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Review

Mechanical winter pruning of grapevine: Physiological bases and applications

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ABSTRACT

Since machine introduction in the early 1970s, much work has been expended to adapt pruners to vine trellis and physiological requirements, especially regarding the higher bud load their non-selective cuts leave compared to manual trimming. While units have successfully met the former requirement, efforts to meet the latter have been hampered by a broad range of variables depending on cultivar, machine type, environmental conditions and any manual follow-up. Several examples are instructive here. Winter hedge pruning usually delivers best results with low-to-medium basal node fruitfulness coupled with some hand finishing, two crucial factors for achieving the desired balance of crop yield and quality similar to hand pruning but at lower cost. Minimal pruning has by and large proved unsuccessful in European environments, although some of its good features like looser, less rot-susceptible clusters, earlier canopy filling, lower individual shoot vigor and higher vine capacity can be reproduced using a semi-minimal pruned hedge (SMPH) system to better control over-cropping while maintaining desired grape composition. For instance, the best option for winter mechanical pruning in Italian districts today is the single high-wire cordon managed to maintain upright canopy growth for fast and physiologically sound cutter-bar pruning with little or no manual follow-up. A more comprehensive outlook seems to presage robotics for "precision" pruning to deliver a bud load that is adjusted to vine vigor and desired crop level.

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1. Introduction

Winter pruning in Europe is closely bound to tradition and still considered a primary field skill. Resorting to mechanical pruning is often skeptically regarded because it is typically non-selective and because manual "aesthetics" still count, especially in premium wine production districts (Fig. 1). Yet this attitude is found in both the Old and New World. One example is Italy. While mechanical winter pruning is on the rise, it is practiced erratically and mainly confined to specific areas like the Lambrusco district that relies on Geneva Double Curtain trellising (Intrieri and Poni, 2000). Another is California. The adoption by 2012 of box-hedged pruning with little or no manual follow-up regarded only 5% of total acreage, whereas machine pre-pruning with hand follow-up was employed

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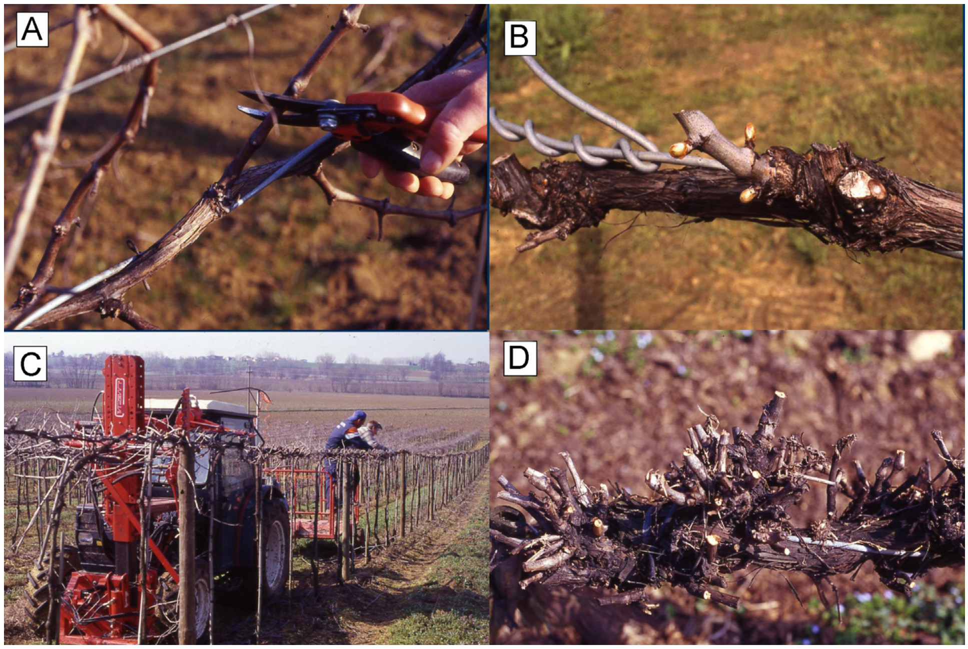

Fig. 1. Hand spur pruning (panels A, B), mechanical pre-pruning followed by hand finishing (panel C) and a detail of a cordon after several consecutive years of mechanical pruning (panel D).

in about 50% of its vineyards (Greenspan, 2007; Dokoozlian, 2013). Yet this comparison must also take into account that, although its skilled vineyard labor pool is shrinking and overhead costs have been steadily rising, California's overall labor supply and overhead remain relatively favorable compared to those in other parts of the country and the world.

The gap between actual adoption of machine winter pruning and the amount of information gathered since the early 1970s on vine physiological and performance responses to it is notable. What is disappointing is that trials carried out in Europe and beyond have shown that the likelihood of a vine reaching an appreciable balance of crop load to grape composition when subjected even to long cycles of mechanical winter pruning is good (Carbonneau and Zhang, 1988; Kliewer and Benz, 1992; Andersen et al., 1996; Martinez de Toda and Sancha, 1999; Intrieri and Poni, 2000; Clingeleffer, 2000; Poni et al., 2004; Gatti et al., 2011). The same papers explain why this happens and, in the few cases where mechanization did not work, adduce the reasons why it failed.

It is thus important to re-assess certain factors in our physiological understanding of the mechanisms winter machine pruning triggers in the vine. Indeed, by including unexpected or negative responses, we shall propose a number of solutions that can accommodate an array of cases depending on cultivar, environment and crop management practices.

2. Physiological bases of winter mechanical pruning

2.1. The gold principles

A good start for explaining the physiological background of a mechanized approach to winter pruning is by asking an apparently naive question: why prune vines in winter? The most obvious answer is "to regulate crop level and achieve the desired grape composition". So, the thinking immediately goes to the need for limiting crop yield and, hence, automatically relating excessive bud load to unacceptably high yield and inadequate grape composition. Yet such a view oversimplifies the gold principles of winter pruning in grapes as cogently summarized in Fig. 2 (Winkler et al., 1974). If it is agreed that an unpruned vine bearing no crop allows maximum

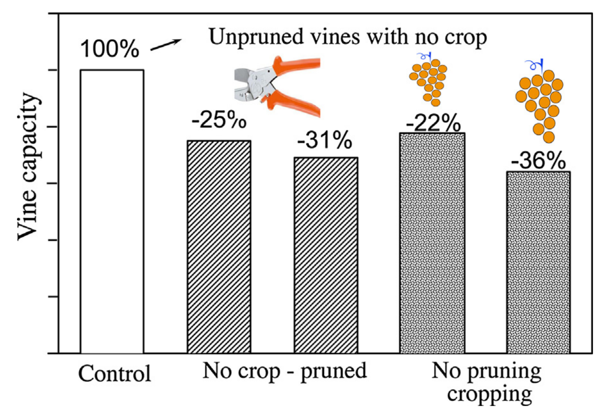

Fig. 2. Changes in vine capacity (*i.e.* total leaf area) depending upon severity of winter pruning and cropping level (redrawn from Winkler et al., 1974).

expression of vine capacity, intended as total leaf area, it follows that the same dormant vine subjected to either light or severe winter pruning will show a significant decrease in vine capacity, *i.e.* off 25% and 30%, respectively, compared to control. Therefore, it should be kept in mind that winter pruning's removal of nodes places constraints not only on yield as well as on vine capacity. To read it backwards, light mechanical pruning may result in increased vine capacity *vs.* traditional hand pruning. If such an increase is roughly proportional to the increased yield, no specific reason is foreseen to predict a worsening in final grape composition. This is the challenge posed by any mechanical approach to winter pruning and our task is to assess case studies providing clarification and matter for rethinking.

2.2. The original trial: early 1970s

In Italy the route towards winter mechanical pruning was laid out in the 1970s by introducing the Geneva Double Curtain training system (Intrieri and Poni, 2000). Once modified subsequently toward horizontal, self-supporting arms, it proved to be an ideal trellis for accommodating a tractor-mounted cutter bar unit per-

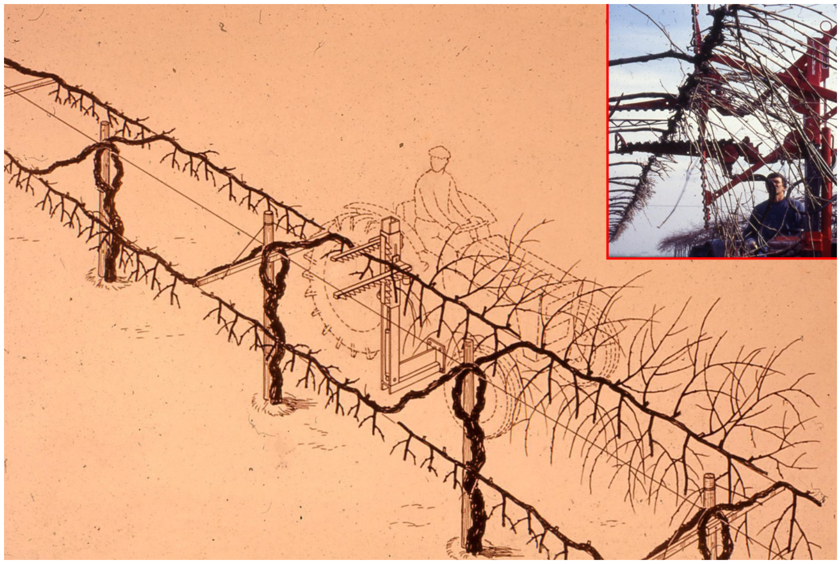

Fig. 3. Modified Geneva Double Curtain (GDC) training system to allow free cutting profiles around the cordon. In the inset a detail of cutter bar assembly during winter pruning.

Table 1
Vine growth, yield components and grape composition of field-grown *cv*. Montuni grapevines subjected to either hand spur-pruning (HP) and medium-length mechanical pruning (MP) without manual follow up. Data are seven-year means. Adapted from Intrieri and Poni, 2000.

Parameter	HP	MP	Diff. (% of HP)
Nodes/m (n°)	52b	96a	+84
Shoots/m (n°)	33b	49a	+48
Bud break (%)	65a	53b	– 23
Clusters/shoot (n°)	0.92a	0.69b	−33
Clusters/m (n°)	30	34	+13
Cluster weight (g)	133	123	−8
Yield/m (kg)	4.06	4.21	+3
Total soluble solids (°Brix)	19.7	19.6	−1

Means separation within row by *t*-test, $p \leq 0.05$.

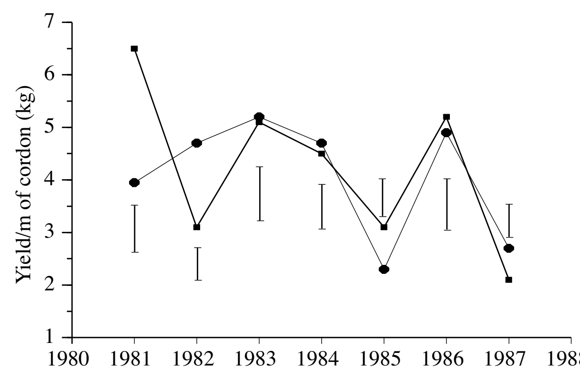

Fig. 4. Variation over years of the yield/m of row length recorded on hand pruned (●) and mechanically pruned (■) *cv*. Montuni grapevines. Within each year, vertical bars indicate Least Significant Difference (LSD) value (taken from Intrieri and Poni, 2000).

forming a C-profile cut, or what is termed 'box' hedging, around the cordon (Fig. 3). A medium-length mechanical pruning (MP) with or without hand finishing was compared over seven consecutive years with hand pruning (HP) in the white cultivar Montuni (Intrieri and Poni, 1995). When MP without manual follow-up and HP were compared, each representing an opposite end of the pruning spectrum, the seven-year means showed that, although MP almost doubled bud load per meter of cordon, vine yield was quite similar to HP due to compensation mechanisms that downregulated bud break, shoot fruitfulness and, to a lesser extent, cluster weight in MP (Table 1). Consequently, grape composition did not significantly differ at harvest and, as an added value, MP was completed in about 5 h/ha *vs.*120 h/ha required for hand pruning. This pioneer study was instructive for two additional reasons. The first concerns yield variation over years (Fig. 4): the significant 62% yield increase exhibited the first year following conversion from HP to MP was temporary as thereafter the vines settled into levels of production that were lower and comparable to their long-term averages under hand pruning; similar findings were also seen in other long-term studies of hedge pruning (Freeman and Cullis, 1981; Pool et al., 1988; Kliewer and Benz, 1992). The upshot is that yield compensation is attainable, although it requires at least three years for vine growth and yield components to acclimate to the increase in bud number per vine, and rushing back to HP after the first year of MP seems to be unwise. Notably too MP in the Montuni trial shifted the frequency of the bearing spurs left on the vines towards shorter units than HP, which typically retains about 5–6 node spurs for cropping and some 2-node spurs for spur renewal. Since *cv*. Montuni shows a progressive increase in node fruitfulness from the base towards the end of the cane, retaining a higher fraction of less fruitful nodes in MP was a primary determinant in avoiding over-cropping. Subsequent work conducted on other cultivars has confirmed that a low-to-medium fruitfulness of the basal nodes (positions 1–4) is a condition favoring yield compensation under MP, and that cultivars of highly fruitful basal nodes have more difficulty reaching the same balance (Poni et al., 2004).

2.3. Single high wire cordon for winter mechanical pruning

Although the cutter bar unit shown in Fig. 1 is very flexible once the bars are equipped with feelers and swinging devices to avoid posts, stakes and trunk so it can successfully negotiate even traditional hedgerows of vertically shoot-positioned trellises, the real breakthrough was the development of the high-wire cordon as the preferred vine training system for MP (Fig. 5). Trellis configuration is simple, a single wire being attached to the top of a metal vine stake positioned 1.6–1.7 m above ground. Since there are no catch wires above the cordon, blades can easily be positioned near the cordon surface in order to make close cuts. If the grower is skilled enough to induce and maintain a mostly erect growth pattern, more

Fig. 5. A reversed C-cut profile during winter mechanical pruning on single high-wire trained wines. It is intuitive that having most of the pruning wood located above cordon greatly facilitates machine work and speed since manual cuts needed to remove ventral wood are kept to a minimum. The inset shows the frame and vine structure of the single high wire trellis.

Table 2
Effects of hand and mechanical pruning on vine growth, yield component and grape composition of *cv*. Croatina (*Vitis vinifera* L.) vines. Data averaged over 2000–2003. Taken from Poni et al., 2004.

Parameter	HP	SMP-LF	SMP-SF	MMP-SF	Sig.[a]
Nodes/vine (n°)	37.5d	50.5c	60.0b	75.2a	**
Shoots/node (n°)	0.91a	0.89a	0.81b	0.74c	**
Leaf area/vine (m^2)	4.79b	5.02b	5.88a	5.10b	*
Yield/vine (kg)	2.82c	3.48b	3.67ab	4.19a	*
Leaf area/yield (m^2/kg)	1.70	1.44	1.60	1.22	ns
Soluble solids (°Brix)	20.7a	20.4ab	20.4ab	19.7b	*
Anthocyanins (mg/g)	1.34a	1.34a	1.28a	1.18b	*
Total phenolics (mg/g)	2.96a	2.93a	2.95a	2.79b	*

ns: non significant.
[a] Mean separation within each row by Student-Newman-Keuls test.
* indicate probability at 5%.
** indicate probability at 1%.

than 90% of the total winter wood will be located above the cordon and any eventual hand finishing needs to eliminate the few canes in ventral positions.

A good case in point is a trial carried out on *cv*. Croatina (*Vitis vinifera* L.), which characterizes for low fruitfulness of basal buds, *i.e*. varying from 0.3 to 0.6 inflorescence/shoot within the 1-to-4 basal nodes (Poni et al., 2004). It compared HP and short mechanical pruning (SMP) with either severe or light manual follow-up (SMP-SF; SMP-LF) and medium mechanical pruning (MMP) with light manual follow-up (MMP-LF) in a 10-year-old *cv*. Croatina vineyard trained to high free cordon and planted at 1.1 × 2.5 m. The mechanical hedging was performed by a cutter bar unit side-mounted on a tractor featuring an over-row reverse-U cut profile; manual follow-up was performed by two field hands with pneumatic shears working from a tractor-drawn platform. SF and LF were defined as the number of machine passages per row, two and one, respectively, thereby allowing the hands more or less time for shortening and/or thinning machine-pruned wood (Fig. 6). SMP stood for cuts made as close as possible to the cordons; MMP-LF was set by maintaining the cutter bars at approximately 10 cm above and sideways of the cordon. A summary of the main results from 2000 to 2003 is reported in Table 2. SMP + hand finishing at 50–60 nodes/vine achieved about 25% higher yield than HP at similar grape quality and 50% time saving. Yield compensation was manifested here primarily as reduced bud-break below the 60 node-per-vine threshold and was indeed aided by the cultivar's natural low fruitfulness of basal buds. The breakpoint was represented by MMP-LF, which at >60 nodes/vine started to show a depressant effect in vine capacity paralleled by a contraction of soluble solids and total anthocyanins and phenolics. MP thus turned out to be an excellent tool to identify vine balance for maximum cropping level at the desired quality.

While the Croatina trial did not include a comparison with long-cane pruning, a recent contribution by Mcloughlin et al. (2011) on Cabernet Sauvignon has shed more light about how varying bearer length, hence node number, in an MP canopy can alter yield components. They show that when node positions two and three were located in the two distal-most nodes made terminal by pruning, they were significantly more fruitful than equivalent nodes on longer bearers. Extrapolating this finding to a more general level suggests there is a realistic chance that when hedge pruning "shortens" bearer length at basal nodes in a somewhat low fruitful variety, increased fruitfulness of the node made apical by pruning may greatly help to achieve a rewarding yield level.

Machine pruned vines on a high wire cordon retain fewer buds per vine compared to machine pruned California Sprawl vines –130 to 160 buds per vine in the former against 250+ in the latter – and also accumulate less dead wood in their fruit bearing region (Dokoozlian, 2013). Because their fruiting zone is positioned at the top of the canopy, vines trained to high-wire cordon also have improved fruit zone microclimate compared to vines on the California Sprawl. Trellis height also allowed between-row spacing to be reduced from 3.6 m to 3.0 m in single curtain vineyards, thereby significantly increasing the amount of fruit bearing area per hectare.

In more general terms, the single high wire cordon seems to combine high suitability to mechanization with other desirable physiological features. Poni and Intrieri (2001) compared light response curves derived for a single leaf and for two canopies having a different growth patterns (VSP *vs*. free-growing single high wire). While it was not surprising to see that the photosynthesis increase with increasing light was more gradual for whole canopies, it was notable that the canopy forced between catch wire, *i.e*. mimicking the change from a single high wire cordon to a traditional VSP, lessened photosynthesis by about 26% as compared to the free growing canopy. This difference likely quantifies the loss of photosynthesis due to less light penetrating the inner part of the canopy

Fig. 6. A typical winter mechanical pruning set-up where machine pre-pruning is followed by hand finishing performed by two skilled workers using power shears.

in the VSP trellis. Additionally, recent findings have elucidated a primary need made quite urgent by global warming effects (Palliotti et al., 2014). In warm climates, bunches might greatly benefit from some leaf cover in summer to prevent or minimize sunburn, lack of pigmentation in red cultivars and a over-fast degradation of malic acid in white cultivars. In other words, a bunch microclimate consisting of mostly diffuse light broken by occasional sun flecks seems ideal, and this configuration can be very easily and naturally achieved with a mostly erect, single high wire cordon canopy.

3. Hedge *vs.* minimal pruning: pluses and minuses

Due to the greater number of buds retained per pruned vine, MP, or box hedged, vines begin to grow earlier in the season than the hand pruned (Pool et al., 1988). While final canopy size is often similar when comparing MP and HP vines, the former have more and shorter shoots with smaller leaves per vine and a greater portion of their total leaf area is exposed to sunlight than the latter (Morris and Brady, 2011). MP vines also have more clusters per vine but fewer and smaller berries per bunch than HP vines (Dokoozlian, 2013).

In general, most of these changes in canopy configuration are considered positive and lead to improved canopy microclimate and fruit composition. However, some notable exceptions exist. For instance, a three year study on Cabernet Sauvignon vines grown in the Clare Valley of South Australia compared berries from machine-, cane- and spur-pruned vines sampled at commercial harvest for analysis of berry size and phenolic composition (Holt et al., 2008). Wines made from each treatment were assessed for quality by a panel of winemakers. Machine berries were smaller and had higher concentrations of anthocyanins, tannins and total phenolics than berries from cane or spur pruning. Surprisingly, however, MP wines also had the lowest quality scores, suggesting that lighter berries presumably having a more favorable skin-to-flesh ratio do not necessarily originate better wines.

An interesting trial focusing on changes in berry properties as to pruning regime is reported by Pezzi et al. (2012), who did a Texture Profile Analysis (Rolle et al., 2011) of single berries sampled from *cv*. Chardonnay vines trained to GDC trellis under winter HP and MP with and without hand finishing. While skin thickness was unaffected by treatment, MP-vine berries with hand follow up had a higher detachment force of the pedicel and higher skin hardness than those of HP vines. This rather unexpected outcome indicates that the work of grape harvesters can be hindered by MP whereas higher skin hardness might better preserve berry integrity during harvest shaking.

As Fig. 7 shows, growth and canopy modifications can be taken to an extreme under minimal pruning, *i.e.* basically no pruning in winter and a low canopy skirt in summer on both row sides to remove part of the foliage and crop (Clingeleffer, 1983,2000; Sommer et al., 1995). Intuitively, according to the "gold principles" in Fig. 2, while minimal pruning can maximize vine capacity, the real challenge is to assess whether this increase is adequate to ripen the expected higher yield. Attention thus shifts to estimating or measuring seasonal light interception and/or carbon fixation of minimally *vs.* hand-pruned canopies. Today's automated, whole-canopy gas exchange systems enable monitoring of CO_2 assimilation even for long periods (Poni et al., 2014). This equipment is especially useful when treatments to be compared are represented by complex canopies in which single-leaf readings usually fail to yield a reliable integral of whole-canopy function. Using one such system, Poni et al. (2000) compared the whole-canopy net CO_2 exchange rate of 4-year-old potted *cv*. Chardonnay grapevines bearing normal crop and subjected to either minimal (MinP) or hand (spur) pruning (HsP). Main growth, vine yield and grape ripening parameters for the two treatments are shown in Table 3. MinP did show typical features triggered by very high bud load: 6-fold shoot and cluster number, notable reductions in shoot length, leaf size, cluster and berry weight, number of berries per cluster. Yield increased by about 71% in MinP (8.4 kg *vs.* 4.9 kg/vine), whereas total leaf area per vine increased in MinP by 19% only, likely due to pot growth constriction. Technological maturity did not differ between treatments, although at harvest MinP had slightly lower soluble solids and titratable acidity than HsP (Table 3). From about 3 weeks after bud-break to bloom, the MinP canopies showed a 4–6-fold higher CO_2 fixation rate than HsP vines (Fig. 8). Most of this gain was clearly due to the faster rate of canopy development rather than a higher average photosynthetic rate per leaf (data not shown). Notably, the whole-vine gas exchange monitoring of HsP vines started when the canopies were still at the compensation point for photosynthesis, which corresponded to a canopy leaf area of about 0.5 m^2, or about 7% of final leaf area per vine. Canopy NCER began to recover in the HsP treatment immediately after bloom, concurrently with the transition from a slower to a faster canopy

Fig. 7. A typical canopy subjected to minimal pruning.

Table 3
Vine growth, yield component, grape composition and carbon balance recorded on potted Chardonnay vines subjected to either hand (HP) and minimal pruning (MP). Adapted from Poni et al., 2000.

Parameter	HP	MP	*t*-test[a]
Shoots/canopy (n°)	62b	366a	**
Leaf area/shoot (cm^2)	1103a	222b	**
Total leaf area (m^2/canopy)	6.83	8.12	ns
Clusters/canopy (n°)	44b	285a	**
Berry weight (g)	2.15a	0.90b	**
Cluster weight (g)	92a	31b	**
Yield (kg/canopy)	4.9a	8.4b	**
Leaf area/yield (m^2/kg)	1.31a	0.97b	*
Total soluble solids (°Brix)	21.1	20.3	ns
Must pH	3.45	3.53	ns
Titratable acidity (g/L)	6.2	5.4	ns
Accumulated berry sugar (g C/canopy)	416b	682a	*
Total C gain from veraison to harvest (g C/canopy)	720	808	ns

ns: non significant.
[a] Means separation within row by *t*-test. Lack of separation implies ns.
* indicate probability at 5%.
** indicate probability at 1%.

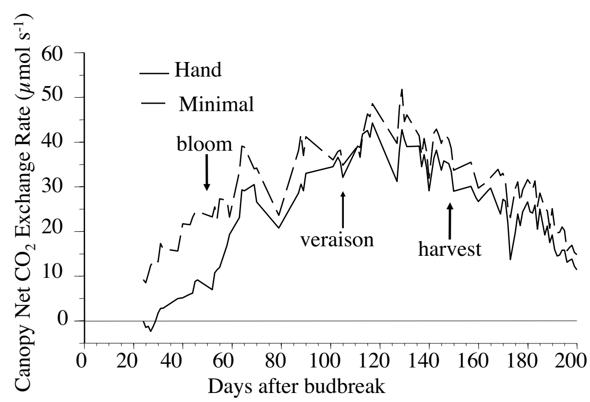

Fig. 8. Seasonal variation of canopy net CO_2 exchange rate (NCER) recorded on hand pruned (HP) and minimally pruned (MP) Chardonnay grapevines using a whole-tree enclosure system (taken from Poni et al., 2000).

Table 4
Vine growth, yield component and grape composition recorded on Sangiovese vines subjected to either hand spur-pruning (HP) and minimal pruning (M). Data are three-year means (1996–1998).Taken from Intrieri et al., 2001.

Parameter	HP	MP	t-test[a]
Shoots/m (n°)	38	266	**
Leaf area/shoot (cm^2)	3310	910	**
Total leaf area (m^2/m)	12.6	24.2	**
Clusters/shoot (n°)	0.83	0.46	**
Clusters/m (n°)	31	129	**
Berry weight (g)	2.62	1.94	**
Berries/cluster (n°)	52	43	ns
Cluster weight (g)	136	83	**
Yield (kg/m)	4.3	10.0	**
Leaf area/yield (m^2/kg)	2.9	2.4	*
Total soluble solids (°Brix)	20.2	18.2	**
Must pH	3.39	3.34	ns
Titratable acidity (g/L)	7.9	7.1	ns
Cluster compactness (OIV rating)[b]	6.5	2.6	**
Bunch rot incidence (% of affected clusters)	65.5	17.6	**

ns: non significant.
[a] Means separation within row by *t*-test. Lack of separation implies ns.
* indicate probability at 5%.
** indicate probability at 1%.
[b] Ranks as 1 "berries in grouped formation with many visible pedicels" and 9 as "misshapen berries".

growth phase. However, by the time of canopy completion (about 80 days after bud break), NCER was still 13% higher in MinP, and the average NCER gain of MinP vines was 19% in the remaining measuring period. Interestingly, photosynthetic CO_2 fixation from veraison to harvest fully met the sugar requirements during berry ripening in both treatments (Table 3), although MinP vines used 84% of the total current photosynthates *vs.* 58% of HsP's. Thus, despite its considerably higher crop, MinP did not seem to suffer any source limitation during the critical period of sugar accumulation in berries, suggesting too that translocation of carbohydrates from the rest of the vine may have been negligible.

When it comes to minimal pruning, which likely maximizes early canopy filling and total leaf area per vine, attention also needs to be devoted to seasonal water use *vs.* traditional pruning, especially within a scenario of global warming. An interesting comparison is provided by Schmid and Schultz (2000), who worked on Sylvoz and MinP field-grown Riesling vines and quantified water use over 130 days using a modified sap-flow Granier system. With a total canopy area ranging from 3.2 to 5.9 m^2 in Sylvoz and from 8.6 to 11.4 m^2 in MinP, cumulated vine water use over the time span reached 282 and 372 L for Sylvoz and MinP vines, respectively, indicating that despite the latter's more than doubling of total leaf area per vine, MinP registered only a 33% increase in water use.

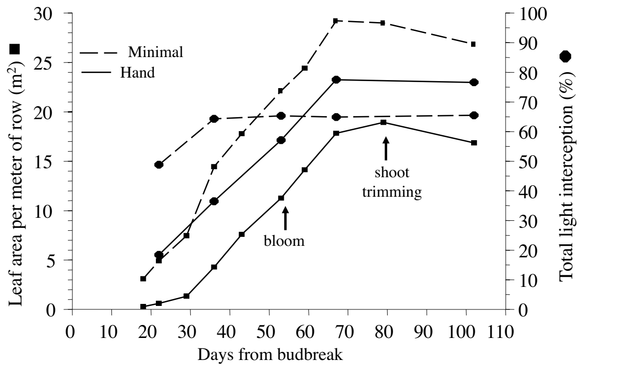

Fig. 9. Seasonal trends of vine leaf area development (■) e canopy light interception (●) recorded on field grown Sangiovese vines either hand-pruned (solid line) and mechanically pruned (dotted line). Redrawn from Intrieri et al. (2001).

The next step in Italy was to assess MinP viability for Sangiovese grown in North Italy's Po Valley on a longer term basis and under field conditions (Intrieri et al., 2001). The three-year average data for growth, yield and grape composition reported in Table 4 suggest that the promising response observed in Chardonnay was not corroborated since MinP yield/vine was excessive and soluble solids concentration at harvest significantly decreased (18.2 Brix *vs*. 20.2 Brix found in HsP). Intriguingly, these findings were found at LA/Y ratios that in both treatments were well in excess of the adequacy threshold Kliewer and Dokoozlian (2005) set at 1–1.5 m^2/kg. Although whole-canopy NCER readings in this trial were not feasible, hints about the relationship between total and functional leaf area could be derived from seasonal Canopy Light Interception (Fig. 9). In fact, unlike leaf area, CLI is able to "detect" to a certain extent the optimal threshold for canopy filling. The data for the MinP treatment show that maximum light interception (about 65% of total incoming light) was achieved at about 15 m^2 of leaf area per meter of cordon, whereas a further doubling in leaf area did not result in any additional CLI gain. Clearly, the leaf area accumulated in the MinP vines beyond the *ca*. 15 m^2/m limit essentially overhung the pre-existing canopy, mostly contributing to internal mutual shading and presumably leading to negligible gain in total net canopy photosynthesis.

Overall, the Sangiovese trial indicated an unsatisfactory balance in MinP Sangiovese grapevines despite marked compensation registered for some yield components, *viz*. lower shoot fruitfulness and cluster weight. Data also confirmed that balancing MinP vines is more troublesome in a medium-to-late ripening, highly fruitful cultivar like Sangiovese at a site allowing prolonged shoot growth well beyond bloom. Similar findings are reported by Rousseau et al. (2013) for the late ripening *cv*. Mourvedre, which under MinP in France's Languedoc-Roussillon had 31% less color than HsP grapes at the same sugar level. Likewise, a three-year comparison of HP against hedge and MinP in cvs. Tempranillo and Bobal showed that while hedge pruning performed excellently, marking higher yield than HP at similar grape quality, MinP vines showed an increase over time of Ravaz index for yield-to-pruning weight ratio, suggesting that increased yield was not assisted by a corresponding increase in vine capacity (Gil et al., 2012). This response matches others and points to an exhausting of MinP effects in the mid-to-long term, leading to a decrease in vine yield and grape quality.

A look back at the Sangiovese trial, indicates that the clusters of MinP vines were distinctly less compact than those produced by HsP (Fig. 10), and that this feature was crucial at preventing or limiting massive bunch rot even in unseasonably wet seasons like 1996 and 1998. This finding led to a new mechanical light-pruning technique that may prove capable of unifying the advantages of looser bunches and proper grape maturity.

Table 5
Vine growth, yield component and grape composition recorded on Sangiovese vines subjected to either hand spur-pruning (HP) and semi-minimal pruned hedge (SMPH). 80 and 120 cm are the heights of the fence. Data are four-year means (2005–2008). Adapted from Intrieri et al., 2011).

Parameter	HP	SMPH-80	SMPH-120	Sig.[a]
Shoots/m (n°)	18b	205a	234a	**
Total leaf area (m^2/m)	5.20b	8.96a	10.83a	**
Clusters/shoot (n°)	1.22a	0.27b	0.30b	**
Clusters/m (n°)	22b	56ab	71a	**
Berry weight (g)	2.38a	1.94b	1.72b	**
Berries/cluster (n°)	113a	73b	67b	**
Cluster weight (g)	265a	141b	116b	**
Yield (kg/m)	5.80b	7.86ab	8.27a	**
Leaf area/yield	0.90b	1.14ab	1.31a	*
Soluble solids (°Brix)	20.8	21.4	21.3	ns
Must pH	3.33	3.36	3.34	ns
Titratable acidity (g/L)	7.47	7.44	7.19	ns
Anthocyanins (mg/g)	674b	714ab	847a	*
Cluster compactness (OIV rating)[b]	6.8a	4.6b	3.9b	**
Bunch rot severity (% of cluster surface)	9.65a	1.40ab	0.43b	**

ns: non significant.
[a] Mean separation within each row by Student-Newman-Keuls test.
[b] Ranks as 1 "berries in grouped formation with many visible pedicels" and 9 as "misshapen berries".
* indicate probability at 5%.
** indicate probability at 1%.

4. The semi-minimal-pruned hedge (SMPH)

The idea of the SMPH was developed at the University of Bologna, Italy, and introduces two main novelties as compared to a traditional MinP (Fig. 11): the "frame" on which the fruiting spurs can be distributed in a VSP trellis is expanded from the cordon to the entire above-cordon trellis structure, and the canopy's more 'fence-like' profile makes mechanical winter topping and side hedging easier to perform while markedly reducing bud load. To test SMPH effectiveness in a trial from 2003 to 2005, 12-year-old *cv*. Sangiovese grapevines of clone 12T/SO4 were traditionally spur-pruned whereas the vines forming SMPH were pruned such that some of the canes from the preceding year were removed and the remaining intact canes were tied and trimmed close the foliage wires to form 80 cm and 120 cm vertical hedge walls; HP control vines retained 18 buds per meter of cordon (Intrieri et al., 2011). Four-year means of growth, yield and grape composition showed a notably desirable balance (Table 5). On one hand, the expected increase in vine capacity (*i.e*. total LA/m) more than offset yield increase and, consequently, the LA/Y ratio significantly increased in SMPH-120 *vs*. HP (Table 5). SMPH markedly modified cluster morphology as well, a bunch architecture that positively impacted tolerance to bunch rot by producing smaller clusters with fewer, much smaller berries than HP. Grape composition showed that while technological ripeness was unaffected, SMPH could increase total anthocyanin count, reaching significance in the SMPH-120 *vs*. HP comparison. Even though no assessment of whole-canopy physiology was undertaken, it seems intuitive that SMPH performed better than MinP for two main reasons: winter SMPH quickly adjusts cluster number and ultimately potential yield, and its higher LA is spread over a larger supporting frame and, especially when trained to 120 cm from the cordon, quite likely improves leaf exposure and, hence physiological functions, compared to MinP.

5. Assisted mechanical winter pruning in long-cane trellis

Guyot is the epitome system of manual long-cane vine pruning. It requires the removal of the old fruiting cane for renewal by a new one placed horizontal on the supporting wire; a short spur on the head of the vine is retained to generate next season's cane renewal. Although the whole process involves a number of operations (cuts,

Fig. 10. Typical cluster morphology observed on Sangiovese vines hand pruned (left) and minimally pruned (right).

Fig. 11. Mechanical pruning on a semi-minimal pruned hedge (SMPH) system (taken from Intrieri et al., 2011).

wood removal, positioning, tying) needing up to about 120 h/ha for a vineyard planted at 4000–5000 vines/ha (Galletto and Scaggiante, 2007), Guyot is still quite popular for a number of reasons, its overall simplicity and unimpeded fruitfulness of basal nodes topping the list. While selective operations like choice of renewal cane and its wire-positioning require human intervention, the non-selective removal of past-year vegetation fed the idea that it could have be mechanized.

Preliminary attempts were made using an over-row pruner mounting rotary disks to break up the old wood, thereby speeding up the whole process (Catania et al., 2007). The limiting factor here was that, to safeguard the length of the renewal cane, the machine had to operate at a some distance from the head of the vine, requiring both low cordon height and tall canopies. The real breakthrough came in 2007 when two new machines – a Vine Stripper and Cane Pruner – were developed and patented in New Zealand along different operating principles.

The vine-stripper idea belongs to Walter Langlois, who conceived an over-row machine (Fig. 12A) equipped with a pair of rubberised counter-rotating disks that lift the excess canes towards a shredding head that then releases the debris as mulch over the inter-row alley. To increase operational efficiency, a model is also available to accommodate two rows in one run. Yet before the machine enters the vineyard, a skilled hand must manually cut the old cane and isolate the new one. It is likewise advisable that, to minimize the risk of vine pulling, some excess canes will have to be shortened to at least 30 cm below the machine's operating plane (Fig. 13A).

The same year the vine stripper was introduced, New Zealand manufacturer Klima® unveiled the cane pruner based on a rather original operating principle. It requires that existing fruiting wire staples be replaced by plastic clips to make the trellis wires movable so they can be fed through the cane pruner head. After the initial hand pass to make the head cuts, the machine lifts the wires clear of the canes, the blades remove the surplus canes, and a mulching unit processes and spreads the debris in the middle of the row; the fruiting wires are then reattached to the intermediate posts. According to the manufacturer, compared to conventional pruning,

Fig. 12. (A) 'Vine stripper' machine showing two counter-rotating disks embarking canes in excess to convey them toward the shredding head. Cane debris are then interspersed in middle of row (www.langlois.co-nz). (B) The Viteco® cane pruner (B, www.ero-binger.it) operating on a vine row.

this unit delivers labor-cost saving between 35 and 70 cents/vine. More recently, Ero® has released the Viteco cane stripper (Fig. 12 and 13B). It differs from Klima® in requiring that all movable wires inserted on one side of the row and the top wire on the opposite side be freed. The best operational performance of these units is achieved for row lengths ≥70 m, allowing a drive speed of up to 8 km/h.

6. A look forward

As remarked previously, much of the mechanization technology currently available for winter pruning seems under-utilized in Italy. Although mechanical pruning or box hedging reduces production costs, it has not been widely adopted. Industry observers have suggested that the economic drivers for full-scale mechanized practices, primarily labor availability and cost, have been insufficient to provide the economic incentive necessary for increased winter mechanization. In effect, a national ISTAT statistics bureau survey in 2010 notes that vineyard properties average 1.6 ha in Italy, a size that hinders mechanized winter pruning because family labor is usually available and the operation can be spread over several months without the calendar rush constraining labor supply in the narrow harvest window. However, other factors have also played a role, one being that many growers still feel the quality of fruit and wine produced from machine-pruned vines is poorer than that of hand-pruned vines in spite of evidence to the contrary.

The message seems clear: mechanization must provide improved production efficiency while maintaining or improving grape and wine quality in order to be widely adopted by industry. Future adoption of winter mechanical pruning may therefore be improved by placing more emphasis on the enhancement of fruit quality rather than focusing on the labor and cost saving benefits. Precision winter mechanical pruning and recent developments in robotics will indubitably play a role. Another issue is matching winter pruning and variability in vine vigor by mapping interaction zones. The idea is to improve the quality of fruit in the low-potential zone by pruning vines in each of the management zones to different levels of vigor, zones identified as high potential being pruned lightly to leave more buds and areas displaying low potential pruned more severely. The philosophy behind this being that fewer buds will result in fewer shoots of higher vigor. The expected overall effect is to provide sufficient leaf area to ripen

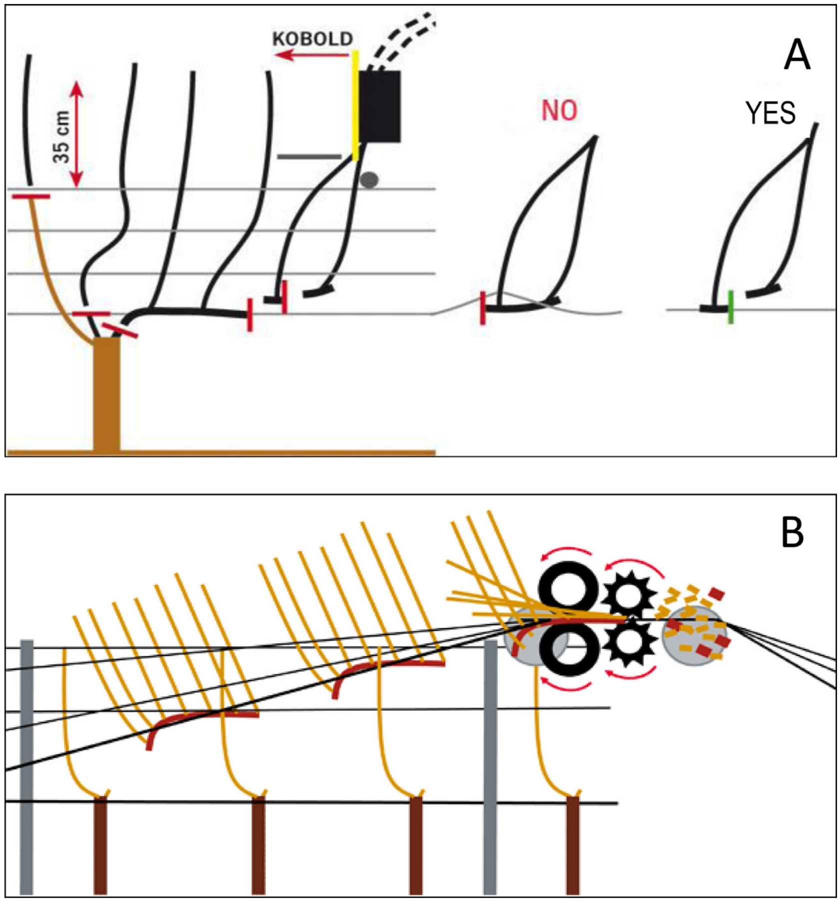

Fig. 13. Preliminary operations and operating field for a "Vine stripper" (A, www.clemens-online.com) and a Viteco® cane pruner (B, www.ero-binger.it).

fruit in the low potential area to the same quality as in the others. Unfortunately, to the best of our knowledge, there is currently no published work on the subject, nor on any variable-rate pruners that would make it possible.

An alternative, indeed original solution to profit from the advent of precision viticulture techniques is proposed by Proffitt et al. (2006), who segmented a vineyard into three zones based on high, medium and low vigor. Pruners are paid piece rates that are adjusted to the degree of difficulty in each zone, with each pruner being allocated a set number of rows in per zone to ensure equal distribution of work and the time required to perform it. This system has the effect of boosting worker self-confidence while completing pruning on time and delivering an estimated cost saving of 11.6%.

The latest frontier in this connection seems to be robotic pruners that are programmed to individual vine vigor and capacity in pursuit of replicating human skills but to greater efficiency. In general, a standard machine features a set of cameras that take photos of dormant grapevines and then builds a three-dimensional image to which it applies various pruning rules, the rules and images determining where to cut. It has two robotic arms end in a pruner, one each side of the vine. The machine makes the cuts and, when done, moves forward taking pictures along the way before stopping to make the next series of cuts.

Regardless of the fascinating prospects these new techniques appear to open up, a few final, cautionary, words are in order. Mechanized or automated winter pruning, whatever form it takes, will ultimately result in labor-saving. It is a necessary but not by itself the sufficient factor for balancing the equation. The real challenge is demonstrating its economic viability, a more complex factor that in the end will depend upon the ability of any such approach to maintain, or it is to be hoped, improve grape quality and wine appreciation.

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