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Sustainable Grape Productivity and the Growth-Yield Relationship: A Review

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Research reports and experimental efforts during the last century are presented with the goal to encourage discussion of balancing grapevine fruit yield and vine growth and leaf area. Fruit and subsequent processed quality are equally relevant economic issues as we strive to create conditions for both sustainable grapevine productivity and vine capacity for tolerating abiotic and biotic stress episodes. It is proposed that methods to achieve vine balance will vary with regard to macroclimate and cultivar, but will be most critical for those macroclimates commonly called cool-climate regions. Regardless, vine balance is most readily understood when based on the principles of vine carbon balance as mediated through well-understood factors such as cm^2 leaf area/gram fresh weight of fruit at harvest and allmetric practices as the Ravaz Index and the Growth-Yield Relationship.

Key words: Vine balance, minimal pruning, leaf area, crop ratio, Ravaz Index, carbon balance, photosynthesis, vine yield, vine size, fruit maturation

The challenge of commercial grapevine culture and production is the ability to consistently produce a quantity of ripe grapes sufficient to cover all costs of production and return a profit to the producer. There are numerous models on which this may be achieved. Variables such as value of the cultivar, viticultural management, perceived quality of the crop, production costs, and production consistency all come together to determine whether the production is sustainable.

In recent years "sustainable" has been co-opted as a buzzword for various methods of culture, including "integrated," "bio-dynamic," and/or "organic." For purposes here the term is used in its earlier, simpler form; sustainable production has both viticultural and economic dimensions. In this sense we say that sustainable production is a collective methodology that produces highest yields of ripe fruit per unit land area with no reduction in vine vegetative growth and does so over a period of years at costs which return a net profit.

Recently, Gladstones [10] used similar words to describe the term "balance." Balance was achieved "when vegetative vigor and fruiting load are in equilibrium, and consistent with high fruit quality." The terms "sustainable" and "balance" are concepts consonant with the material to follow.

A few premises are worth noting. Viticulture in cool-climate portions of viticultural production requires accommodation of those climatic factors near the limits of commercial grape production. These environmental limits are the basis for the following premises: (1) for any genotype-environment interaction there is an optimum method of culture to achieve highest yields of ripe grapes of acceptable quality over years; (2) good viticultural practices must result from the application of sound principles of vine growth and development; (3) sustainable levels of highest fruit quality at maximum yield can occur only through the achievement of vine balance through the application of the leaf area:fruit weight ratio or the Growth-Yield Relationship.

Minimal Pruning and the Growth-Yield Relationship

The introduction of minimal pruning (MP) by Clingeleffer and associates in Australia [3-5,57,58] has proven to be a major breakthrough for winegrape culture in that region. It has been shown to be superior to traditional spur-pruned and cane-pruned approaches in both sustainable yield and fruit and wine quality.

On the surface, the data would seem to challenge the validity of premise 3. Clearly MP works well for winegrapes in Sunraysia, Australia, and the vine physiology on which the method is posited seems to suggest that once vines equilibrate, the approach should be broadly applicable even in cool-climate

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regions. The following material is presented with two goals: (1) to share the basis of our concern about applicability of MP technology in cool, short-season viticultural macroclimates; and (2) to encourage a carbon-budget approach toward finding solutions to problems involving an array of abiotic and biotic stresses as well as vineyard practices.

Vine Balance

Although the discussion of vine balance has expanded in recent years, it is not new. Ravaz [47] is the earliest source of relevant information, and the Ravaz Index suggests that the ratio of fruit to wood is the key to achieving both fruit quality and consistent production. He also showed a general relationship between leaf production and fruit production. As he assessed the close relationships between leaf and wood production, he chose the latter for his Ravaz Index, as he sought a means for viticulturists to put the relationship into practice. He chose this allometric approach because he wanted growers to use it.

In the early 1920s, Partridge [37-42] put forward a very similar concept. He reasoned that a vine produced two forms of yield each growing season: reproductive yield and vegetative yield. Balance was achieved when yield of ripe fruit was maximized with no detrimental impact on vegetative growth. If the contribution by Partridge had stopped there, he would be of only passing note; it was merely a modification of Ravaz's concepts. His genius was to take the next step. He proposed to use the weight of cane prunings produced in year 1 as an indicator of the upper limit of a vine's capacity to produce and ripen a crop in year 2. While numerous factors can reduce yield in a given year, this upper limit was a major improvement in achieving vine balance. This was a major step. Balance as defined by the Ravaz Index was a postharvest evaluation. It could tell the viticulturist how nearly actual balance had been approached, but only after the fact. Partridge called his approach the Growth-Yield Relationship.

I compare the contribution of Partridge and the subsequent practical refinements by Shaulis [22,48-52,59] to that of Darwin with relation to organic evolution. Gould [11] argues convincingly that the idea of evolution had been around for centuries prior to Darwin's time. The genius of Darwin was his definition of a means by which it could be achieved—natural selection. Partridge and Shaulis, analogous to Darwin, produced a practical methodology by which the process could be both explained and put to practical use [37-39,42,48,52] to achieve balance and sustained production.

The application of vine balance concepts is complicated by several considerations: (1) grapevines are perennial plants and for that reason the positive or negative impact of a season's vineyard management can be measured for one or more years afterward [20]; (2) in cool-climate viticultural regions there are strong annual fluctuations in weather conditions during the growing season [16]; and (3) under conditions of high bud number relative to vine capacity, the weight of mature canes relative to leaf area declines [32,33]; there is more leaf area per unit weight of canes. In any event, a prescription approach to vineyard management under such conditions is unacceptable as it limits both yield and quality in good vintages and will yield unripe fruit and reduced vine growth, measured as vine size (Kg cane prunings/meter of row), or as actual area of exposed foliage, in poor vintages.

Leaf Area and Crop Balance

As noted by Ravaz, Partridge, Shaulis, and subsequent researchers [14,17,18,43,44], balance may also be considered as the amount of leaf area required to ripen a unit of crop weight. This is commonly expressed as cm^2 leaf area /gm fresh weight of fruit. The literature reports a range of 7 to 14 cm^2 /gm to achieve ripening. The proposal of a 2 X range of difference immediately attracts our attention. What makes it possible for a cultivar to achieve vine balance at 7 cm^2 in one cultural situation and require 14 cm^2 in another will be addressed in this discussion.

Crop Balance and Growing Season Length

Grapevines cultured in a region allowing a significant period of time postharvest with vines retaining functional, exposed leaf area will require less leaf area to ripen the crop. This postharvest period allows vine crop levels that likely not only use the current season's photosynthetically produced carbohydrates but also mobilize carbohydrates stored in vegetative tissues [23,26,55]. A long foliated period after harvest could allow the reaccumulation of carbohydrates in storage tissues that will be necessary for the final stages of bud and inflorescence differentiation and support the spring growth flush in year 2 [50]. Thus, a long foliated period postharvest could potentially ripen a larger crop per unit leaf area.

Crop Balance and Light Intensity

Another likely factor related to crop balance is light intensity over the growing season [25]. Grapevine culture in California's Central Valley or the Sunraysia district of Australia is greatly facilitated by high light intensity. Few days in these viticultural regions do not exceed the 800 to 1000 μ E m^{-2} s^{-1}, which is saturation for leaf photosynthesis [25,53,54], and many days the level is nearer 2000 μ E m^{-2} s^{-1}. By contrast, cool-climate regions may be limited by growing season length, light intensity, or both. Smart [53] has reported that about 8 to 10% of photosynthetically active radiation (PAR) striking a canopy passes through the leaf, and that is a key component of his canopy management philosophy regarding leaf layer number. When the light intensity is at or above 2,000 μ E m^{-2} s^{-1}, the second leaf layer can receive 200+ μ E m^{-2} s^{-1}, well above the leaf compensation point. When ambient PAR is at 800 μ E m^{-2} s^{-1}, the resulting 80 μ E m^{-2} s^{-1} PAR is at or below the compensation point (Howell and Trought, 1997, unpublished data). Further evidence suggests that such shade leaves lack the capacity to achieve the rates of photosynthesis of "sun leaves," even when placed in full sun [21]. Consistently high light intensities improve photosynthesis of interior, shaded leaves and can reduce the leaf area necessary to ripen the crop.

Limitations in Cool-Climate Viticulture

The culture of grapevines near the cool-climate limits of commercial production often lacks one or both of the above-

Table 1 Growing season length and heat accumulation in different viticultural regions. After Gladstones [10], Van Den Brink et al. [60], Shaulis et al. [50], and Mills [personal communication, 2001].

Viticultural region	Growing season length	Growing degree days (10°C)
Mildura, Australia	>230	1700-1800
Fresno, California	>230	1700-1800
Coonawara, Australia	200-210	1300-1400
Napa, California	200-210	1330-1400
Bordeaux (Medoc)	>210	1400
Central Washington	190	1350
Long Island, New York	>200	1275
Marlboro, New Zealand	190-200	1110
Hobart, Tasmania	>210	1100
Geisenheim, Germany	>200	1105
Burgundy (Dijon)	180	1190
Champagne (Reims)	180-190	1082
Geneva, New York	170-175	1150
Benton Harbor, Michigan	170	1250
Traverse City, Michigan	170	1050

mentioned advantages [10]. Consider the growing season characteristics of a range of viticultural regions (Table 1). The long, warm growing seasons of Mildura and Fresno (>230 days; 1750 growing degree days; base 10°C [GDD]) decline in Coonawara, Napa, and Bordeaux (≃200 to 210 days; ≃1300 to 1400 GDD), which have similar season length as Marlboro, Hobart, and Geisenheim (200 to 210 days), but have a reduction in season warmth (≃1100 to 1110 GDD). The remaining cool regions include Dijon, Champagne, Geneva, New York, Benton Harbor, and Traverse City, Michigan (170 days; ≃1050 to 1125 GDD).

Further, light intensities in the Great Lakes Region are well below the Fresno or Mildura examples, and leaf loss as a result of the first autumnal freeze very nearly coincides with harvest date. All of these factors suggest a viticultural condition requiring greater leaf area/unit crop weight so that important physiological functions—bud initiation and differentiation [50], crop ripening [50], carbohydrate storage [23], wood and bud maturation, and acclimation to freezing temperature and maintenance of vine cold hardiness [12]—can be accomplished with the available exposed leaf area.

Vine Carbohydrate Stress and Crop Balance

In the mid-1960s, Dr. Nelson Shaulis spent a sabbatical leave in Australia at the Merbein Research Station near Mildura. His experiences there involved efforts with varying levels of leaf removal and vine defoliation. Our discussions with him in the early 1970s led to the initiation of similar experiments as we were interested in carbohydrate stress and grapevine cold hardiness in Michigan.

Table 2 provides a synopsis of that data [19]. The data resulted from a factorial experiment with different cropping levels (thinned to one cl/shoot or not thinned), two balanced pruning formulae (60+10, 30+10), and defoliation at veraison (yes or no) over 3 years.

Under Michigan conditions the impact of excess crop and inadequate leaf area resulted in reduced vine size (weight of dormant cane prunings). Vine yield was reduced by inadequate leaf area, and the grapes produced were unripe and of no economic value. Bud hardiness (Table 2) and cane hardiness (data not shown) were also reduced when vines were subjected to stresses imposed by the various treatment combinations.

In a second experiment (Table 3) we employed defoliation at veraison in a different manner [26]. To Hudson River Umbrella (a bilateral cordon at 1.8 m above ground) trained vines, we created foliated (F) and defoliated (D) controls with three methods of achieving 50% defoliation per vine: (1) removal of the leaf at alternate node positions on the shoot yielding node F and node D treatments; (2) removal of all leaves on alternate shoots yielding shoot F and shoot D treatments; and (3) removal of all leaves on one-half of the bilateral cordon in the 2.4 meter within row spacing, creating cordon F and cordon D treatments. The 1.8 m trunk length, the employment of two trunks, and the 1.2 m cordon joining each trunk result in 6.1 m of above-ground perennial structure.

These data are interesting on several levels, but the key point of focus for this discussion is the dynamics of sugar accumulation in the fruit postveraison. Removal of 50% of vine leaves was insignificant as node D, measurable as shoot D, and very detrimental as cordon D (Table 3). Of interest was the ability of

Table 2 Influence of crop load produced by different pruning severities (30+10 or 60+10), thinning to one cluster per shoot (T), or not thinned (NT), and foliated (F) or 100% defoliation (D) at veraison on Concord grapevines. After Howell et al. [19].

Treatment	Vine size (Kg)	Yield (Kg)	% SS	Primary bud hardiness °C	
				Fall[a]	Spring[b]
F-30-T	1.69	8.2	16.5	-19.0	-8
F-60-T	1.51	10.0	16.3	-18.0	-7
F-30-NT	1.52	12.2	16.1	-19.0	-7
F-60-NT	1.35	12.9	16.1	-18.0	-6
D-30-T	1.13	4.6	12.2	-13.0	-6
D-60-T	1.04	5.1	12.3	-12.0	-6
D-30-NT	1.04	6.1	12.6	-12.0	-5
D-60-NT	0.73	6.5	12.1	-12.0	-5
Tukey's HSD	0.55	3.3	1.0	1.5	1.0
Main effects					
F vs D	**[c]	**	**	**	ns
30 vs 60	*	ns	ns	ns	ns
NT vs T	*	*	ns	ns	ns

[a] Hardiness assessment made on 21 Nov 1971.

[b] Hardiness assessment made on 15 April 1972.

[c] *, **, and ns indicate significance at 0.05, 0.01, and not significant, respectively.

Table 3 The influence of differential defoliation at veraison on year 1 Brix response (**A**), year 1 and year 2 yield and bud hardiness response (**B**), and the relative impact of these treatments on Brix in year 1 and bud fruitfulness in year 2 (**C**). After Mansfield and Howell [26].

A. The influence of defoliation at veraison on year 1 Brix response

Treatment[a]	Veraison[b]	September 3	September 20[c]	Δ °Brix
Control F	9.6	13.8 a[d]	17.0 a	7.4 a
Cordon F	9.1	13.2 a	16.7 ab	7.6 a
Shoot F	8.9	12.7 a	16.1 bc	7.2 a
Node F	9.0	12.5 a	15.9 c	6.8 a
Node D	9.0	12.5 a	15.9 c	6.9 a
Shoot D	8.9	12.2 ab	15.5 c	6.6 a
Cordon D	9.1	11.2 b	14.2 d	5.1 b
Control D	8.7	9.4 b	11.2 e	2.5 c
F-test	ns[e]	**	**	***

B. Year 1 and year 2 vine yield and bud hardiness response.

	Yield/node (g)		Bud hardiness		
Treatment	Year 1	Year 2	% of shootless nodes	% of primary bud mortality	% of control D
Control F	136 ab	270 a	22 e	6.6 d	7 d
Cordon F	190 ab	237 a	35 bc	13.3 c	15 c
Shoot F	144 ab	253 a	32 cd	11.6 cd	13 c
Node F	183 ab	238 a	21 e	7.8 d	9 d
Node D	197 a	233 a	19 e	8.1 d	9 d
Shoot D	155 ab	239 a	38 c	14.8 c	17 c
Cordon D	149 ab	153 b	45 b	41.4 b	47 b
Control D	125 b	23 c	69 a	88.4 a	100 a
F-test	**	***	**	**	**

C. Relative impact of imposed carbohydrate stress on % soluble solids in year 1 and bud fruitfulness in year 2.

	% Soluble solids		Fruitfulness	
Treatment	Δ % SS	% of control F	gm/node	% of control F
Control F	7.4 a	100 a	270	100 a
Cordon F	7.6 a	103 a	237 a	88 a
Shoot F	7.2 a	97 a	253 a	94 a
Node F	6.8 a	92 a	238 a	88 a
Node D	6.9 a	93 a	233 a	86 a
Shoot D	6.6 a	89 a	239 a	89 a
Cordon D	5.1 b	69 b	153 b	56 b
Control D	2.5 c	34 c	23 c	9 c
F-test	***	***	***	***

[a] F = foliated; D = defoliated; control = either fully foliated (F) or fully defoliated (D). Cordon, shoot, and node treatments were 50% foliated (F) or defoliated (D). For cordon, all leaves on 50% of the vine cordon were removed. For shoot, all leaves from alternate were removed. For node, leaves were removed from alternate nodes.

[b] Timing of defoliation: 17 August.

[c] Harvest date.

[d] Numbers within a column having the same letter are not different by Duncan's New Multiple Range Test.

[e] **, ***, and ns indicate significance at 0.01, 0.001, and not significant, respectively.

the fruit sink on the cordon D treatment to mobilize carbohydrate from the cordon F treatment and move it up to 6 m and result in increased sugar in fruit. Even more impressive was the response of the fruit on the control D treatment vines. In the absence of leaves, the fruit mobilized stored carbohydrates and resulted in a 2.0 °Brix increase in the fruit. The power of the postveraison fruiting sink is great.

Training System and Vine Carbohydrate Dynamics

In the 30 years of the 1970s through the 1990s, a revolution in cultivars used for wine has occurred in Michigan and other portions of the Great Lakes region. The cultivars used for 95% of Michigan wine in 1970 accounted for less than 5% of the wine in 1995 (Mich. Liquor Control, personal communication). This cultivar change resulted in questions concerning whether approaches deemed desirable or acceptable for a *Vitis labruscana* Bailey cultivar with a procumbent, growth habit would be appropriate for cultivars possessing a more upright growth habit. To resolve this question, experiments were undertaken involving a range of training systems. These have been recently summarized [15].

Our effort sought to understand principles, not just evaluate practices. New approaches to vine training occur nearly every year. Once principles are uncovered, the application of those principles should be possible after an initial assessment of a cultivar's growth habit. We should not be required to reinvent the wheel every time a new training system is suggested. We employed four training systems that differed in height of the fruiting zone and were head or cordon trained systems: low head, high head, low cordon, and high cordon.

We have conducted this kind of experiment on nine cultivars and conducted each for a minimum of five years [17,18]. The amount of perennial wood varied significantly with each training system tested. All vines were double trunked so the length of perennial wood for each system was: 1.8 m for low head; 3.6 m for high head; 4.3 m for low cordon; and 6.1 m for high cordon. With the exception of the cultivar Aurore, we have invariably seen the relationship: high cordon > low cordon > high head > low head. This has been true whether we were considering vine size, vine yield, fruit composition values, or bud and cane cold hardiness. The impact of perennial vine structure on vine performance has also been reported by May [27] in Australia.

Similarly, work in Switzerland [23,24] employing a trunk modification yielding a 12 to 15% increase in perennial wood resulted in significant increases in fruit °Brix as compared to the traditional trunk conformation.

Collectively, these data suggest that choice of training system has considerable impact on the level of sustainable production of ripe grapes. Training systems with more perennial wood show favorable response of yield, vine size, fruit composition, and cold hardiness [15,17,18].

Old vines make better wine? These experiences also led us to a conjecture: as vine training systems with greater quantity of perennial wood resulted in fruit with superior fruit composition values, could the oft-expressed sentiment that "old vines make better wine" be a result of greater volume of perennial wood and concomitant increased carbohydrate storage area? If so, the response would be most often expressed in poor vintages. That, of course, would be the condition when it could be most readily detected. This speculation can be easily subjected to critical experimental evaluation, and I expect it will be in the coming decade.

Grapevine Photosynthesis and Carbohydrate Partitioning

Experiments in grapevine photosynthesis and carbohydrate partitioning have been conducted in cooperation with an array of associates in Switzerland [1,20,23,24], New Zealand [2,43,44], and Michigan [6-9,13,31,33,34]. The methods employed involved assessment at the level of the single leaf, whole potted vines, and whole mature vines in the vineyard. Potted vine studies have been of two types: vines produced by the Mullins Technique [36] and two-year-old bearing vines in 20-liter pots [6-9,31-34].

An array of cultivars has also been employed, including Chambourcin, Chardonnay, Concord, Niagara, Pinot noir, Seyval, and Vignoles. The following principles are consistent with data derived from these very different cultivars.

Predicting Vine Carbon Status

Single-leaf versus whole-vine assessment of photosynthesis. Since CH_2O is the vine's metabolic currency for growth, differentiation, fruit ripening, and a host of other processes, photosynthesis becomes a candidate for assessing a circumstance in vine culture that may influence sustainability. One goal in a vine photosynthesis study is to produce a measurement that can predict whole-vine performance. One approach to achieve that goal is to assess the photosynthetic CO_2 fixation of a precise area on a single leaf and then multiply that by the leaf area on the vine. An alternative approach involves the assessment of CO_2 fixation by the entire canopy [31]. Using vine dry weight and whole-vine photosynthesis as the basis for assessment, the single-leaf assessment is not predictive for either factor; the whole-vine assessment is predictive of vine dry weight status [7-9,33,34]. Based on these data, the perceived influence of vine photosynthesis on sustainable yield of ripe grapes will be influenced by the methods used to measure it and the manner in which such data are interpreted.

Single-leaf measurements do have considerable utility. The key to their effective use is to define precisely the question asked and to be very critical in any extrapolation of leaf response to canopy response [34,43].

Crop load and carbohydrate partitioning. One of the findings often reported based on single-leaf assessments has been the positive influence of crop load on vine photosynthesis [5,57]. That seems to be intuitively obvious; more fruit should reduce any fruit-based feedback inhibition of photosynthesis to a minimum. Thus, more CO_2 should be fixed per vine and that should be shown as increased dry weight per vine.

Table 4 suggests that the assumption is untrue. An evaluation of partitioning data at fruit set, veraison, and harvest shows shifts in the relative dry weight of the various vine organs but shows no difference in total vine dry weight on any measurement date [7-9]. The amount of crop per vine influences where the carbohydrates produced accumulate. At harvest, fruit accounted for over 40% of the total vine dry weight for the most heavily cropped vine. This high percentage of dry weight accumulates at the expense of vegetative tissues, particularly the roots. This dry weight data is supported by a subjective assessment of root quality (Table 5). Between 60 to 80% of the grape-

Table 4 Influence of vine crop load on the quantity and percentages of dry matter partitioned to different vine structures at fruit set (**A**), veraison (**B**), and harvest (**C**). After Edson et al. [9].

	Percent of total					Total vine
Clusters/vine	**Fruit**	**Leaf**	**Shoot**	**Wood**	**Root**	**dry wt. (g)**
A. Fruit set						
6	2.2	8.8	8.3	18.9	61.3	54
4	2.0	10.0	8.6	26.3	53.1	50
2	1.0	11.4	9.0	24.2	54.4	48
1	0.7	11.9	8.6	20.5	58.3	53
0	na[a]	na	na	na	na	na
Linear regression	**[b]	ns	ns	ns	ns	ns
B. Veraison						
6	32.3	16.6	11.0	11.3	28.8	207
4	28.9	17.1	13.9	9.6	30.5	201
2	25.0	18.3	13.6	12.1	31.0	193
1	15.1	21.0	19.2	9.7	35.0	209
0	na	na	na	na	na	na
Linear regression	***	***	***	ns	*	ns
C. Harvest						
6	42.9	11.0	10.5	8.9	26.7	277
4	41.0	12.6	12.0	7.9	26.5	307
2	28.1	14.6	16.6	8.0	32.7	299
1	21.9	15.2	17.2	11.0	34.7	289
0	0.0	19.1	29.8	10.4	40.7	286
Linear regression	***	***	***	ns	***	ns

[a] na: not available.

[b] *, **, ***, and ns indicate statistical significance at 0.05, 0.01, 0.001, and not significant, respectively.

Table 5 Influence of vine crop load on roots at different phases of the growing season. After Edson et al. [9].

	Fruit set		Veraison		Harvest	
Clusters/vine	Dry wt. (g)	Root[a] class	Dry wt (g)	Root class	Dry wt. (g)	Root class
6	33.1	2.8	59.6	2.3	74.0	1.8
4	26.6	3.0	61.3	2.7	81.4	1.8
2	26.1	3.0	59.8	2.5	97.8	2.8
1	30.9	2.8	73.2	4.5	100.3	2.7
0	na[b]	na	na	na	116.4	4.5
Linear regression	ns[c]	ns	*	*	***	***

[a] Rating system: 1=poor, few active roots; 5=good, many vigorous roots.
[b] na: not available.
[c] *, ***, and ns indicate significance at 0.05, 0.001, and not significant, respectively.

vine roots produced each growing season die, an ongoing process of turnover of the fibrous white roots [28]. The data in Table 5 support the dry weight data and suggest that the observed decline in root quality results from reduced replacement of roots as older roots die [28,60,62].

This observation differs from the Australian experiences [3] and that of Robert Wample in Washington State [personal communication, 2001]; no reduction in roots was measured. As noted above in the discussion on light intensity and growing season length and in Table 1, near-ideal conditions for culture eliminate factors that commonly limit carbon assimilation and accumulation in cooler climates.

Grapevine Crop Level and Fruit Maturation on Vines

Potted vines. The data collected to date suggest that if the growing season with adequate growing conditions is long enough, the vine will ripen the crop (Table 6) [9]. What is not shown is a critical component of grape quality—varietal character. Anecdotal experience and micro-vins produced from grapes in the experiment reported in Table 6 suggest that fruit composition is generally associated with varietal character (data not shown) but is not predictive of the intensity of that varietal character. The grapes that achieved mature °Brix earliest had greatest varietal character for this cultivar. Importantly, this will vary with variety and the compounds that collectively produce varietal character.

Table 6 Influence of vine crop load on vine yield and fruit composition. After Edson et al. [9].

		Two weeks preharvest			Harvest		
Clusters/vine	Yield (g)	Brix	pH	TA	Brix	pH	TA
6	507	19.0	3.00	14.3	21.4	3.53	8.2
4	521	19.4	3.05	13.8	21.0	3.67	7.6
2	384	19.6	3.08	15.0	21.7	3.70	7.3
1	288	19.6	3.10	14.3	21.8	3.63	8.1
Linear regression	***[a]	*	***	ns	ns	ns	ns

[a] *, ***, and ns indicate significance at 0.05, 0.001, and not significant, respectively.

Grapevine leaf area and veraison. Under conditions of serious leaf area reductions occurring prior to veraison, a source:sink imbalance can result. The created source inadequacy can have an impact similar to that of excess crop with a resulting delay in the onset of veraison. As with fruit maturation curves [43], all berries ultimately pass through veraison, but the treatment with most restricted leaf area to fruit weight ratio was delayed by over 30 days.

Mature vines in the vineyard. While potted vines are convenient for partitioning studies, we would never be comfortable putting a conceptual viticultural principle into practice without first evaluating the response of mature, bearing vines in a vineyard.

The data in Table 7 result from an experiment on Concord vines conducted with a factorial statistical design. There were three vine size categories selected with the number of nodes retained at pruning ranging from 20 to 160 per vine. The experiment was conducted from 1991 to 2000 [35]. Similar data have been produced in other research efforts [29,30]. The key point of these vineyard data is their agreement with those gained by experimentation on potted vines. The above-ground response is very similar. We therefore make the inductive inference that the factor not measured, that is, root dry weight, also responded in a similar manner to the potted vines. This inference should be subjected to critical direct assessment in the vineyard.

Early Development of Leaf Array and Crop Maturation

Another idea that seems intuitively obvious is the positive impact of early leaf array on total vine carbon assimilation over the growing season. Early canopy fill, it would seem, should trap sunlight that would otherwise strike the vineyard floor [57,58].

Like the previously mentioned case of increased Pn and crop load, the data do not support the hypothesis. Data in Tables 7 and 8 show a different response. Concord vines were at equilibrium with a range of either 15 to 91 buds (Table 7) or 17 and 66 buds (Table 8) retained per meter of row. Differences in leaf area at bloom and veraison coupled with the leaf area:fruit weight ratio favor the larger bud number in every case, but fruit maturation (based on fruit composition values) is delayed for the larger bud number treatments. Early leaf area development was not an advantage once vines were at equilibrium with the imposed treatments.

Photosynthesis and Leaf Age

Data reported by Kriedemann [25] and Poni and Intrieri [46] raises one concern

Table 7 Influence of early season leaf array on yield and fruit composition of Concord grapevines. Vines at equilibrium after eight years of treatment, 1998. After Howell, Miller, and Stocking, unpublished.

Nodes retained per meter of row	Yield (Kg) per meter of row	% SS	cm^2 leaf area/g final fruit wt.	
			Bloom	Veraison
15	4.55	17.1	3.13	11.49
34	6.71	16.3	2.83	11.10
44	5.90	14.0	4.54	15.47
55	6.80	13.2	5.80	18.15
91	5.33	14.2	8.51	17.18
F-test	**[a]	**	**	**
Linear regression	*	**	***	**

[a] *, **, and *** indicate statistical significance by linear regression at 0.05, 0.01, and 0.001, respectively.

Table 8 Influence of multiseasonal cropping stress on yield, leaf area, and total vine sugar production of Concord grapevines. Vines at equilibrium after six years of treatment, 1996. After Miller and Howell, unpublished.

	Nodes retained[a]		
Factor analyzed	17.00	66.00	F-test
Vine size (Kg cane prunings)	0.37	0.05	***[b]
Leaf area at harvest (cm^2)	57967.00	75252.00	***
Yield (Kg)	6.37	4.65	**
Clusters	60.00	104.00	***
Clusters/node retained	3.53	1.58	***
Cluster weight (g)	106.10	42.90	***
Berry weight (g)	2.86	2.41	**
Berries/cluster	37.00	18.00	**
% Soluble solids	15.00	14.70	*
Leaf area (cm^2)/g fruit	9.10	16.20	**
Crop load (yield/vine size)	17.20	89.20	***
Kg sugar	0.96	0.66	**
Kg sugar/leaf area (10^{-6})	16.50	9.10	***

[a] Per meter of row.
[b] *, **, and ***, indicate statistical significance at 0.05, 0.01, and 0.001 levels of probability, respectively.

about cultural methods with large shoot number per vine. Such vines are characterized by a single growth flush in the spring, and little additional canopy is added over the growing season [3,4,33,34,57,58]. The potential to have an "old" canopy during the critical period from veraison to harvest was an issue.

Research on Pinot noir [44,45] using potted Mullins [36] vines and on mature bearing Chardonnay vines (Howell and Trought, unpublished) suggests that leaf age response varies with the ratio of the leaf area to fruit weight. Treatments that greatly reduced leaf area (nearly 100%) per vine resulted in leaves on the shoot that were active photosynthetically well after leaves at similar positions (same age) were senescent on fully foliated vines (Table 9).

The data in Table 9 appear to disagree with the earlier point that induced carbohydrate stress via cropload resulted in no increase in total vine dry weight (Tables 4 and 5). This potential misunderstanding is based on the factors being measured: single-leaf photosynthesis in the first instance and total vine dry weight in the latter. The capacity of individual leaves to remain photosynthetically active and compensate when leaf area is reduced is clear (Table 3). However, when leaf area was severely reduced (Table 9), the increased leaf Pn rate could not compensate for the loss of the majority of other leaves in relation to fruit maturation or total vine dry weight [43; data not shown].

Minimal Pruning and Vine Balance

Earlier, we mentioned our concern about the direct application of MP technology to cool climates. Further, we noted that this new approach to vine culture had the potential to refute concepts of vine balance. There are several reasons why I do not believe that to be true. First, traditional Australian cane or spur-pruning did not create balance. Based on the principle of the Ravaz Index, the Growth-Yield Relationship, and leaf area:fruit weight, traditionally pruned vines retained inadequate bud number to produce crop levels at the vine-environment potential [3,5,57]. Lower yields, excessive vine vigor, and canopy shading were the results. Employment of MP under the conditions of Sunraysia, Australia, produced a bud number and subsequent crop that resulted in balanced leaf area and crop. As Ravaz [47] noted, there is a close relationship between vine size and leaf area. MP Cabernet Sauvignon vines were in balance based on the ripening criteria and the ability of those vines to produce at high levels over years of culture. The victory of MP is a victory of balance, sustainability, the Growth-Yield Relationship, and leaf area:fresh weight ratio over prescription application of bud number regardless of vine growth status.

Achieving Highest Yields in a Situation with Varying Vintage Conditions

A major characteristic of cool-climate viticulture is the annual variation in growing conditions. Achieving highest sustainable yields of ripe grapes must involve cultural methods that consider this potential limitation.

Table 9 Pre- and postveraison photosynthesis. Different levels of within-shoot leaf removed two weeks postbloom, Chardonnay. After Howell and Trought, unpublished.

	μ moles/cm^2/sec		
% Leaves removed	Preveraison	Postveraison	F-test
100	10.36	7.69	**
66	10.57	5.94	**
33	9.92	6.68	**
0	9.48	5.53	**
F-test	ns	ns	
Linear regression	*	**	

*, **, and ns indicate statistical significance by linear regression or the F-test at 0.05, 0.01, and not significant, respectively.

The 1990s produced the greatest variation among growing seasons in Michigan since temperature recording began. The years 1991, 1998, and 1999 were among the best on record for growing degree days. The 1992 vintage was the worst.

Such variation creates a dilemma for the producer. Does a producer crop at the level to achieve balance in 1992, and lose the amount of ripe crop possible in 1991, 1998, and 1999? Alternatively, does the producer crop for vintages like 1991, 1998, and 1999 and risk an unsaleable crop in 1992? This is a reality in cool-climate viticulture, with major economic implications for the viticulturist. In fact, we do not know how much crop level should be adjusted downward in response to one or more environmental and/or biotic stresses. This area deserves much more attention by viticulturists for two reasons: the scenarios on global warming suggest a more variable climate situation, and we will have fewer pest control options in the future. We must anticipate conditions that will result in variable ability to ripen a crop. In any event, it is clear that a prescription approach cannot be satisfactory.

Crop adjustment and vine balance. Crop adjustment provides one solution. This approach would allow the viticulturist to crop at the level that would achieve balance in the historical "best" vintage and adjust the crop downward prior to veraison based on the status of GDD accumulation halfway between bloom and veraison. The vine would easily adjust [35,38,55,56] and even compensate [1].

Pest Control, Sustainable Grape Production, and the Growth-Yield Relationship

The future of commercial viticulture is perceived through a cloudy crystal ball under the best of circumstances, but one fact seems very clear: future grape production will have fewer chemical tools to combat pest problems. A likely result will be periodic episodes of stress when vines are subjected to insect or disease attack on vine foliage. Greatly limiting our ability to predict the impact of these episodes is the lack of information about economic thresholds. How much leaf damage occurs before there is an economic impact? We do not know the impact of powdery or downy mildew, leafhopper burn, or Japanese beetle reduction of leaf area on leaf CO_2 assimilation or net photosynthesis. Nor do we know whether the impact of the biotic stress changes with relation to shoot and fruit growth and maturation phenology of the vine. Based on work with abiotic stresses reported above, we expect that timing will be important. Unfortunately such data are very scarce (2).

Applying the principles of the Growth-Yield Relationship to abiotic stresses provides direction for future efforts on pest-induced stresses. In a poor vintage, crop adjustment can produce the balance appropriate for that season's climatic conditions. A similar approach for pest stress should be possible once the physiological and economic impact of the pest stress has been determined.

Within vineyard variation and sustainable production. In addition to seasonal variation is the reality that soil variation within the vineyard can produce a considerable range of vine vigor and resulting vine size and leaf area. Again, a prescription approach cannot work: each vine must be considered individually or small vines will be overcropped and large vines undercropped. This can result in the smaller vines becoming weaker and producing unripe fruit and the larger vines producing inadequate yields of fruit ripened in the shade of an excessively vigorous vine canopy [29,30]. At most vineyards, crop control is done at pruning, based on numbers of nodes retained. Because this pruning is being done by hired pruners, the ability to achieve such individual attention is very small. However, the future does hold promise.

The Future

Several features of the viticultural future are visible now:

1. Site mapping via global positioning satellites (GPS) to determine where "problem" areas exist.
2. On-board harvester yield assessments are a reality. In the future, these data coupled with GPS data will monitor low production areas within a vineyard and provide a basis for attention and cultural modification.
3. Vine size or estimates of exposed canopy at veraison will be possible using existing tractor-mounted computer-based visual technology coupled with GPS positioning. The potential crop based on leaf area or Partridge's Growth-Yield balance concepts will be determined by the computer for each individual vine.
4. Crop load estimates will be made using methods noted above in item 3 at the time of the prebloom spray when flower clusters are easily visible.
5. Crop adjustment in mid-July (for northern hemisphere) or about halfway between bloom and veraison will be accomplished mechanically so that the input of each individual vine from items 3 and 4 above plus GDD status are integrated and individual vine balance achieved.

These five features are now possible. The databases and the research required to produce these databases are lacking. In addition, it will become increasingly important for the viticulturist to employ the most advanced methods of monitoring vineyard growth and pest status and to adopt the principles of vine balance. As yields approach the upper limit for any macro- or mesoclimate, the buffering capacity of photosynthesis compensation will be reduced, and further stresses that negatively influence vine carbon balance, regardless of origin, can produce disastrous results. That is the challenge for sustainable viticulture in the twenty-first century, and meeting that challenge will have its roots in the leaf area:fruit weight ratio, the Ravaz Index, and the Growth-Yield Relationship, as understood by Newton Partridge and Nelson Shaulis.

Conclusions

The concept of vine balance is nearly 100 years old. Ravaz introduced the concept and Partridge and Shaulis pursued methods to use it as a means to predict vine performance via the Growth-Yield Relationship. This allometric method substituted vine growth or vine size (weight of cane prunings per vine) for leaf area per vine and the leaf area relationship to fresh fruit weight (7 to 14 cm^2 per gram). That relationship is tied to vine balance and long-term sustainable viticulture.

Training systems employing maximum amounts of perennial wood that also facilitate sunlight penetration into the fruiting and renewal zone are to be preferred. Spur systems on cordons may be unacceptable on some cultivars due to low fruitfulness of basal buds [15].

Photosynthesis in the period preveraison is not source-limited under typical vineyard conditions, and leaves seldom exceed 50% of their measured photosynthesis capacity. This has been demonstrated on Mullins vines, two-year-old potted vines, and mature bearing vines using several cultivars and different *Vitis* species.

Single-leaf photosynthesis measurements are not correlated with either whole vine photosynthesis or total vine dry weight increases. Whole vine photosynthesis is closely related to vine dry weight increases.

Minimal pruning and/or machine hedging in some form, coupled with a capacity for timely crop adjustment, offers a good potential for future likelihood of achieving maximum sustainable yield of ripe grapes across a range of cultivars. The key to the success of this effort will be vine-by-vine control of crop adjustment to achieve vine balance under conditions of variable crop load, previous year's vine size, and current season's growth and maturation status preveraison.

Leaves on vines with either inadequate leaf area or excess crop (low source:sink ratio) retain chlorophyll, delay senescence, maintain high photosynthetic rates, and delay the aging response characterized by leaves on similar vines possessing fully expressed canopies.

Inadequate leaf area delays veraison and lengthens the time from veraison to ripening.

Vine balance as understood by Ravaz, Partridge, Shaulis, and others remains a key to the achieving of maximum consistent production over long years of production. Modifications in our approaches to vine culture and management should begin with an assessment of that modification's impact on vine balance as understood based on the Ravaz Index, the Growth:Yield Relationship, and cm^2 leaf area/gram fresh weight of fruit at harvest.

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