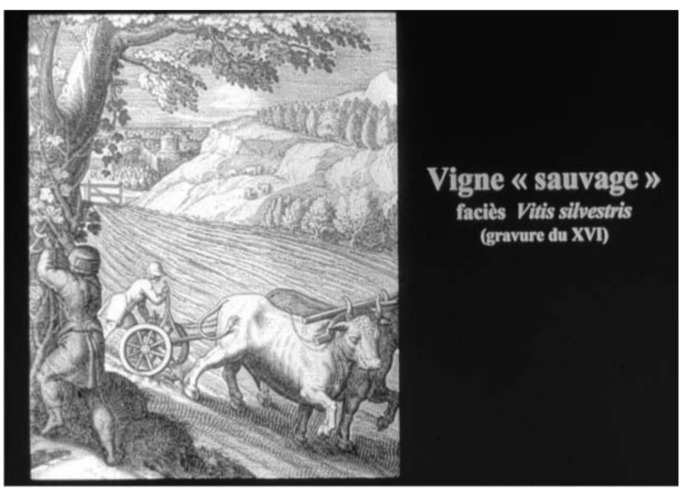


Figure 10: Picture of the XVIth century showing the presence of productive vines climbing in trees, adjacent to a cultivated field, which illustrates the empiricism of the Middle Age.

Western Europe, Viticulture was widely developped, with the motivation created by the expansion of the Christianism, but the technics, as far as we know, were less sophisticated than under the Roman period, and empiriscism replaced rationalism. A possible exchange between imported genetic material by the Romans and local wild varieties is important to take in account, particularly whe growers were obliged to renew their vineyards after series of battles and had to find woods in adjacent trees (figure 10). Canopy management seemed to be governed by very practical reasons, such as layering ('marcottage') which led to very close spacings such as 'crowd vineyards' (figure 11). This step can be called *'Middle-Age Empiriscism'*.

Rationalism developped in Western Europe since the 'Renaissance' period till nowadays. Viticulture re-discovered some Roman experiences, vineyards were adapted to the animal which were used for helping man for painful tasks, technics were perfectly described, codified, and divulged. Gobelet-types under Mediterranean situations (figures 12,13), Vertical trellising in close spacing under oceanic or continental situations, were the main choices for canopy management, well precised and then recognized as a tradition (figures 14, 15, 16). This step can be called *Tradition regulation in Europe'*.

The 'New World' of Viticulture expanded rather quickly without the constraint of the tradition, even if the first behaviour was to reproduce overseas the European models and wines, leading to the expantion of 'international varieties'. The choices for canopy management were mainly governed by practical reasons: reduce of investment when establishing the vineyard, simplification of operations because labour was rare, necessity to produce high yields for a fast increasing population or to quickly get money back. Thus wide spacings, free bearing vegetations were the most common practices in wine grapes, and highly yielding 'roof-types' in table grapes or cheap wine grapes (figures 17, 18, 19, 20, 21). This step can be called *'Open choices in the New World'*.

In Europe, the situation was also changing. A major step

Figure 11: Reconstitution of an old 'Crowd' vineyard, using one stick per vine in a very close planting based on layering, in Moët&Chandon vineyard, Champagne (France).

Figure 12: Example of a Vase with a wide spacing in the arid Mancha (Spain).

Figure 13: Large Vase with long and separated arms, in productive vineyards for sparkling 'Cavas' in the Penedes (Spain).

Figure 14: Vertical Shoot Positioning in very close planting (1m apart), with a very low trunk and a severe summer pruning, in a traditional vineyard originally adapted to the ox, in the Médoc AOC (France).

Figure 15: Vertical Shoot Positionning in a classical close planting (1.8m between rows) with a good equilibrium 'foliage height/row spacing', at Domaine INRA de Couhins, Graves 'Pessac-Léognan' AOC (France).

Figure 16: Vertical Shoot Positioning in a semi-large row spacing (2;5m), with a double 'Cordon de Royat', a minimum trellising, in Nemea (Greece).

Figure 17: Vertical Shoot Positioning in wide rows, with an anti-hale net individual row covering, in San Raphaël (Argentina).

Figure 18: Vertical Shoot Positionning in wide rows, with a simple trellis and short hedge pruning, in Hunter valley (Australia).

Figure 19: Umbrella or ‘free high cordon in wide spacing, at Lodi in the central valley of California (USA).

Figure 20: Latada or Parral or ‘horizontal roof’ on productive cultures of table grapes, in a tropical vineyard (North’East of Brazil).

Figure 21: Gable trellis or ‘Factory roof’ or ‘roof inclined in opposition’ on productive wine grapes in South Africa.

occurred after 1950 due to the connection of different currents: necessity to rebuild vineyards after war or climatic accicent (frost), availability of mechanization concomitant to the quick increase of labour costs, change in varieties and wine types for different socio-economical reasons, some ‘feed back’ from the ‘New World’ showing the success of wide spacings, cheap trainings or ‘free bearing’ canopies. That created a movement of evolution which had to face the tradition; and many vineyards changed after 1960, such as: in Austria and Central Europe due to Lenz Moser’s experiences (1952) taking advantage of some experience in Northern Italy with the Sylvoz or the Casarsa (figure 22); in France due to the development of wide rows (figure 23), mechanical harvesting, and some efficient groups (CETA: Centre d’Expérimentation Technique Agricole). This step can be called *‘Impact of mechanization’*.

The Vertical Shoot Positioning appeared to be well adapted to mechanical harvesting (figure 24) or pre-pruning; it expanded in many vineyards which had to be reniewed; it replaced most of the ‘Vase’ or ‘Gobelet’ vines; nevertheless it was limited because it is difficult to reconcile wide spacing or economical attractiveness and wine quality potential which can be good only when yield/ha is low enough. That explained the araising of a general questionning about canopy management in Europe. In the ‘New World’, the problem was at the beginning mostly concentrated on yield performances in so far as they are not restricted by any regulation; the cheap ‘free bearing’ systems were improved on this point by the GDC (figure 25) which was designed by Shaulis et al. (1966) and also profited by a complete mechanization (figure 26); the Minimal pruning appeared also to be an attractive technics for some vineyards (figure 27); more recently, the Precision Close Pruning proved to be also a cheap way for vines which need to have a control of pruning level (figure 28). All those tendencies, criticisms, trials, led to the emergence of *new training systems*, and particularly a series of

Figure 22: Casarsa friulano adapted to productive vineyards, in wide spacing with an high canopy allowing the extension of the vegetation and the crop (North-East of Italy).

Figure 23: Vertical Shoot Positioning in wide spacing (double than the tradition), interesting for reducing the costs of production, while maintaining the quality potential when the yield is limited, as shown at ‘Sainte Croix du Mont’ AOC in Bordeaux (France).

Figure 24: Vertical Shoot Positioning in narrow spacing, showing a good adaptation to mechanical harvesting by lateral shaking; first trials in Domaine INRA du Grand parc at Latresne in AOC ‘Premières Côtes de Bordeaux’ (France).

Figure 25: The Geneva Double Curtain proposed by Pr Nelson Shaulis in New York, first divided canopy in wide spacing and downward bearing (USA).

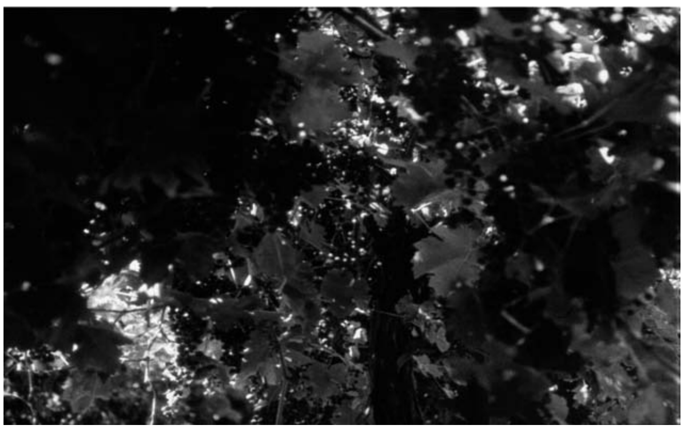


Figure 27: Minimal Pruned Cordon Trained vines, or Minimal Pruning, attractive due to minimal costs and full mechanization, providing interesting results in many vineyards which can delay harvest – Dr Peter Clingeleffer – and requiring vigour control – Pr Alain Carbonneau; here a 4 years old Minimal pruning on Cabernet-Sauvignon in Coonawarra (Australia).

Figure 26: Mechanical harvesting by vertical shaking a GDC, process also used on single curtain or 'free bearing cordons', performed by Bologna University – Pr Cesare Intrieri and Tanesini Company (Italy).

Figure 28: Precision Close Pruning applied on the basis of studies of Bologna University, here on Petit Verdot by Patrick Henry in Camargue (France).

'Divided canopies'. The GDC was the first example which was either an *application of the Biology of production*, or a target revealing the importance of microclimate.

The family of Lyre architectures (figures 29, 30) was developped firstly to optimize wine quality, and also, in comparison with canopies which are suitable for quality, to allow higher yields and a restriction of production costs; the Lyre vines offers interesting solution to sustainable viticulture in relation to sanitary situation (figure 31); they are well adapted to manual harvesting (figure 32), can be mechanized for pre-pruning (figure 33) or for harvest when a foldable trellis is used (figures 34, 35); the series of experiments involving the Lyre in comparison to different controls in the world led to a significant progress of the knowledge of grape berry or wine *quality*, of the expression of *Terroir* as well (figure 36). Some others divided canopies were also developped, particularly the 'unfolded family' such as different types of Casarsa, Scott Henry, Lily (figure 37).

- For the present and the future, and particularly with the perspective of *sustainable Viticulture*, it is possible to rely on the choice proposed by the *Gi*ESCO:
- - the *Vertical Shoot Positioning – VSP*, as a reference for most of vineyards;
  - the ***Modulated VSP***, in wide rows, with a movable stick, will offer an interesting adaptative ability in front of the climate change (figures 38, 39);
  - the ***Minimal Pruning*** or the ***Precision Close Pruning***, for lowering costs while maintaining a good viticultural potential;
  - the ***Lyre*** and the ***foldable Lyre***, for top quality or high yielding vineyards, offering a wide adaptation scale;

Figure 29: Lyre architecture, 'open Lyre' type, developped at INRA Domaine du Grand Parc at Latresne in AOC 'Premières Côtes de Bordeaux' by Pr Alain Carbonneau (France).

Figure 30 : Lyre commercial vineyard on steep slopes at Domaines Henri Latour in Burgundy (France).

Figure 31: Lyre commercial vineyard in Uruguay – Juanico, presenting advantages to reduce parasite attacks and, in combination with grass covering, to fit with sustainable Viticulture.

Figure 32: Table grape vineyard, Danlas variety, which showed the economical advantage of the Lyre due to hand picking convenience, in Carpentras experimental center – Vaucluse (France).

Figure 33: Pre-pruning machine working in a Lyre vineyard, at Domaine du Grand parc at latresne in AOC ‘Premières Côtes de Bordeaux’ (France).

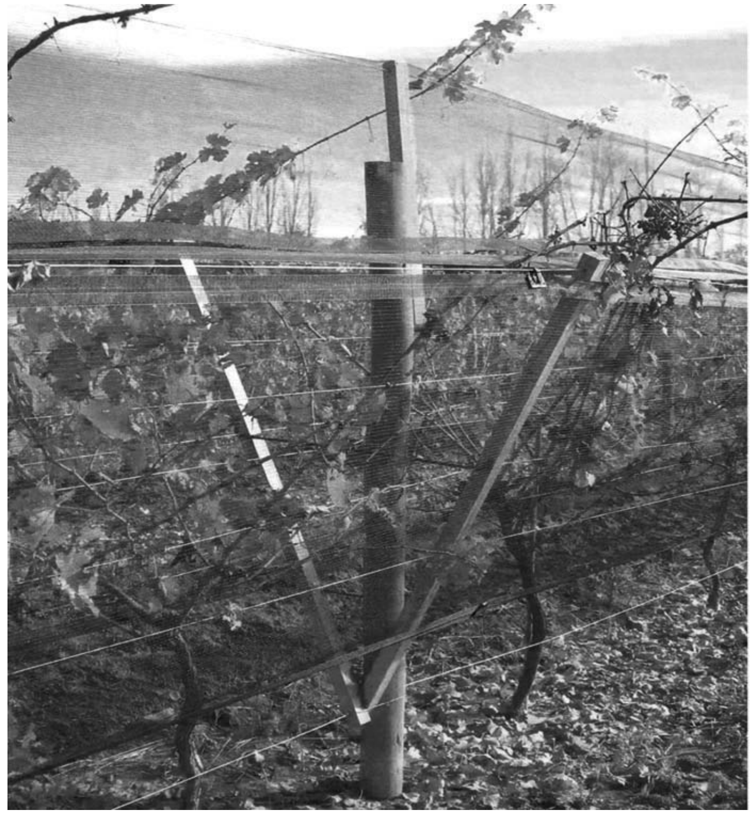


Figure 34: Foldable Lyre, with movable sticks and a covering with anti-hale net, in an experimental vineyard of INTA Mendoza (Argentina).

Figure 35: Foldable Lyre in the closed position before the entrance of the harvesting machine (see long attached slappers for lateral shaking), at Domaine du Chapitre Montpellier SupAgro/INRA (France).

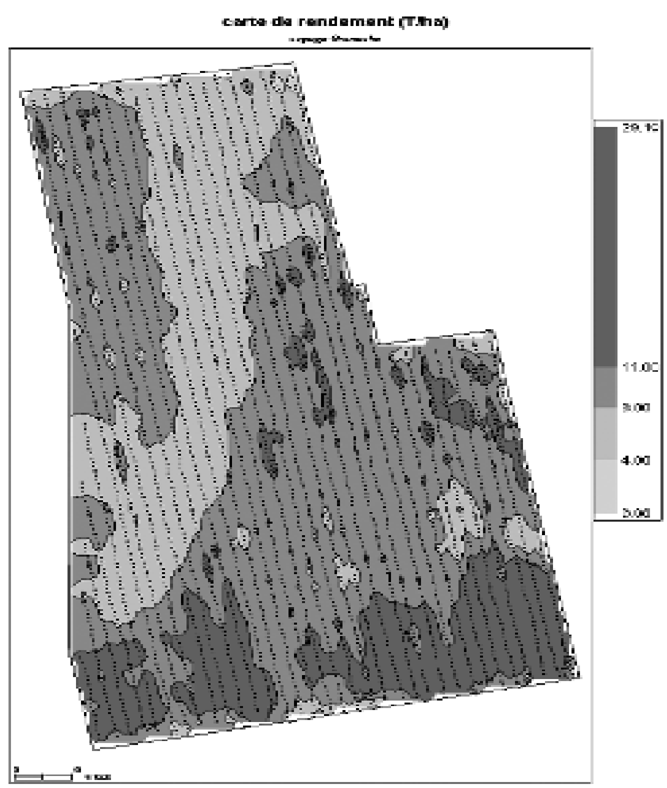


Figure 36: Map of vine vigour (pruning weight), useful for studying Basic Terroir Units, as a result of precision viticulture obtained in a heterogeneous plot due to micro-zones of drought, at INRA Pech Rouge Experimental Unit (France).

Figure 37: Lily training system, designed around the Pr Rogerio de Castro's up/down concept, on Merlot at Domaine de La Valette of Montpellier SupAgro (France).

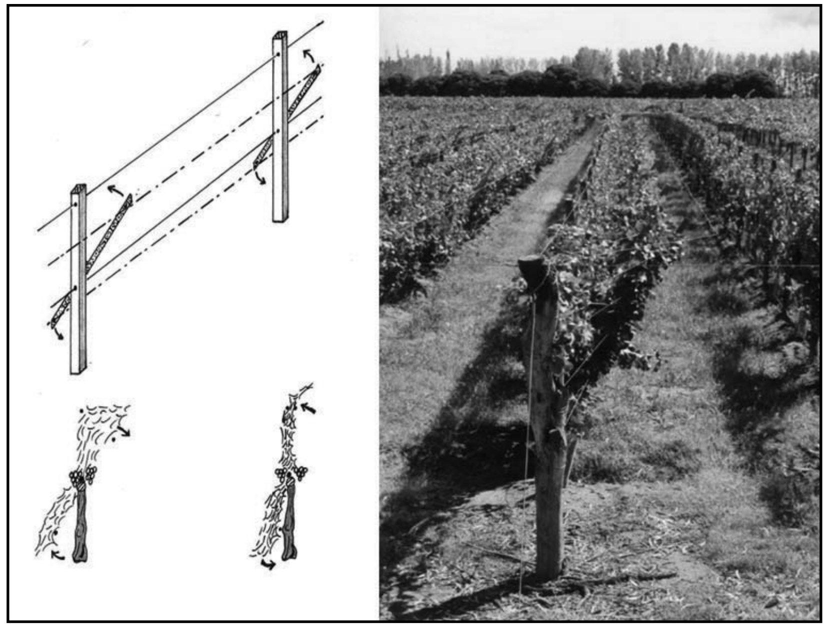


Figure 38: Scheme of the 'Espalier modulé' or 'Modulated Vertical Shoot Positioning' expanding or reducing the canopy by a movable stick to fit the solar energy interception requirement (Pr Alain Carbonneau), on the basis of the model proposed by Ing Raül del Monte for mechanization at INTA Mendoza (Argentina).

- the ***Lily***, with an unfolded and divided vegetation, is useful for vigorous vines while maintaining a simple trellis;
- the ***Harp*** for narrow terraces vineyards (figure 40) in which the potential can be subtantially increased (the Gobelet being still adapted to weak vines and irregular slopes).

III – RESEARCH ASSOCIATED WITH CANOPY MANAGEMENT

The recent evolution of training systems justified to launch a research directly connected to vine canopy architecture. The main reasons were to better understand what happens when the form of the vegetation changes, and to find new technics to reconcile the tendency to reduce the costs of production by using wide row spacing, and the control of production and wine quality. From this point, series of researchs and experiences developped in the world, which could be presented in different steps. The GESCO proceedings n°s1-15 provide most informations about this evolution.

1/ The 'boom' of Vine Biology and its application to canopy management:

Many fundamental works were done on vine Physiology in relation to the different organs: bud development and fertility (Huglin and Schneider, 1998; Pouget, Huglin, May, Buttrose, Smart, in Carbonneau et al., 2007), vegetative development and growth (Huglin and Schneider, 1998; Bouard, Winkler, Huglin, Champagnol, in Carbonneau et al., 2007), photosynthesis and assimilates (Kriedemann, Smart, Koblet, in Carbonneau et al., 2007), berry development and metabolism (Kliewer, 1977; Ribereau-Gayon, Kliewer, Coombe, Iland, Ojeda, in Carbonneau et al., 2007). The main application was the elaboration of the concept of 'divided canopy in wide rows', and the first model designed in this category, the Geneva Double Curtain – GDC (Shaulis et al., 1966). The importance of leaf microclimate was demonstrated and used in relation to bud fertility and yield control (Smart, 1976). This step was important because it was the first time it was proved that a low density of planting can give the best ecophysiological results – about yield components at that time – and the concepts of canopy microclimate with this one of divided canopy were validated.

2/ The Vine Ecophysiology and its application to wine quality and canopy management:

The previous works extended towards grape berry physiology, taking into account the concepts of wine type or 'typicity', wine quality, and Terroir. This new generation of trials revealed the importance of divided canopies to optimize wine quality. The 'Lyre' architecture appeared to give the best ecophysiological potential, either for controlling leaf and berry microclimate, a moderate water stress, plant carbon balance, berry maturity and health, wine quality. The main part of this research was monitored by Carbonneau (1980) who developped a fundamental approach based on 10 canopy models (figure 41), and a factorial experimental design including yield and vigour levels. A worldwide development of related research was performed by the GESCO ('Groupe d'Etude des Systèmes de COnduite de

Figure 39: ‘Niof Casarsa’ pruning as an adaptative method for positioning free short canes in the suitable direction, useful for the modulated VSP, proposed by Pr Giovanni Cargnello at Conegliano (Italy).

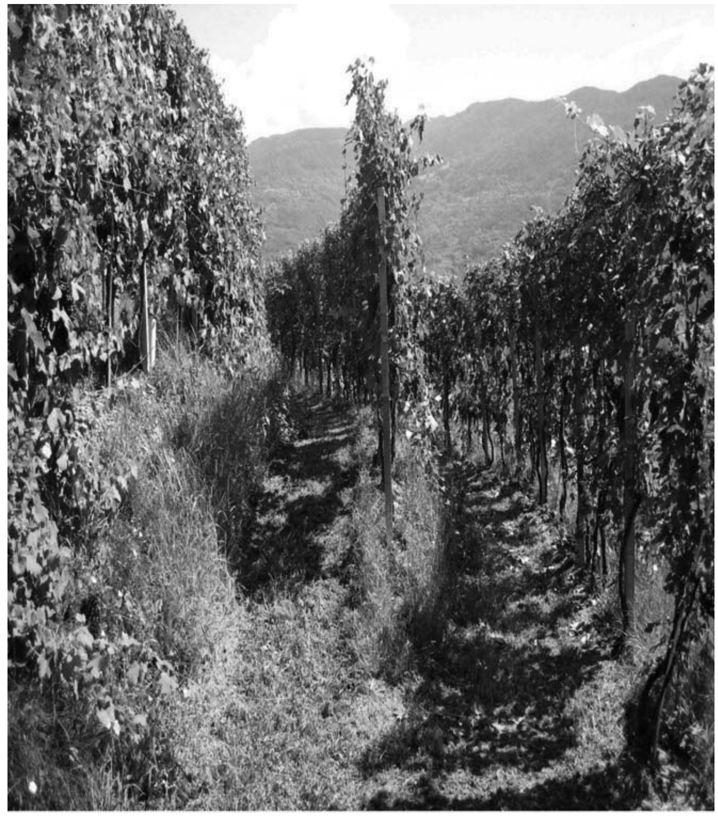


Figure 40: Arpava or Harp, designed by Pr Giovanni Cargnello, as a dissymetric unfolded and divided architecture, well adapted to the space of narrow terraces, as here in the Valtellina (Italy).

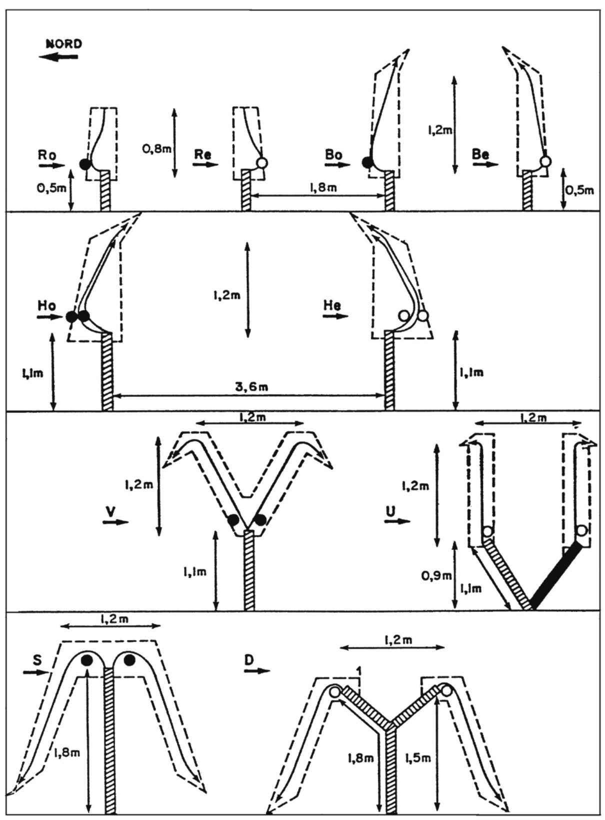


Figure 41: Drawings of the canopy models studied by Carbonneau (1980).

la vigne' / 'Grapevine Training Systems Study Group'; now: G*i*ESCO, 'Groupe *international* d'Experts en Systèmes vitivinicoles et CoOpération' / 'Group of *international* Experts in vitivinicultural Systems and CoOperation'). A general presentation of those works, and of Vine Physiology, Cultivation and Terroir in general, is presented in Carbonneau et al. (2007).

3/ The evolution of modeling of Vine Biology in relation to canopy management:

From this point, it is interesting to check what changes occurred in the representation or the modelling of the Grapevine Biology associated to canopy management.

- Concepts used in the period 1960 – 1980:
  - Close planting is more efficient than large spacing due to a better occupation of space, more dense rooting, better plant vigour control, higher yield/ha, better wine quality;
  - Moderate yield/plant and /ha, versus high yield, is the determining factor of wine quality and storage capacity in general; bunch thinning has a positive effect on wine quality.
  - Vigour (shoot growth) increases fertility and yield; vigour excess may reduce fruit-set, and delays maturity (summer vigour, particularly on lateral shoots).
  - Summer pruning is useful for controlling vigour, increasing fruit-set, improving berry maturity.
  - Canopy morphology is part of the plant vigour, very often assimilated to shoot vigour), without specific effects.
  - Bunch position is related to the closeness from the soil surface, which improves earliness, but gives more susceptibility to frost injury, and to some diseases such as *Botrytis cinerea*; leaf removal around clusters is efficient to reduce such risks while improving some elements of quality.

As a general consequence of the second generation of researchs, those concepts linked to canopy management evoluated.

- Concepts used in the period 1980 – 2000:
  - Yield is firstly related to pruning level/ha (whatever be the density of planting), to light microclimate and vigour (fertility), to plant water status (berry weight).
  - Vigour, precisely shoot vigour, is related to pruning level, to a medium leaf exposure, to plant water status, to summer pruning (extending lateral growth).
  - Rooting is governed by a leaf/root ratio, canopy light interception (independantly of row spacing 'per se'); root depth is basically stimulated by plant vigour (big roots and trunks), then by a relatively wide spacing; but that induces the necessity to control leaf exposure in the same time; root depth is also better when spacing in the row is reduced.
  - Reserves are used preferably when they are stored near the sink, are abundant when vigour and yield are limited, canopy exposure is high, canopy is divided by extending progressively the perennial wood.
  - Berry maturity is basically expressed as sugar loading (g sugars/berry), then in sugar concentration; is optimized by medium-maximum leaf exposure, and a relatively high exposed leaf area/yield ratio.
  - Wine quality is mainly related to secondary metabolites, polyphenolic compunds and some aromatic compounds; maximum leaf exposure is generally required, which is linked to moderate water limitation in yhe canopy; but only optimal berry exposure is suitable.
  - Self-regulation as a response to high pruning levels or to Minimal Pruning, is efficient to balance the Vine functionning, but is active all along the growing cycle, and thus tends to delay maturity which may be an adapted choice or not depending on the interaction 'variety – environment'.
  - Terroir expression into wine typicity is dependent of the training system, in so far as cultivation practices adapted to the variety modifies the natural level of environmental factors (Carbonneau et al., 2007); at this level, the new technologies and precision viticulture can offer a progress to control those effects.

Focus on some modeling processes

Ecophysiology leads to modeling as soon as some laws can be quantified. It is also possible to use the fuzzy logic or the neurone network methodologies to represent the reality. Different modeling processes, based on deterministic approach, are under progress (in Carbonneau et al., 2007), such as Schultz and Stoll in Geisenheim (photosynthesis, growth, water relations), Lecoeur and Lebon in Montpellier (growth, architecture), Zufferey in Changins (photosynthesis), Matthews in Davis (water relations), Poni in Piacenza (photosynthesis), Vivin in Bordeaux (berry development and maturation), Walker in Merbein (vine development). The aim of most of models is to quantify the general carbon assimilation and balance of the vine.

A more simple model, but already used for field evaluation, was proposed by Carbonneau (1980, 1995). It allows, for all kind of architecture, to evaluate the ***'Exposed Leaf Area'***

(SFE = 'Surface Foliaire Exposée' / 'Exposed Leaf Area'), which is the estimation based on a representative scheme of the canopy, of the leaf area per unit of soil area, which is able to reach the potential of photosynthesis with a positive carbon balance. To do so, the canopy is shared in different zones: high photosynthetic potential, medium potential, nul potential, negative carbon balance; thus, leaf area is weighted according to physiological potential (Figure 42). This SFE model was applied to rank the canopy shapes according to their physiological potential (Carbonneau, 1995), or more generally to evaluate the potential of a vineyard (Carbonneau et al., 2007). In fact, SFE model was mainly validated through the link with wine sensory analysis records. The variables of the model which predict the potential of quality are: SFE/P±V (P is the dry matter production or the yield; V is an estimation of summer vigour as a 15% ponderation of the SFE/P ratio, high summer vigour having negative effects).

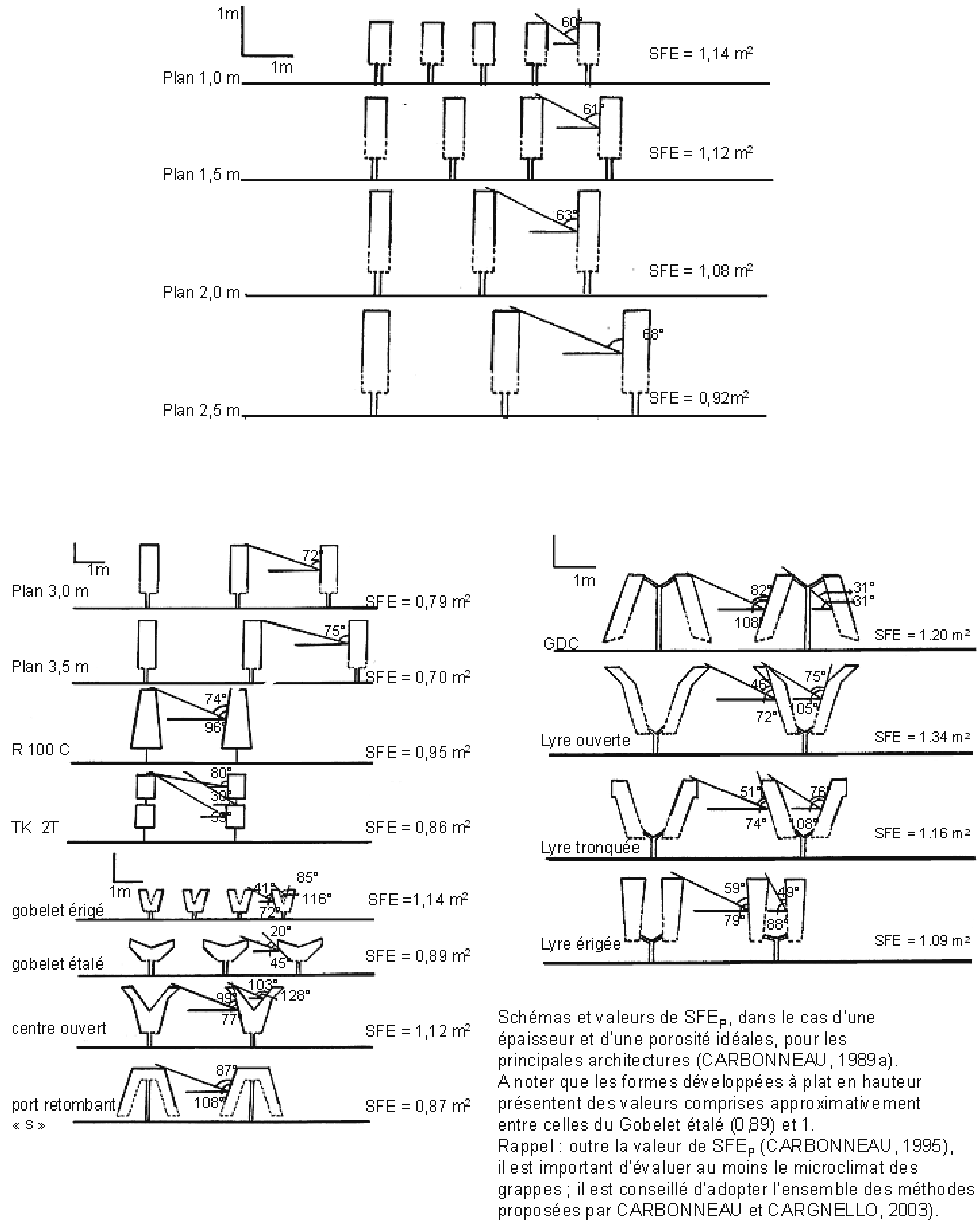


Figure 42: Results of potential Exposed Leaf Area 'SFE' for the main canopy shapes (Carbonneau, 1995; Carbonneau et al., 2007).

Recent developments of Vine Ecophysiology or modeling, which were presented during the last GESCO meetings in Geisenheim (2005) and Porec (2007), can be summarized as follows:

- ***Water relations:*** Canopy management effects are included in the general water relations, growth and photosynthesis of the plant (Schultz, 1995); those general responses can be modified under specific stressing situations such as photoinhibition (Palliotti, Silvestroni et al., 2007); and the influence of the root system, could be introduced simultaneously in the modelling process, particularly the rooting depth, which is optimized by large row spacing and divided canopies such as the Lyre (Carbonneau, Ojeda et al., 2006; figure 43).
- ***Canopy architecture*** modeling, particularly canopy reconstruction, is a new research field (Louarn, Lecoeur, Lebon,

2006); the interaction with water limitation will be the extension of this research.

- ***Reserves*** in old wood and roots are concerned by new researchs, in relation to water management (Smith, Quirk and Holzapfel, 2007).
- ***Berry maturation and typicity*** is also under a modeling process; a first basis is provided by the link between the berry sugars loading (g/berry) which measures the physiological activity of the maturing berry, and the observed occurrence of aromatic characteristics detected on large series by sensory analysis in the future wines (Carbonneau, 2007; figure 44); original results on berry maturation come also from the study of berry withering on vine (Carbonneau, Murisier, Cargnello, 2008).

CONCLUSIONS AND PERSPECTIVES

Canopy management will continue to provide science with new ideas and ecophysiological laws, and technology with new training systems and models for sustainable Viticulture.

Facing the future, it appears that we need:

- to unlock some fundamentals, particularly to study physiological responses to fluctuating environment, which corresponds to the reality of the climate change in most vineyards;
- to develop deterministic modelling associated with vineyard validation, for instance the management of reserves along the growing cycle, the adaptation to drought, or the typicity of the berry;
- to insure some links between Ecophysiology and Genomics, focusing on some key regulating genes.

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INTEGRATED CANOPY MANAGEMENT: A TWENTY YEAR EVOLUTION IN CALIFORNIA

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Abstract: In the mid-1980's, grape production in California was largely dominated by a single trellis system, plant density and row orientation. This paper examines how vineyard design and grape training/trellising systems have changed during the past two decades, as well as how canopy management practices and other cultural manipulations including irrigation management and mechanization have been successfully implemented. Highly integrated vineyard production systems, in which anticipated site vigor and vine capacity are the primary considerations for design and management, have developed as a result.

In 1986, when Dr. Mark Kliewer organized the first formal scientific meeting on grapevine canopy management held in California, viticulture in the state was primarily a monoculture utilizing a single trellis type, vineyard design and row orientation. The meeting, entitled "Symposium on Grapevine Canopy and Vigor Management", highlighted the central concern of the era – the management of excessive vine vigor and associated problems with productivity and fruit quality under excessive vigor conditions (Kliewer et al, 1988). At this time the importance of proper irrigation management, as well as the integrated nature of canopy management practices with overall vine balance and vineyard productivity, was not fully understood. The papers presented at that meeting provided new insights regarding the physiological regulation of light and temperature on fruit development and composition, as well as the impacts of rootstocks and vineyard cultural practices such as irrigation, growth regulators, hedging and basal leaf removal on canopy development and fruit zone microclimate. The meeting proved to be a revolutionary event, stimulating a decade of critical academic research and rapid industry innovation in vineyard canopy management systems in California. A related circumstance, the discovery of a new biotype of the root-louse phylloxera, which attacked AXR#1, the primary rootstock used in the north coast of California at the time, occurred nearly simultaneously. Affected vineyards declined rapidly and were removed from production, leading to thousands of acres of new plantings. This accelerated the pace of canopy management research and allowed newly developed concepts regarding trellising and vineyard design to be rapidly incorporated into commercial vineyards. In many ways the symposium held in 1986 was the birth of modern viticulture in California.

Today, nearly countless variations in trellis and vineyard design, row orientation and the use of canopy management practices can be found in commercial vineyards in California. Regardless of their specific design and production goal, new plantings are developed using the physiological principals and industry innovation brought forth during the past quarter-century. The diversity in production systems also underscores that desirable results can be obtained using different management techniques and approaches. This has perhaps been the most critical learning – the fact that vineyard production and canopy management practices are highly integrated, and must be applied in this fashion for the most efficient results. For example, it is now clear that when vineyards are properly designed, trellised and irrigated, relatively little additional canopy manipulation may be necessary to achieve the optimum fruit zone microclimate. This knowledge has led to the development of integrated vineyard production systems in which anticipated site vigor and vine capacity are the primary considerations for design and management.

CANOPY AND FRUIT ZONE MICROCLIMATE RESEARCH

Despite the pioneering work performed by Nelson Shaulis in New York in the 1960's and 1970's, few studies intensively focused on the light microclimate within California grape canopies until the late 1980's. The work revealed that vigorous grapevines in California had lower amounts of light reaching their canopy interior than any other horticultural crop reported in the literature (Dokoozlian and Kliewer, 1995a). This work also revealed that the fruiting zone of canopies grown to the standard trellis system of California – the two-wire vertical, non-shoot positioned trellis also referred to as the California sprawl – was generally the least exposed portion of the canopy, and that the light environment within this region changed little following fruit set. This work supported the concept that canopy manipulations to alter fruit zone microclimate – such as basal leaf or lateral shoot removal – should be performed immediately after fruit set in heavily shaded canopies for maximum benefit. It should be noted that prior to the mid-1980's, the fruiting zone within most California sprawl vineyards received no

Table 1. Indices for low and high density Cabernet Sauvignon grapevine canopies at harvest in the North Coast of California. Taken from Dokoozlian and Kliewer, 1995b

	Low density canopies	High density canopies
Canopy leaf area (m^2m^{-1} canopy length)	<4.0	>8.0
Fruit zone PPFD (% ambient)	>5.0	<2.0
Fruit zone R:FR	>0.35	<0.20
Canopy area receiving sunflecks in the fruit zone (%)	>20.0	<10.0
Point quadrant LLN in fruit zone	<2.5	>4.0
Point quadrant canopy gaps in fruit zone (%)	>20.0	<10.0
Evaporative potential in fruit zone (% ambient)	>70.0	<60.0
Canopy pruning weight (kg m^{-1} canopy length)	<1.0	>1.5

more than 1% or 2% of total ambient radiation, while optimum values were approximately 10% (Dokoozlian and Kliewer, 1995b). While light quality and sunflecks were also characterized in these studies, light quantity (PAR) was believed to be the primary light microclimate parameter of interest in terms of physiological regulation (Dokoozlian, 1990). Metrics for high and low density California Sprawl canopies resulted from these studies (Table 1).

By the late-1980's it was clear that increased sunlight exposure improved fruit quality in the California Sprawl trellis system (Kliewer and Smart, 1989). This resulted in canopy manipulations such as shoot thinning, basal leaf removal and summer pruning or hedging, long-time common practices in California table grape vineyards, being adopted as standard practices for wine grape production. Due to the pendant nature of shoot growth and general configuration of the traditional California trellis systems; these manipulations increased the levels of dappled or indirect sunlight reaching the canopy interior without increasing fruit exposure to direct sunlight. However, modern trellis and vineyard designs, as well as improved cultural practices which led to decreased vine vigor including lower vigor rootstocks, deficit irrigation, cover crops and more judicious use of nitrogen fertilizers, greatly increased inherent fruit exposure to sunlight. By the end of 1990's, it was becoming clear that fruit exposure to sunlight could be excessive in some cases. While sunlight *per se* may not be detrimental to berry quality, the increase in berry temperature as a result of greater cluster exposure to sunlight can inhibit color accumulation, for example (Bergqvist et al., 2001). Figure 1 shows that the color of Cabernet Sauvignon berries increased linearly as cluster exposure to sunlight on the north side of the vine canopy increased (east to west row orientation). In contrast, berry color leveled off and then declined with increased sunlight exposure on the south side of the canopy. While clusters on both sides of the canopy were exposed to similar levels of sunlight, the temperature of clusters on the south side of the canopy became excessive for optimum pigment accumulation as sunlight was increased (Bergqvist et al., 2001). Temperature differences between the different sides of the canopy may be explained by the fact that clusters on the north side of the vine received large amounts of indirect or dappled sunlight, while clusters on the south side of the vine received direct exposure to sunlight. Subsequent work showed that the combined use of VSP, north/south row orientations and deficit irrigation in warm regions resulted in excessive fruit exposure including reductions in wine aroma, color and yield (Keightly, 2002).

Initially, there was much speculation regarding the nature of the photoreceptor responsible for regulating berry growth and development. It was initially suggested that phytochrome was involved (Smart and Robinson, 1991) but subsequent work suggested that a photoreceptor linked to light quantity (PAR) was more likely responsible for light-mediated effects on fruit composition (Dokoozlian, 1990; Dokoozlian and Kliewer, 1996). This work revealed that a reduction of light quantity or PAR, regardless of the R:FR ratio, decreased sugar and color accumulation and berry size. The study also showed that varying the R:FR ratio (levels ranging from 1.0 to 0.1) under continuous illumination had no influence on pigment accumulation, while night interruption using R or FR light also did not impact berry color. While the nature of light-mediated regulation of berry growth and composition appears to be characteristic of other high-irradiance plant responses to light (Dokoozlian, 1990), additional work is needed to thoroughly elucidate the photoreceptor(s) responsible.

ADVANCES IN VINEYARD DESIGN

Prior to the 1990's, nearly all California vineyards were planted using an east-west row orientation. This was based on the traditional row orientation employed by the raisin industry to best facilitate sun-drying of grapes laid on paper trays between the vine rows. The distance between vine rows was typically

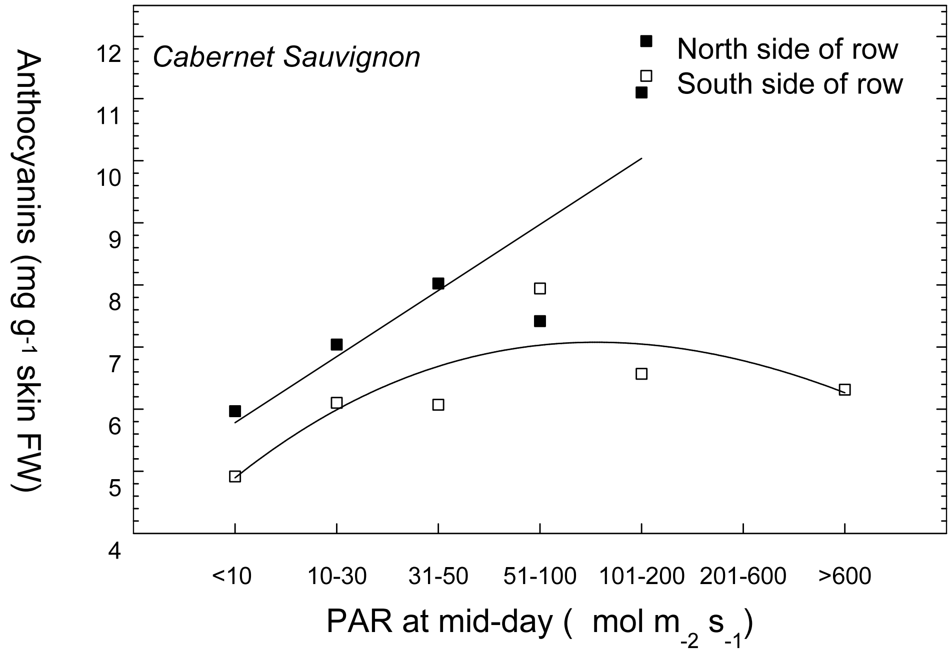

Figure 1. Influence of mid-day PAR levels on the pigment content of Cabernet Sauvignon grape berries on the north and south sides of the canopy row. Taken from Bergqvist et al., 2001.

3.1 m to 3.4 m, while the distance between vines within the row ranged from 1.8 m to 2.4 m. Vine densities ranged between 900 and 1400 per hectare. This wide spacing by modern standards was necessary for the high vine vigor common during the period, as well as the large machinery employed for cultivation.

With the birth of modern vineyard design in the 1990's, a new philosophy to construct lower vigor vineyards that would fit the new spacing and trellising paradigm was formed. Growers rapidly adopted closer row and vines spacings, along with VSP trellis systems, as the production standard in coastal regions. The use of lower vigor rootstocks, as AXR #1 was replaced, fostered this foundation. The identification of vineyard sites with lower inherent fertility, as well as the reduction of deep tillage prior to planting in order to limit potential rooting depth, was also part of the equation. This was in stark contrast to the traditional approach, where trellis design and vine spacing were selected based on the potential production and vine capacity (yield and canopy size) of the site.

Beginning in the late 1980's, two major changes were observed in California wine grape vineyard design. The most radical was the increase in vine density, which typically ranged between 2000 and 3000 per hectare. Previous work in California had shown that vineyard yield per acre increased approximately 11% for each foot that row spacing was reduced (Figure 2), a function of greater numbers retained per hectare at pruning and improved land use efficiency. The rapid transition to the VSP trellising system in coastal regions facilitated closer row spacing, with most VSP vineyards spaced between 1.8 m and 2.4 m between rows. Even California Sprawl trellises, still commonly employed in the higher vigor vineyards of the San Joaquin Valley, were spaced more closely between rows, typically 2.6 m. In-row vine spacing, or the distance between vines within the row, was also reduced. In-row spacings between 1.6 m and 1.8 m became common, and in some cases in-row spacing was reduced to 1.0 m or less.

While reducing the distance between rows proved effective in increasing vineyard yield, closer in-row spacings had less impact on yield and in some cases led to more dense canopies due to an increase in leaf area per unit row length (Kliewer et al., 2000). Closer in-row spacings were initially considered a tool for increasing vine competition and reducing vine vigor, however, the data provided evidence for the contrary in California. Figure 3 shows that while total canopy size per vine decreases as the distance between vines is decreased, canopy density or the amount of leaf area per foot row length increased.

The other major change in California vineyard design centered on row orientation. In the early 1990's, many vineyards strayed from the traditional east-west row orientation and were planted north-south (approximate). This change was driven by previous research indicating that north-south rows intercepted up to 15% more sunlight compared to east-west rows (Smart, 1973). However, California grape growers quickly discovered that north-south row orientation, combined with VSP trellis systems, deficit irrigation and common canopy manipulations such as leaf removal, often resulted in over exposure of the fruit to sunlight in warm (≥Region III) growing regions. In some cases clusters exposed to sunlight on the west side of north-south oriented rows were removed from the vine or harvested separately due to their lower color, aroma and desiccated berries (Keightly, 2000). Today, true north-south row orientations are generally avoided in warm coastal growing regions when VSP trellis systems are employed. In some cases row orientation is offset by 25 to 45 degrees from true north-south to favor north-east/south west orientations. This prevents direct exposure of the fruiting

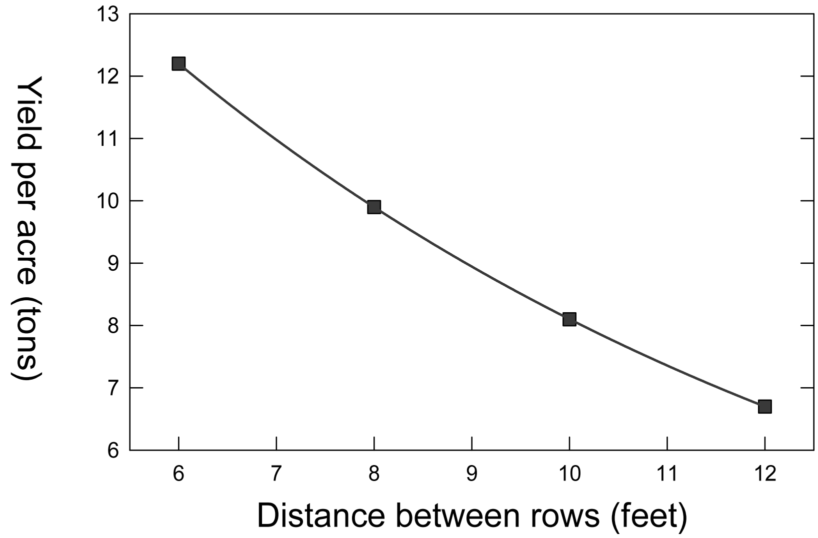

Figure 2. Influence of row spacing on the yield per acre of Cabernet Sauvignon grapevines trellised to the traditional California Sprawl in Livingston, California. N. Dokoozlian, unpublished data.

zone to sunlight during the late afternoon, reducing the likelihood of over-exposure of the fruit. East-west orientations are still generally used in the San Joaquin Valley.

COMMON TRAINING AND TRELLISING SYSTEMS FOR WINE GRAPE PRODUCTION

Today, a wide range of training/trellis systems are routinely employed in California wine grape production (Figure 4). The trellises encompass single to divided curtain systems, and employ both horizontal and vertical canopy division. Due to both cost and durability, metal replaced wood as the material of preference for trellis construction in the late 1980's. The trend is to use heavier weight and stronger materials, thus requiring that fewer stakes be used per hectare. A brief summary of each system is presented below.

California Sprawl

Prior to the mid-1980's nearly all California wine grape vineyards were trellised to the California two-wire trellis or California sprawl. Traditionally, the single curtain system consisted of a cordon wire placed at approximately 1.1 m, with two or three vertical foliage support wires, or two foliage support wires attached to a horizontal cross-arm ("T trellis"). Today, the system consists of a cordon wire placed approximately 1.4 m above ground. Compared to the earlier systems, the increased cordon height improves light penetration into the fruit zone and spur renewal area. In most cases, a single wire is placed approximately 0.3 to 0.4 m above the cordon wire to support foliage and reduce shoot breakage from spring winds. This wire also helps to protect fruit from direct exposure to the sunlight in warm regions, reducing the potential for sunburn. In almost all cases, vines trellised to the California Sprawl are bilateral cordon trained and spur pruned. Vine spacing is typically 3 m to 3.3 m between rows and 2.1 m to 2.4 m between vines. The system is easily adaptable to mechanical harvesting and pre-pruning. Based on it relatively low establishment and production costs and ease of mechanization, this remains the dominant system used in the San Joaquin Valley. Due to improved irrigation management and the wide scale adaptation of deficit irrigation for optimizing vine vigor and crop load, many of the problems regarding over-vigor and poor fruit zone microclimate observed prior to the 1980's are much less common today.

Vertically Shoot Positioned (VSP)

Few VSP systems existed in California prior to the mid-1980's. At present, VSP is the most commonly installed trellis system in the north and central coast regions. The primary advantage of this system is that, under low to moderate vine vigor, the distance between rows is commonly reduced to 2.0 m or less. This allows more efficient vineyard design and improved productivity due to increased plant density per hectare compared to the traditional California Sprawl. The VSP is constructed by placing a fruiting wire (used for cordons or canes) approximately 0.8 m above ground. Three sets of moveable shoot positioning wires, placed approximately 0.25 m, 0.55 m and 0.90 m above the cordon wire, are attached to each stake. The positioning wires are usually attached directly to the stake, or to a cross-arm attached to the stake, and spaced approximately 10 to 15 cm apart. In some vineyards over-exposure of the fruiting zone has been addressed with canopy modifications. In many cases the upper cross-arms are much wider, up to 0.6 m, to allow the shoots to spread out in the fruiting zone and partially shade the fruit and provide a canopy configuration more similar to the California Sprawl (modified VSP). In other cases shoot positing wires on the afternoon sun slide of the vine, par-

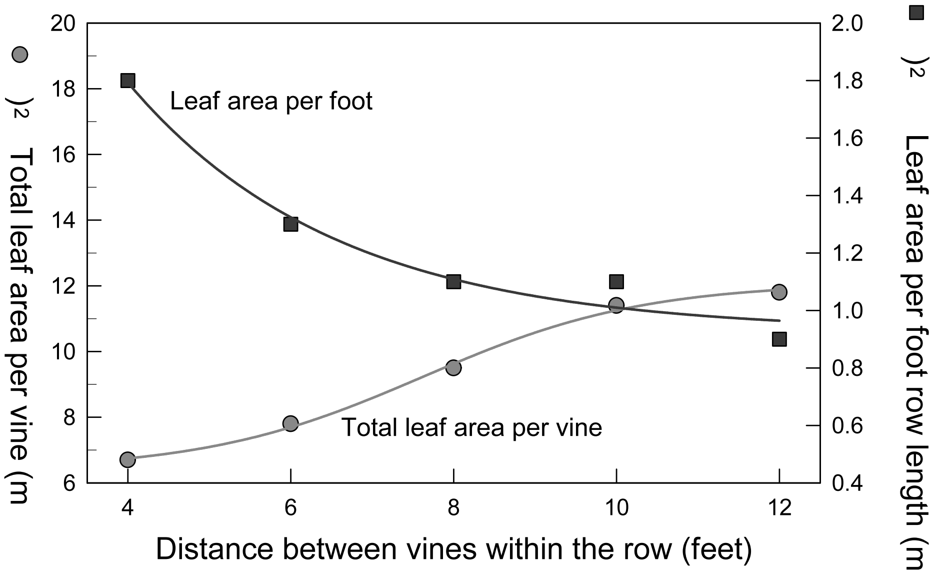

Figure 3. Influence of in-row spacing on total leaf area per vine and leaf area per foot row length for Syrah grapevines in Parlier, CA. N. Dokoozlian, unpublished data.

Figure 4. Common trellis systems currently used in California: California Sprawl (upper left); Wye (upper right); VSP (lower left); Smart-Dyson (lower right).

ticularly in north-south oriented rows, are left un-positioned and become pendant to protect clusters from direct sunlight exposure.

The VSP system is best adapted to low to moderate vigor conditions in the coastal growing regions, and is normally established using bilateral cordon trained vines. In the case of bilateral cordon training, within-row spacing normally ranges between 1.5 m to 2.1 m, depending upon anticipated vine vigor; within-row spacing usually becomes greater as vine vigor increases. Unilateral cordons may also be used when anticipated vine vigor is low, and the distance between vines will not exceed 1.5 m. In-row spacing for head training, to allow cane pruning, usually ranges between 1.5 m to 1.8 m. The system has also been used in the northern San Joaquin Valley, utilizing in-row spacings between 1.8 m and 2.4 m. Between-row spacing is typically 2.4 m. Production costs are significantly higher compared to the traditional single curtain (California sprawl) due to greater vine density, as well as the additional costs for canopy management (shoot positioning). The VSP is well adapted to mechanical harvesting, pre-pruning, leaf removal and shoot trimming.

Wye

The wye trellis system used in California was adapted from the Geneva Double Curtain trellis system developed by Nelson Shaulis of Cornell University in the 1960's. The trellis was used to a limited extent beginning in the late 1970's, and reached wide scale use by the mid-1980's. The system is constructed by forming two horizontally divided curtains, approximately 1.4 m above the vineyard floor. The distance between the curtains is variable, ranging from 0.3 m to 1.1 m, based on anticipated vine vigor, growing region and desired potential for mechanization. Wider separations are used when anticipated vine vigor is high, however, recent work in the San Joaquin Valley revealed little difference in the productivity or fruit composition of this system when curtains were spaced either 0.6 m or 1.2 m apart. In some cases, foliage support wires are placed above the fruit zone to protect clusters from direct sunlight. Vine foliage typically becomes pendent after berry set, and shoots grow downward. It is believed that the natural downward orientation of these shoots reduces shoot growth rate, reducing vine vigor.

Canopy division has typically been accomplished by training vines to the quadrilateral cordon system. Four permanent arms are established from a single vine (2 on each side of the canopy). Growers have also utilized bilateral cordon trained vines, arranged in a variety of configurations, to establish horizontally divided curtains. The main advantages cited for this method are more rapid and less expensive vine training and larger yields the first few years after planting. A potential drawback to this training method, when comparing vines at similar in-row spacing, is that the cordon length of bilateral trained vines is double that of quadrilateral trained vines. In-row vine spacing for this system normally ranges between 1.8 m and 2.4 m, while between row spacing is 3.3 m to 3.4 m. Adjustments within this range are based upon anticipated vine vigor; larger vines require greater vine spacings and larger separations between fruiting curtains. Most wye systems in California are not shoot positioned, but shoot positioning can be used to maintain curtain separation. Mechanization should be a major consideration when determining the distance between curtains. Most of the current machine harvesting systems used in California are not adapted to curtains spaced more than 0.8 m.

Smart-Dyson

The system was originated by wine grape grower John Dyson and viticulturist Richard Smart in the late 1980's. Commercial use of the system is limited to the north and central coast growing regions, and the system primarily utilized as a retrofit for over-vigorous VSP vineyards after planting. Vine foliage is vertically divided by positioning half the canopy upward, and the remaining half downward. Bilateral cordon trained vines are utilized, with the cordon or fruiting zone height normally placed 0.8 m to 0.9 m above ground. During vine training, care is taken to develop and retain equal numbers of upward and downward positioned spurs. Three sets of moveable positioning wires, located 0.25 m, 0.55 m, and 0.9 m above the cordon, are used to position shoots originating from upward oriented spurs. One set of wires, located approximately 0.55 m beneath the lower cordon, is used to position the growth from spurs oriented downward. The system is adapted to moderate vigor conditions, where anticipated vine vigor is too high for the VSP trellis but insufficient for the wye system. In the late 1990's, many acres of VSP were retrofitted to Smart–Dyson in an effort to decrease canopy congestion and increase vine productivity. Because spur pruning is utilized, downward positioning may be difficult and result in shoot breakage. To partially alleviate this problem, many growers practice *passive shoot positioning*; in this case little attention is paid to whether a shoot oriented from an upward or downward oriented spur when positioning. Shoots are simply retained in their initial orientation; upright shoots are placed in the upper curtain and downward shoots in the lower curtain. The system is adaptable to machine harvesting, pre-pruning and leaf removal. Using this system, little difference in fruit or wine composition has been observed among clusters on upward and downward oriented shoots (Bettiga and Dokoozlian, unpublished data).

COMMON CANOPY MANAGEMENT PRACTICES

Prior to the 1980's, canopy management practices such as basal leaf removal were not commonly performed in California wine grape vineyards. This changed quickly once the benefits of leaf removal were observed, particularly under the California sprawl trellis system (Bledsoe et al., 1988). Basal leaf removal consists of the removal of primary leaves and lateral shoots subtending the basal 5 to 6 nodes of each primary shoot. Work in California has shown that leaf removal increases light penetration in the canopy interior 5 to 10%, and reduces humidity in the fruit zone 25 to 30%, compared to the untreated control (Bledsoe et al., 1988; Kliewer et al, 1989). In most wine grape vineyards leaves are removed on the morning sun side of the row only (ex. the north side of east-west oriented rows or the east side of north-south oriented rows) to avoid excessive exposure in the late afternoon. Leaf removal is normally performed shortly after berry set to allow clusters to acclimate to increased sunlight exposure and higher temperatures, and reduce the likelihood of sunburn. Leaf removal is avoided immediately before berry softening or veraison, as fruit grown in the canopy shade is highly susceptible to sunburn if exposed at this time.

Shoot thinning, also referred to as crown suckering, is performed in the early spring to reduce shoot congestion and crop load. Sterile shoots, and in some cases cluster-bearing shoots from non-count nodes or multiple shoots from the same node, are removed when average shoot length is 15 cm to 25 cm. Initially, shoot thinning increases light reaching the basal buds of the remaining canopy. However, following berry set, little difference in canopy light microclimate is typically found between thinned and unthinned vines of moderate vigor (Figure 5). Work

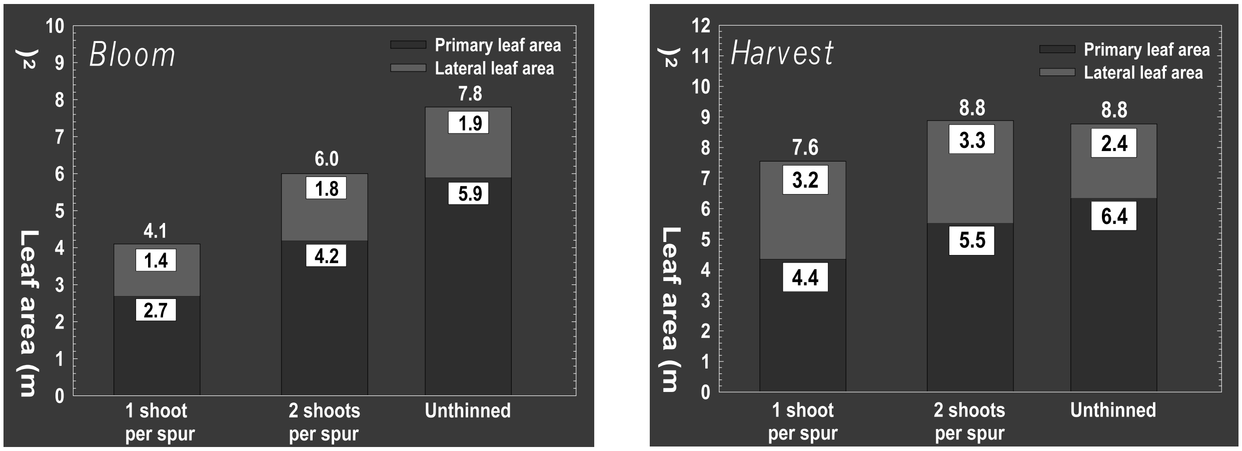

Figure 5. Influence of shoot thinning on the canopy characteristics of Chardonnay grapevines at bloom (left) and at harvest (right). Bettiga and Dokoozlian (unpublished data).

in California has demonstrated that shoot thinning reduces crop load 20% to 30%, depending upon the cultivar and season (Bettiga and Dokoozlian, unpublished data). It has also been shown that the practice does not impact bud fruitfulness the following growing season.

Shoot positioning is performed in vertically shoot positioned canopies (ex. VSP) to maintain canopy form and foliage separation, as well as to facilitate narrow row spacing. Shoot positioning is also performed on horizontally divided canopies (ex. wye, lyre) to maintain canopy separation. Shoot positioning improves light penetration to the canopy interior, particularly in vigorous, horizontally divided vineyards where the row middle or area between the fruiting zones becomes shaded following fruit set. The vine foliage is separated or positioned using movable wires. Shoot positioning is typically performed manually; however, mechanical shoot positioning on the VSP trellises has been used to a limited extent.

Hedging is used to maintain canopy shape, prevent shading and facilitate cultivation and mechanization. VSP canopies are commonly trimmed when their foliage reaches beyond the positioning wires at the top of the canopy, sometime near veraison. Hedging prior to this period is not recommended, as increased lateral shoot growth and canopy density may result (Kliewer and Bledsoe, 1988). California Sprawl canopies in the San Joaquin Valley are also trimmed near the vineyard floor following veraison as needed to facilitate air movement and decrease humidity. Extensive hedging, in which one or both sides of the canopy are trimmed heavily in order to expose the fruit zone, delays ripening and reduces berry color. It is generally not practiced in California.

IRRIGATION MANAGEMENT

Until the early 1990's, irrigation scheduling in California was largely performed by monitoring soil moisture levels and correlating desired shoot growth rates and canopy size with irrigation amounts. Irrigation levels were increased if vine vigor was deemed too low, and reduced if canopy growth was excessive. However, during the past twenty years, most growers have moved toward using evapotranspiration or ET based measurements for irrigation scheduling (Grimes and Williams, 1990). A pre-determined fraction of estimated total vine water use is normally applied (ETc), depending upon the stage of vine growth and desired productivity and fruit quality. In generally, this amount ranges between 80% and 50% of estimated total vine water use (ETc) for wine grapes, depending upon the growing region and production objectives.

Improved irrigation management and the rapid adoption of deficit irrigation practices for wine grapes, in particular, had a major impact on canopy growth, fruit zone microclimate and fruit composition (Table 2). Growers quickly recognized that by reducing irrigation levels, major improvements in fruit quality could be achieved. It was later shown that in some cases these impacts were direct effects of deficit irrigation due to reduced berry volume and/or altered berry metabolism, while in other cases the impact could be linked to improvements in canopy microclimate. Perhaps more than any other single practice developed during the past two decades, improved irrigation methods have had a major impact on how canopies are managed – particularly with regard to canopy manipulations such as basal leaf removal and hedging. The need for these practices may be reduced, or in some cases even eliminated, if canopy growth can be optimized via proper irrigation. However, in many regions of California, including the north coast, normal winter rainfall may result in large amounts of stored soil moisture and rapid spring growth. In this case it is difficult to optimize canopy growth and size, even with proper irrigation management following budbreak.

PRUNING AND CANOPY MANAGEMENT MECHANIZATION

Due to the increased cost and reduced availability of labor in California, at present there is strong interest in mechanizing pruning and canopy management practices. While mechanical pre-pruning (machine pruning prior to hand pruning) is com-

Table 2. Influence of irrigation management practices on Cabernet Sauvignon in the northern San Joaquin Valley – 1995.

Irrigation treatment	Shoot length (cm)	Pruning wt (lbs/vine)	Light in fruit zone (% ambient)	Wine color units at 520nm
No deficit	313	8.7	5	1.4
Pre-veraison deficit	162	6.3	19	4.3
Post-veraison deficit	202	6.9	14	4.1

(Prichard, unpublished data)

monly employed, only a small portion (<5%) of the vineyards in the state are mechanically pruned or box hedged with little or no manual follow-up. This is true in spite of the fact that mechanical pruning offers many advantages compared to hand pruning including improved fruit zone microclimate, decreased berry size and improved fruit and wine composition (Clingeleffer, 2000). The data also reveals that the primary disadvantage of the system, over-cropping in the first few crops or years following the conversion from hand to machine pruning, decreases over time. The use of this practice will increase as economically viable methods to reduce excessive crop loads when necessary, such as mechanical or chemical thinning, are more widely employed. This transition will be accelerated if labor becomes more limited in the future.

Mechanical leaf removal in the fruit zone has been commonly employed in California for nearly 20 years, particularly in VSP trellis systems. Recent work has shown that properly adjusted equipment can remove up to 75% of the leaf area in the fruit zone, compared to 95% with hand leafing (Dokoozlian, unpublished data). However, the level of leaf area removal is extremely variable depending upon trellis configuration and the equipment utilized. Mechanical leaf removal can be performed for approximately 30% of the cost of hand leafing.

Mechanization of shoot thinning and shoot positioning has been implemented to a very limited extent in California to date.

ADVANCES IN TABLE AND RAISIN GRAPE CANOPY MANAGEMENT

During the past two decades, the canopy management systems used by the California table and raisin grape industries have also advanced significantly. Since the early 1990's, the majority of the new table grape acreage in the state has been planted on the Gable trellis system – a modified version of the system commonly found in South Africa and other regions of the world (Figure 6). While the system requires extensive inputs for shoot thinning, leaf removal and shoot positioning, when properly managed yields and fruit quality (size and color) are 50% to 100% greater compared to the California sprawl system traditionally used for table grape production.

In an effort to improve efficiency and reduce production costs, the California raisin industry is steadily moving away from the traditional harvest method where the fruit is picked by hand and placed on paper trays between the rows to sun dry. Mechanized systems, in which the fruit bearing canes are severed at maturity and the clusters dry on the vine and are then harvested by machine, are advancing rapidly. One of the most innovative systems is the overhead trellis, alternating cropping middle system (Figure 7). The fruiting zone of this system alternates annually, as renewal canes for next year's crop grow in the opposite row middle as the fruiting canes for the current year's crop. Canes in the cropping middle are severed at harvest, and the dried clusters harvested from the vine by machine, while the renewal canes remain intact. Since the renewal canes for the next crop develop in nearly full sunlight throughout the year, with little or no shading from adjacent vine foliage or competition from ripening fruit, they are generally 2 to 3 times more fruitful compared to canes on the standard system. Average dry weight (raisin) yields are 5 tons per hectare for the traditional system, and over 12 tons per hectare for the alternating cropping middle trellis.

LOOKING AHEAD – WHAT'S NEXT?

A progressive grower once prodded me with the following paradigm: "*my vineyard produces high yields, excellent fruit quality and can also be harvested at full maturity very early in the season. The problem is that I can only achieve two of these three outcomes in any given year*". The analysis seems simple, but elegantly links the complicated physiological limitations of vine productivity to basic grape production metrics. Despite tremendous innovations in canopy management systems made during the past two decades, much remains to be investigated and improved.

While wine grapes have received most of the attention from the research community, it could be argued that production systems in the raisin and table grape industries have advanced most rapidly during the past two decades. As mentioned above, these industries have implemented production systems which increase yield dramatically while maintaining, or even improving, fruit quality. In contrast, in spite of improved trellis and vineyard designs, wine grape productivity in the north coast of California has remained constant during the same period (Figure 8). We must develop practices to increase the yield of

Figure 6. Redglobe table grapes grown on the open gable trellis system near Bakersfield, CA.

Figure 7. Dried on the vine raisins grown on the overhead trellis system near Fresno, CA.

wine grapes while maintaining or increasing key grape and wine quality constituents. We also need to understand how vineyard design and canopy manipulation, combined with irrigation and crop load management, can be more thoroughly integrated to achieve this goal. Canopy management will continue to evolve in California, but a sharper focus on production efficiency and the relationships between crop load and wine aroma and mouth feel compounds is needed. Yield and quality must be improved simultaneously in order to maintain the economic viability and competitive advantage of the California wine industry in the future. Lastly, the need for more thoroughly mechanized production systems – based on both cost and the diminishing availability of skilled vineyard laborers – must provide a major focus for future research and innovation.

As with all modern viticultural investigation, canopy management research will advance as rapidly as robust analytical methods for determining fruit and wine quality are developed and implemented. Improved objective measures of fruit and wine quality parameters, closely linked with grape and wine sensory properties, will be necessary before significant advances are possible.

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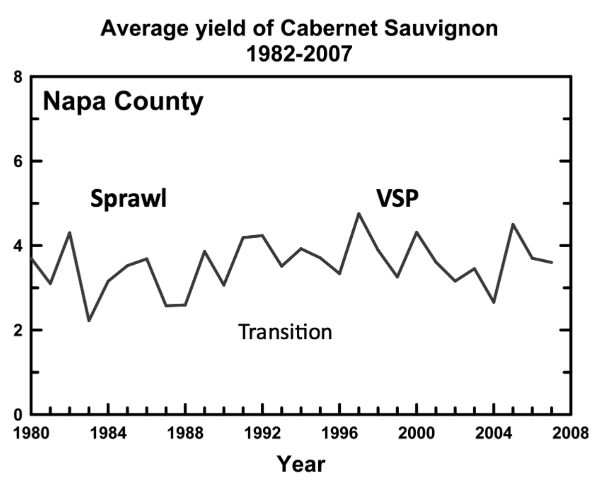

Figure 8. Historical yield trends for Cabernet Sauvignon in Napa County, California (1980 to 2007).

EVOLUTION OF CANOPY MANAGEMENT IN ITALY: A KEY TO RECONCILE REMUNERATIVE YIELD, DESIRED GRAPE COMPOSITION AND COST REDUCTION IN THE VINEYARD

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Abstract: A general trend of shifting from big-sized pergola or arched cane-trained vines to vertically-shoot positioned (VSP) hedgerows has been registered in Italy over the last two decades. This change has occurred along with a concurrent increase in vine density, posing in turn the still unresolved and lively debated issue of vine vigor control and balanced growth. Concurrently, VSP and U-shaped trellises have been modified to make them suitable for the softer vertical mechanical harvesting. Increased sensitivity has also matured towards modeling and direct assessment of gas exchange of whole canopies through enclosure approaches. The latter methodology has led to precious information in relation to changes at the whole canopy level in net CO_2 exchange rate due to shoot positioning and trimming, leaf removal carried out at different dates and severities shoot and row orientation. More recently, canopy management has evolved primarily towards a more focused application of summer pruning. The major change is that a given summer pruning operation is not solely or exclusively seen as something the grower "has to do" but, rather, as something that the grower may "use" to head vine and cluster growth towards better grape composition. A successful example is that of pre-flowering leaf removal, which, under a large array of genotypes and growing conditions, has proven to be consistently effective in ameliorating cluster morphology (less compact, hence, less susceptible to rot), in controlling crop level through mechanisms which largely differ from those inherent to traditional cluster thinning and in improving grape and wine composition. Canopy management in Italy as well as in the remaining main grape producer countries will have invariably to face the challenges imposed by global climate change. Scientists are increasingly coming round to the idea that in warm climates with hot summers a cluster microclimate described by a prevailing regime of diffuse light broken by occasional sunflecks would be the most recommendable. Another concern stemming from increasing heat summations is that ripening can be greatly accelerated and marked by final alcohol content that is too high, an acidity that is too low and untypical flavors. Thus, in prospect, a new frontier of canopy management is that a modulated ripening delay may well turn out to be desirable.

Keywords: *Vitis vinifera* L., photosynthesis, transpiration, leaf water potential, shoot growth, yield.

Canopy management is a special challenge in Italy whose viticulture is typically characterized by a multitude of training systems (more than 40 are those described by Eynard and Dalmasso, 1990) that, besides being a legacy of tradition, accommodate a broad range of vegetative vigor conditions and yield potential. Yet, over the last two decades a fairly consistent trend of replacing old-fashioned, non-mechanisable pergola-type or arched-cane trellises with either undivided (vertically shoot positioned or free-growing) and divided (e.g. GDC) canopies has been confirmed and sustained. While this move towards structurally simpler and highly mechanisable training systems appears to be a wise choice with broad support, it is a shift that in quite a number of cases has triggered the issue of vine balance and, perhaps unexpectedly, has brought even further to the forefront the importance of proper "canopy management". This has often happened when vineyards originally established at low to medium vine density have been replanted under the rule of thumb that "the denser, the better". Reducing within-row vine spacing below a given threshold has made growers realize that the expected increase in vine-to-vine root growth competition is unable to offset the increase in shoot vigor caused by lowering node number per vine. As a paradox, these high density vineyards have turned out to be more demanding in terms of canopy management than the old ones.

Evolution of training systems, pruning techniques and machine design.

Over the last two decades, a renewed impulse has been put into rendering the Geneva Double Curtain (GDC) an even more efficient example of full mechanization (less than 50 hours of labor /ha), representing the ideal alternative to older large trellises established in vigorous sites. Adoption of a semi-mechanized device for shoot positioning made of a pivoting arm mounted on top of one out of every 4-5 posts along the row, which creates a barrier preventing shoots to grow inward once it is opened, has greatly relieved the very time-consuming manual shoot positioning (Intrieri and Poni, 2004). This device has also affected shoot growth direction (more erect), thus contributing to relieve cluster over-exposure upon hand shoot positioning while helping to create a microclimate dominated by diffuse light. Given its suitability to the softer vertical shaking mechanical harvest principle GDC has also inspired the latest training system devised in Italy. It is called COMBI and shares with GDC horizontal canopy splitting and suitability to vertical shaking while presenting instead a VSP canopy that eliminates the need for manual shoot positioning, which here is achieved with quick positioning of pairs of catch wires (Intrieri and Filippetti, 2007).

Progress has been made as well in regard to the single, high-wire trellis, either unmodified or modified, to make it suitable to vertical harvesters, which is gaining popularity in terms of reduced planting and management costs as the trellis is essentially limited to posts, stakes and one main supporting wire while winter pruning is very quick even if not mechanized. Provided that a decent upright shoot growth is achieved, this training system has a great aptitude for mechanical winter pruning and it is becoming a valid competitor for VSPs, particularly in areas where simplicity of management needs to be reconciled with the need to control vine vigor.

Despite advances in winter pruning achieved in Italy since the first cutter bar pruning machine was introduced in the early 1970s, and publication of long-term studies showing that short mechanical pruning followed by hand finishing might lead the vines to a yield/quality balance comparable or even more advantageous than that of hand pruning while obviously reducing overhead (Poni et al., 2004), growers are still fairly reluctant to move from cane pruning to spur pruning. Among other factors, this uneasiness involves the suspicion that basal nodes might turn out to be not fruitful enough and, above all, that cordon productivity might decline over time. The best and most convincing answer that canopy management has underscored to prevent loss of cordon productivity over time is to combine a mechanical pre-pruning with a subsequent quick manual follow-up. The non-selective machine run is determinant to assure a "not so clean" pruning, which is itself a warranty of cordon duration and yield maintenance.

Pruning techniques have evolved worldwide from manual to hedge and then minimal pruning (MP), allowing drastic time savings usually associated with increasing number of nodes retained on the vines. The success or failure of a given technique primarily depends upon on the balance of genotype, vegetative growth and yield components. In Italy, while MP of high yielding cultivars such as Sangiovese is satisfactory as to improved cluster looseness and decreased berry size, it induces an alternate biennial bearing pattern of vines coupled with a notable crop-linked variation of grape composition (Intrieri at al., 2001). Designed to balance vine response through a more severe pruning while maintaining suitability to full mechanization, the semi-minimal pruned hedge (SMPH) system was developed from spurred cordon-trained vines by attaching a few of the previous' season canes to the horizontal trellis wires. This "hedge" shape was maintained over time by winter mechanical hedging and topping. A three-year study comparing SMPH and traditional spur pruned VSP cordons in Sangiovese has shown an average 30% higher yield in SMPH, with no overall detriment to grape composition, and preserves the features of looser clusters and less incidence of rot (Intrieri and Filippetti, 2007).

Efficiency of training systems and cultural practices: a whole-canopy approach

A fundamental branch of canopy management is related to method and parameters available to quantify "crop load", which has traditionally relied upon yield-to-pruning weight and total leaf-to-yield ratios (Smart, 1991). While the former is very easy to calculate and useful for a rough assessment of excessive vigor or tendency to over-cropping, a major weakness of this index is that one-year-old pruning weight does not necessarily relate to actual vine capacity. The total leaf area-to-fruit ratio, albeit more troublesome to calculate, overcomes the problem, and it is remarkable that saturation of such primary grape composition criteria as the concentration of soluble solids or phenolics has been reported to occur across a threshold of 1.2 -1.5 m^2/kg despite a large variation in genotypes, environmental conditions and cultural practices (Kliewer and Dokoozlian, 2005). Especially over the last two decades, grapevine physiologists have attempted to comply with the inherent limitations of the above indices. Modeling is a currently fascinating tool aimed at bypassing the typical stillness of the traditional vine balance indices (usually benchmarked "at harvest"), thereby allowing estimates of the seasonal variation of canopy assimilation potential as well as patterns of dry matter partitioning. Further steps were also taken to investigate microclimate and function of specific organs or canopy segments (Schultz 1995, Poni et al. 1996), while attempts have recently been conducted to model the fraction of foliage which is actually well-exposed to light and, ultimately, the photosynthetic efficiency of a canopy (Louarn et al., 2008). Here resides one of the major methodological concerns, as it is still debated whether and how single leaf-based gas exchange readings can represent the complexity of a "canopy", where a multitude of factors like age, light exposure, and so on, act simultaneously.

Over the last 15 years, several working groups have set up and evaluated custom-built tree-enclosure systems that are able to wrap the entire canopy, or portion thereof, and provide, often under an automated and unattended operation, direct evaluation of CO_2 and H_2O gas exchanges (Poni et al., 1997). While the direct assessment of whole-canopy gas net CO_2 exchange rate (NCER) can certainly not be proposed as a user-friendly method for evaluation of grapevine canopy efficiency, its value for studying basic principles of canopy physiology surely must be recognized. The simplest approach would be to provide for a series of training systems a parallel comparison of single leaf vs. whole-canopy derived gas exchange rates. Once the data are expressed on a per leaf area basis (i.e. μmol CO_2 m^{-2} s^{-1}), it is conceivable that the calculated differential will represent "how much" the "whole canopy" is less efficient as compared to the ideal situation of a healthy leaf. In other words, the difference between the two calculated rates accounts for effects due to mutual shading, exposure and any factor influencing leaf function.

Figure 1 typifies the pattern of light response curves derived for a single leaf and for two canopies having a different growth pattern (VSP vs. free-growing) (Intrieri et al 1997). While it is not surprising to see that photosynthesis increases with increasing light, which is more gradual for whole canopies, it is notable that the canopy forced between catch wires lessens its photosynthesis by about 26% as compared to a free growing canopy. This difference likely quantifies the loss of photosynthesis due to less light penetrating the inner part of the canopy in the VSP trellis. Another noteworthy example is shown in Figure 2 (Intrieri et al. 1997), where the pattern of canopy NCER is plotted against leaf area per vine. Here variability in vine leaf area was obtained by progressively removing internal leaves according to a decreasing level of shade (i.e. the most shaded were removed first). The graph shows that beginning from the initial level of about 13 m^2 leaf area per vine, removing about 3.5 m^2 of foliage did not produce any significant lessening of NCER. Beyond the threshold of 9 m^2 leaf area per vine, NCER started to decline sharply, suggesting that such a level of vigour represents, for the specific site and vineyard condition, the optimal canopy filling, i.e. enough leaf area to fill the canopy volume and reach maximum photosynthesis with minimal effects of mutual shading.

Summer pruning in the vineyard; a different perspective.

More recently, canopy management has evolved primarily towards a more focused application of summer pruning. The major change is that a given summer pruning operation is not solely or exclusively seen as something that the grower "has to do" (i.e. to accommodate adjustments for excessive shoot growth or canopy density). Rather it is now viewed as something that the grower may "use" to head vine and cluster growth towards better grape composition.

A successful example is that of pre-flowering leaf removal (Table 1), which under a large array of genotypes (Sangiovese, Trebbiano, Barbera, Lambrusco) and growing conditions has proven to be consistently effective in ameliorating cluster morphology, in controlling crop level through mechanisms that largely differ from those inherent to traditional cluster thinning and in improving grape and wine composition (Poni et al., 2006). The temporary source limitation induced by removing an average of six main basal leaves before bloom has led, as expected, to a significant decrease in fruit-set, which in turn increases cluster looseness and tolerance to rot. Yet, the most relevant outcome was that, regardless of genotype, this early leaf removal markedly improved grape composition as compared to non-defoliated shoots. The mechanisms involved in such a positive response are multiple. Defoliated shoots generally had a higher final leaf-to fruit ratio than control, thus implying that the yield reduction induced by defoliation treatments through a fruit set and berry size effect was more than proportional to the leaf removal constraint. Then, too, it is known that a precocious source limitation carried out in the form of defoliation or darkening the basal shoot zone hastens translocation of assimilates towards the cluster. Improved grape composition in the defoliated shoots also relates to the "quality" of the source. It is indeed true that removing, for example, the six basal main leaves at pre-bloom causes an abrupt and severe decrease in vine photosynthesis (75% less as compared to ND according to Poni et al., 2008). However, removing source leaves around bloom also triggers a series of dynamic changes in canopy growth, age and photosynthesis. Defoliated vines have a "younger" canopy at

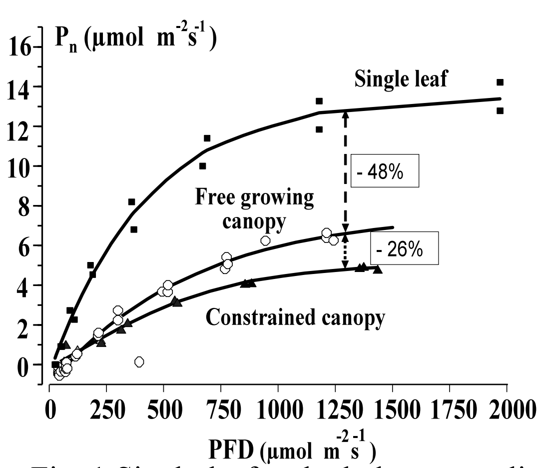

Fig. 1 Single-leaf and whole canopy light response curves on "Sangiovese" (from Intrieri et al. 1997).

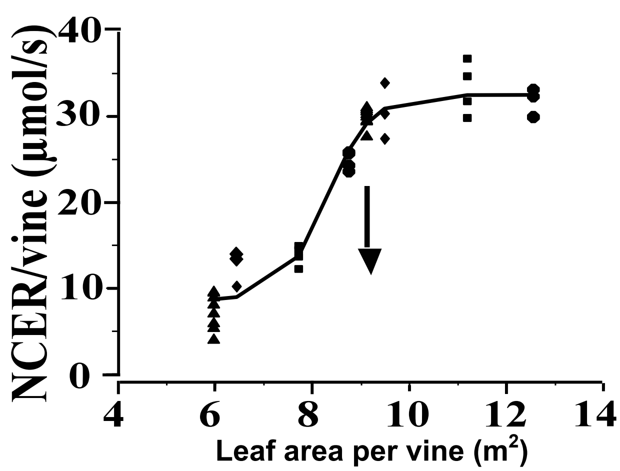

Fig. 2. Whole-canopy net carbon exchange rate (NCER) vs. leaf area per vine (from Intrieri et al. 1997).

Table 1. Influence of hand pre-bloom defoliation on fruit-set, yield components and must composition of different cultivars as compared to a non defoliated control (from Poni et al., 2006, 2009).

Source of variation	Fruit-set (%)	Berries cluster	Cluster weight (g)	Berry weight (g)	Brix (%)	TA	Anth. (mg/g)	Phenols (mg/g)	Leaf-to-fruit ratio (cm^2/g)
Sangiovese[1]									
Control	35.2[a]	143.7[a]	305[a]	2.59[a]	18.3[b]	5.7[b]	0.79[b]	2.154[b]	8.4
Defoliated	29.5[b]	123.8[b]	245[b]	2.22[b]	20.1[a]	6.1[a]	1.13[a]	2.385[a]	11.4
Barbera[1]									
Control	27.4[a]	174[a]	391[a]	2.25[b]	19.4[b]	10.8[a]	0.80[b]	1.43[b]	5.5[b]
Defoliated	19.1[b]	116[b]	278[b]	2.40[a]	23.2[a]	9.9[b]	1.28[a]	1.99[a]	8.9[a]
Lambrusco[1]									
Control	26.4[a]	128[a]	191[a]	1.49	15.6[b]	12.5[a]	1.95[b]	3.93	5.0[b]
Defoliated	17.9[b]	78[b]	117[b]	1.50	17.7[a]	10.4[b]	2.58[a]	4.31	10.2[a]
Trebbiano[2]									
Control	42.7[a]	210[a]	400[a]	1.97	19.0[b]	5.8	-	-	6.2[b]
Defoliated	27.5[b]	111[b]	210[b]	1.86	21.4[a]	5.6	-	-	8.9[a]

[1]. Defoliation performed as removal of the first 6 main basal leaves (one-season data). [2]. Defoliation performed as removal of the first 8 basal leaves (three-season data). Letters within columns indicate significance at $p \leq 0.05$ by t test

veraison, since median and apical shoot leaves at this time are now mature and more lateral leaves can be present as a compensating reaction to early main leaf removal, while some, albeit temporary, photosynthetic compensation usually occurs in both main and lateral leaves of defoliated plants. Poni et al (2008) have recently shown that whole canopy net CO_2 exchange rates (NCER) monitored uninterruptedly for three months in defoliated (D) vs. non-defoliated Sangiovese vines indicated no differences for data expressed on a per-vine basis. Yet when the same data were given on a per-unit leaf area basis, defoliated vines showed higher rates than ND vines (4.75 μmol $m^{-2}s^{-1}$ vs. 4.16 μmol $m^{-2}s^{-1}$) and, most importantly, NCER/yield increased by 38 % in D vines, thus resulting in enhanced carbohydrate supply for ripening. Finally, the most intriguing outcome from these early-season defoliation studies is that a significant increase in relative skin mass was found regardless of absolute berry mass (figure 3), indicating that berry size per sè is not the primary factor determining final grape composition, which instead seems to depend upon factors differentially affecting the growth of the various berry components (Poni et al., 2009).

Once verified that this pre-flowering defoliation has a strong physiological basis and shows high results repeatability across a wide range of genotypes and environments, the second step was to see whether it was mechanisable. A recent report from Intrieri et al. (2008) has shown in a three-year survey that both pre- and post-bloom mechanical defoliation are effective in limiting the yield of a high-cropping cultivar like Sangiovese while improving must soluble solids and total anthocyanins on a fresh-weight basis. These data indicate that mechanical defoliation is viable and delivers most of the advantages delivered by hand removal. Indeed, fast mechanical leaf removal to limit yield, enhance quality and obviate expensive manual shoot and cluster thinning is appealing and broadens the number of potential users. Work is in progress to investigate whether the precocious, albeit temporary, source limitation on which this technique relies can be induced through the non-invasive and easy-to-do application of antitranspirants. Their use would sort out the inherent limitation of high labor demand of manual intervention while eliminating the risks of direct damage to the inflorescences bound to the use of a leaf plucker.

Canopy management and the new challenges of climate change

Canopy management in Italy, as well as in the other main grape producer countries, will invariably have to face the challenges imposed by global climate change (Jones et al. 2005). Under the stimulus of increasing heat load worldwide, a great deal of experimental work is being conducted on the effects that radiation and temperature exert on the biosynthesis and degradation of different categories of flavonoids. While an increasing body of knowledge suggests that light exposure and temperature exert a fairly independent role on many components (i.e. anthocyanins are more sensitive to temperature, whereas flavonols do respond more directly to light intensity), scientists are increasingly forming a consensus that in warm

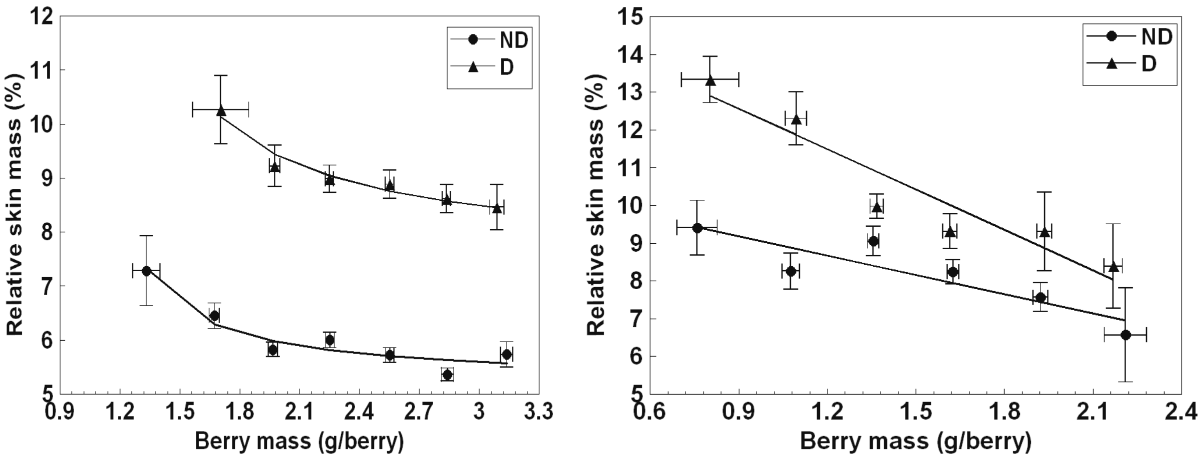

Fig. 3. Relative skin mass vs. total berry mass for non defoliated (ND) and defoliated (D) Barbera (left) and Lambrusco (right) vines. D consisted in removing the first six basal leaves pre-bloom (from Poni et al. 2009).

climates characterized by hot summers, a cluster microclimate described by a prevalent regime of diffuse light broken by occasional sunflecks would be the most advisable (Downey et al. 2006). This impinges directly on canopy management as the supposedly ideal microclimate noted above is in reality a complex function of cultivar growing habit, vigor and the steps taken at winter and summer pruning. Italian experience of canopy management has strengthened the conclusion that such a microclimate is most easily achievable under a single high-wire training system provided that an upright shoot growth pattern predominates. Adopting a coiled support wire and practicing timely shoot trimming are crucial factors in promoting such a growth pattern even in the most recalcitrant varieties like Trebbiano and Pinot types.

Canopy management has a great impact indeed on local cluster microclimate and affects berries susceptible to scorching or burning, an issue that is rising to utmost importance in warm climates with hot summers. More knowledge is needed about the long-term effects of summer pruning. Once again, the practice of leaf removal seems an appropriate example: recent work from Mescalchin et al. (2008) has shown that the earlier the defoliation, the lesser the incidence of skin burning on VSP and pergola trained varieties due to both more time allowed for cluster cover after treatment and adaptation towards the formation of a thicker skin. Another concern raised by the increasing heat summations is that ripening can be greatly accelerated and marked by final, overly high alcohol content, an acidity that is too low and disruptions or alterations of balanced grape composition and flavor. Thus, one facet of the new frontier in canopy management is the prospect that a modulated ripening delay might turn out to be desirable.

CONCLUSIONS

The market itself, rather than the grape producer or the “label” is the factor playing the major role, and the quality/cost ratio is truly becoming the top issue in the very competitive and globalised wine trade. This requires that three factors, which at least for Old World viticulture have been traditionally judged as very unlikely to co-exist, should rather be regarded as compatible issues. They are (a) production in the field of good-to-excellent grapes, (b) rewarding yield per hectare (a pertinent question is: why crop no more than 4-5 t/ha when a good terroir, my own expertise as a grower and the law would allow me to crop 7-8 t at the same quality?), and (c) reduction in vineyard overhead outlays. Canopy management is, and will continue to be, a key factor in trying to reconcile these apparently incompatible goals.

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Table 2. Influence of hand (H) and mechanical (M) defoliation (D) at pre- (I) and post- (II) flowering on fruit set traits, yield components and must composition of different cultivars as compared to a non-defoliated control (reworked from Intrieri et al., 2008).

Source of variation	Fruit-set (%)	Berries cluster	Cluster weight (g)	Berry weight (g)	Brix (%)	TA	Anth. (mg/g)	Phenols (mg/g)	Leaf-to-fruit ratio (cm^2/g)
Control	33.6[a]	260[a]	508[a]	1.83	19.1[c]	9.34	0.82[c]	2,23[b]	4,7
HD-I	21.2[c]	174[b]	292[b]	1.70	22.2[a]	8.48	1.04[a]	2,72[a]	5.9
MD-I	27.5[b]	216[ab]	398[ab]	1.85	21.8[a]	8.46	0.90[b]	2.39[b]	5.0
HD-II	23.2[c]	177[b]	304[b]	1.57	20.9[b]	8.78	1.01[a]	2.61[a]	6.9
MD-II	25.8b[c]	194[b]	368[b]	1.80	20.8[b]	8.67	0.89[b]	2.69[a]	5.7
Main	**	*	*	ns	**	ns	**	*	ns

Means separated within columns by SNK test. *,**, ns: p ≤ 0.05, 0.01, or not significant, respectively

CANOPY MANAGEMENT, FROM 1986, AND BEFORE, TO 2009, AND BEYOND

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Abstract: This paper will review the modern history of canopy management, but will attempt to put the subject within the context of evolutionary aspects of the botanic family Vitaceae. Appropriate acknowledgement will be made of the founding fathers of the discipline of canopy management, especially Charles Darwin of London, Nelson Shaulis of Cornell University in NY State, and of his inspiration from Lens Moser of Austria. Nelson's disciples included among others Alain Carbonneau from Bordeaux, Cesare Intrieri and Giovani Cargnello from Italy, Mark Kliewer from Davis, and myself from Australia and then New Zealand. Finally, important issues are raised about the present status of canopy management research, and of the failure of canopy management to be more widely adopted.

This is not a scientific paper in the normal sense, and so I will take the liberty of using the first person. I have been asked to review the state of canopy management in the world's vineyards. I am pleased to respond to the invitation, especially in association with a G(i)ESCO meeting, and more especially at a UCD symposium honouring Professor Mark Kliewer, a colleague and good friend.

I have not been actively involved in full-time research since 1990. My occupation since has been consulting, and I have had the good fortune to work in over 30 countries, and many wine regions. Much (but not all) of my consulting has to do with canopy management, so I do have some international perspective about adoption of this technology.

My recent lack of contact with the scientific literature means that this piece will not be a literature review, as it might be. Rather, it will be a personal reflection about the topic, dwelling on the immediate past, but going back in history some 100 million years or more, and forward a few years, not millions.

THE GENUS VITIS, THE BEGINNINGS

The flowering plants or angiosperms emerged in the Cretaceous period, some 130 million years ago. These plants dominate the present terrestrial landscape and are the most successful plant groups, with something like a quarter of a million species described. The flowering plants are classified into more than 300 families, largely on the basis of the flower, their reproductive organ. One family is the Vitaceae, containg Vitis vinifera, the grapevine.

We have become so obsessed botanically with flowers it is important to remember that a flower is nothing more than a cluster of spore-bearing leaves surrounded by whorls of protective and often albeit attractive leaves.

A feature of the Vitaceae is that they are climbing plants, and this all important fact dominates grapevine eco-physiology, and indeed canopy management if you think about it. Within forests, the evolutionary habitat for many Vitis spp, the principal environmental gradient is sunlight, varying from canopy top to bottom of up to more than one-hundredfold, compared to gradients of ambient temperature of only a few degrees C and of humidity only a few percent. One of several statements of Nelson Shaulis which I recall is that "Grape growers have replaced the shade of forest with shade caused by other grapevine leaves...". True indeed.

This means then that the stimulus governing switching to fruiting behaviour as opposed to further climbing is likely light mediated, as many studies have indeed shown. Further, many studies have shown the impact of sun light on leaf function, and fruit composition. When I say sun light, I mean the total solar shortwave electro-magenetic spectrum out to around 3,000 nm, which incorporates ultra violet, visible (and photosynthetically active), and near infra red wave bands. Grapevines have been shown to be affected physiologically by smaller wave bands within these regions, and also thermally, including longer wave radiation emission. Exceptionally fine research from Washington State has recently been able to separate thermal from light stimulus effects on fruit composition.

GRAPEVINES CLIMB TO AVOID SHADE

Grapevines use coiling tendrils and some gravimorphic response, to climb. No doubt some of you may wonder why I included in the Abstract the name of Charles Darwin as a canopy management researcher. Was it my sentimentality about his 200^{th} birthday anniversary this year, on the 12^{th} February. Or could he be considered a viticultural researcher?

While I am sentimental about Darwin (he was reputed to be one of the first Europeans to taste New Zealand wine, in December 1835, on his homeward voyage on the "Beagle"; he also visited Tasmania and said he would like to move there! I followed his advice), this is not the reason for inclusion.

Darwin was, among other things, a viticultural scientist. See what he wrote in his classic study *The Movement and Habits of Climbing Plants*.

In his words: "*This Essay first appeared in the ninth volume of the 'Journal of the Linnean Society,' published in 1865. It is here reproduced in a corrected and, I hope, clearer form, with some additional facts. .... It is, also, an interesting fact that intermediate states between organs fitted for widely different functions, may be observed on the same individual plant of Corydalis claviculata and the* ***common vine****; and these cases illustrate in a striking manner the principle of the gradual evolution of species*".

The underlining is mine, and is worthy of re-reading. Darwin says that the range of transitional forms of flowering structures in the grape vine, from tendril to inflorescence, is illustrative "in a striking manner (of) the principle of the gradual evolution of species". What an extraordinary statement, by the Father of Evolution, to state that the grapevine in its inflorescence variation shows the principle of evolution!

In what follows we can be sure that Darwin studied the "common" grape vine. I have visited Down House, in the village of Downe, south east of London, and have seen a grapevine growing near an old glass house beside a stone wall. I assume it was the subject of his study.

Darwin wrote this in *The Movement and Habits of Climbing Plants*. He studied members of the families Cucurbitaceae, Vitaceae (Vitis and Cissus), Sapindaceae and Passifloraceae. Of the grapevine he concluded:

"Vitis vinifera.--The tendril is thick and of great length; one from a vine growing out of doors and not vigorously, was 16 inches long. It consists of a peduncle (A), bearing two branches which diverge equally from it. One of the branches (B) has a scale at its base; it is always, as far as I have seen, longer than the other and often bifurcates. The branches when rubbed become curved, and subsequently straighten themselves. After a tendril has clasped any object with its extremity, it contracts spirally; but this does not occur (Palm, p. 56) when no object has been seized. The tendrils move spontaneously from side to side; and on a very hot day, one made two elliptical revolutions, at an average rate of 2 hrs. 15 m. During these movements a coloured line, painted along the convex surface, appeared after a time on one side, then on the concave side, then on the opposite side, and lastly again on the convex side. The two branches of the same tendril have independent movements. After a tendril has spontaneously revolved for a time, it bends from the light towards the dark: I do not state this on my own authority, but on that of Mohl and Dutrochet. Mohl (p. 77) says that in a vine planted against a wall the tendrils point towards it, and in a vineyard generally more or less to the north.

.... Various authors (Palm, p. 55; Mohl, p. 45; Lindley, &c.) believe that the tendrils of the vine are modified flower-peduncles.

..... I have twice seen sub-peduncles which bore from thirty to forty flower- buds, and which had become considerably elongated and were completely wound round sticks, exactly like true tendrils. The whole length of another sub-peduncle, bearing only eleven flower-buds, quickly became curved when slightly rubbed; but even this scanty number of flowers rendered the stalk less sensitive than the other branch, that is, the flower-tendril; for the latter after a lighter rub became curved more quickly and in a greater degree. The gradations from the ordinary state of a flower-stalk, as represented in the drawing (fig. 10), to that of a true tendril (fig. 9) are complete. We have seen that the sub-peduncle (C), whilst still bearing from thirty to forty flower-buds, sometimes becomes a little elongated and partially assumes all the characters of the corresponding branch of a true tendril. From this state we can trace every stage till we come to a full-sized perfect tendril, bearing on the branch which corresponds with the sub-peduncle one single flower-bud! Hence there can be no doubt that the tendril is a modified flower-peduncle.

....Another kind of gradation well deserves notice. Flower-tendrils (B, fig. 10) sometimes produce a few flower-buds. For instance, on a vine growing against my house, there were thirteen and twenty-two flower-buds respectively on two flower-tendrils, which still retained their characteristic qualities of sensitiveness and spontaneous movement, but in a somewhat lessened degree. On vines in hothouses, so many flowers are occasionally produced on the flower-tendrils that a double bunch of grapes is the result; and this is technically called by gardeners a "cluster." In this state the whole bunch of flowers presents scarcely any resemblance to a tendril; and, judging from the facts already given, it would probably possess little power of clasping a support, or of spontaneous movement. Such flower-stalks closely resemble in structure those borne by Cissus. This genus, belonging to the same family of the Vitaceae, produces well- developed tendrils and ordinary bunches of flowers; but there are no gradations between the two states. If the genus Vitis had been unknown, the boldest believer in the modification of species would never have surmised that the same individual plant, at the same period of growth, would have yielded every possible gradation between ordinary flower-stalks for the support of the flowers and fruit, and tendrils used exclusively for climbing. But the vine clearly gives us such a case; and it seems to me as striking and curious an instance of transition as can well be conceived".

The underlining is mine. The last part of this quotation expresses Darwin's amazement at the variation in floral structures in Vitis, and their very differing functions (climbing or fruiting), as an example of gradual evolution within one species. Darwin admired the common vine! On this basis, and that of Darwin's research into the transition from the "climbing" to the "reproductive" habit, in my opinion the quintessential essence of canopy management, I classify him as a canopy management researcher.

THE GOLDEN AGE OF CANOPY MANAGEMENT RESEARCH 1965-1995?

We move forward by almost exactly one hundred years from the publication of "The origin of species ..." in 1859, to the Geneva campus of Cornell University, in the early 1960's. There, Nelson Shaulis and his agricultural engineering colleague Stan Shepherd were developing a new grapevine training system, the Geneva Double Curtain, and machinery for its commercial adoption. Shepherd designed the first mechanical harvester, the first mechanical pruner and the first shoot positioning machine, all to operate with the new Geneva Double Curtain. Shaulis published about the GDC in 1966. For me, that paper was the viticultural equivalent of "The Origin of Species".

Shaulis took inspiration from Lens Moser, an Austrian viticultural scientist, who showed that the manipulation of the shoots of a grapevine (the canopy) could affect yield and fruit composition. Shaulis coined the term "grapevine canopy", but I believe the term "canopy management" is a Californian derivation, and maybe Mark Kliewer's.

Here was a concept that not only introduced a new training system which could improve yields and fruit composition for Concord, but introduced a new concept in viticulture, which we now take for granted. On a recent visit to a friends' farm in the Finger Lakes, New York, and near the Geneva Experiment station, I noted a European harvester in his barn, as one also sees elsewhere in the world! How paradoxical, American invention originally, and now mass produced off-shore!

The period of the 1970's and 1980's was one of major research activity in the area of canopy management, accompanied by many conferences. Leading players were Carbonneau in France, Intrieri and Cargnello in Italy, and Mark Kliewer and his students at UCD. New training systems were proposed including some with difficult to pronounce indigeneous names. Some accuse me of immodesty over the name "Smart Dyson"; few realise that this term came about from a translation from Spanish of Mr Dyson's Mexican manager. He said " intelligente (Mr) Dyson", which translates to Smart Dyson.....

Why did the Golden Age come to an end? Surely not because all the relevant science had been done, I think this is not the case. And certainly not because the technology was so widely accepted, as I will soon discuss. I do not know the answer to this, but can make a few guesses.

As in most things, like the wine market, viticulture research fashions come and go. Canopy management was replaced by, among other studies, molecular biology, "precision" viticulture and terroir studies. Certainly the extravagant claims made by molecular biologists (matched only by their voracious appetite for research funds) made st,udies using wire and grapevine shoots seem rather ordinary! And unappealing to research funders.

HAS CANOPY MANAGEMENT BEEN COMMERCIALLY SUCCESSFUL?

In many regions, Vertical Shoot Positioning VSP has replaced "sprawl" canopies. Some growers think that this is good adoption of canopy management. Often it is not, both systems can be shaded and compromised in performance. Leaf removal has become very common, and in my opinion is often done excessively. Some practices such as minimal pruning were touted as "canopy management", but I think this was an extension of the true meaning of the concept.

The interaction between vine vigour and the propensity for canopy shade is very well understood in the literature, but not so well recognised commercially. Many if not the majority of VSP vineyards I see around the world are shaded. The "band aid" treatment of leaf removal has become the commercial antidote to fruit shading, but practitioners forget that leaf shading is not relieved.

The need for canopy management can be easily diagnosed, using for example pruning weight per unit row length, and the effects of shading can be easily demonstrated. Yet I meet so many growers who will want to retain VSP "because it is simple!" Who is intellectually challenged here, the manager or the workers? In my experience, workers can be easily trained to use correct practices to achieve cost-efficient shoot positioning. Moving shoots with wires is not difficult if you get the timing right.

As well as overcoming human perceptions, another hurdle to increased adoption of canopy management procedures is the need for more mechanisation, especially of shoot positioning. I think it very paradoxical that such a machine was available in early 1960, but a suitable commercial machine in my opinion is not now available.

In my experience in Australia, some of the most successful producers of wine as related to wine show awards use canopy management techniques and improved training systems. I am always surprised that others do not follow suit, but not disgusted. After all, this provides commercial opportunity for a canopy management consultant.

Some producers seem frightened of change, and, from an evolutionary viewpoint, Darwin had a view point about these. He said *"It is not the strongest of the species that survives, nor the most intelligent, but the one most responsive to change*." I think the same sentiment can be applied to the commercial world.

What of the future? I think most of the likely permutations of canopy division and shoot orientation have now been proposed. Therefore, the future remains with mechanisation, and especially robotics. This will involve video imaging and analysis to guide robotic "arms", to achieve such functions as winter pruning, shoot and cluster thinning, shoot positioning and "hand" harvest. It will take some developments in robotics to replace vineyard labour, whereby a pair of eyes, a brain and a pair of hands can be had for around $15 per hour!

CONCLUSION

The concepts of canopy management have given a great deal to viticultural science, enabling explanations of many other issues, including terroir and vigour and yield effects on wine quality. Despite this, the basic concepts are not understood by some viticultural researchers and commercial growers alike. The amount of research in the discipline has decreased dramatically, and commercial adoption is limited. The potential of many vineyards to achieve improved yield and fruit composition and wine quality will not therefore be recognised.

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