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# The effects of low-input training systems on viticultural costs on flat terrain and steep slope sites

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ABSTRACT

Low-input training systems, such as minimal pruning (MP) and the semi-minimal pruned hedge (SMPH), require less working hours as a result of fewer viticultural process steps and permit a higher degree of mechanisation. However, their effect on viticultural costs and per litre costs on both flat terrain and steep slopes has not yet been analysed. This study quantifies the viticultural costs of vertical shoot positioning (VSP) and low-input training systems for standard processes on different types of flat terrain and steep slope vineyards. The costs were obtained from a dataset of 1,519 working time records of labour and machine hours from 20 vineyards belonging to five German wine estates over three years. The costs for standard viticultural processes were compared across three pairs of VSP and low-input training site types with different mechanisation intensities. The comparison was carried out by univariate analysis of variance with fixed and random effects, and by descriptive analysis of mean values. On flat terrain, SMPH significantly decreased the costs for the viticultural steps of winter pruning, tying, shoot positioning and defoliation, but it increased the cost for pest control. Hence, the total cost on flat terrain decreased marginally, but still significantly, by 46 %. The cost effects on steep slopes were similar, decreasing by 34 % for SMPH in unsupported steep slope harvester sites and by 46 % for MP rope and winch-supported steep slope sites. The per-litre costs were calculated for different yield levels. Since the yield in low input systems is higher than in VSP, the production costs per litre further decreased.

The study confirmed the high cost-saving potential for wine growers of the mechanisation of canopy management and the omission of winter pruning in low-input systems. Combined with higher yields, the cost savings from low-input systems are particularly suitable for producers of bulk wine and market entry and mid-level wine profiles.

By converting to low-input systems, the costs associated with mechanisable steep slope vineyards can be reduced to amounts approximating VSP on flat terrain. For certain wine profiles, low-input systems should therefore constitute an integral part of strategies to increase the economic sustainability of steep slope viticulture. The estimated cost benchmarks provide critical input for the cost-based pricing policy of steep slope growers. These benchmarks also give agricultural policy reliable indicators of the subsidies required for preserving steep slope landscapes.

KEYWORDS

production costs, mechanisation, low-input training systems, minimal pruning, semi-minimal pruned hedge, economic sustainability, steep slopes, viticulture

**Supplementary data can be downloaded through: https://oeno-one.eu/article/view/4619**

## INTRODUCTION

The wine sector generally suffers from insufficient economic sustainability (Loose *et al*., 2021). Profitability is particularly low for bulk wine producers (Strub *et al*., 2019), who have to act as price-takers in a globally oversupplied bulk wine market (Capitello *et al*., 2015; Loose and Pabst, 2018). Bulk wine producers cannot differentiate themselves through image building and value-adding branding, and they rarely benefit from higher product quality. Production cost and production volume are the two main drivers of the profits made by bulk wine producers (Couderc and Marchini, 2011).

Since the 1950s, viticultural costs have been significantly reduced through mechanisation (Schreieck, 2016). However, on flat terrain the potential for further mechanisation and cost reduction is unlikely for traditional viticultural systems. For the most common training system in Germany, vertical shoot positioning (VSP), winter pruning and canopy management require a substantial amount of manual labour. These two sets of processes each represent one-third of the total viticultural cost and are therefore important cost drivers for standard flat terrain sites (Strub and Loose, 2021).

In addition, steep slope wine producers suffer from viticultural cost disadvantages. New developments in viticultural mechanisation, such as steep slope harvesters and rope and winch systems, can only partially reduce viticultural costs (Strub and Loose, 2021). The total viticultural cost of mechanisable VSP on steep slope sites is still 60 to 110 % higher than that of standard VSP on flat terrain sites (Strub and Loose, 2021). Any option that would further offset this cost disadvantage could contribute to the sustainability and preservation of steep slope viticulture.

Low-input training systems permit the full mechanisation of viticultural processes (i.e., pruning), and thus substantially reduce the demand for labour. Switching from a VSP to a low-input training system may therefore be a viable option for further reducing the cost of manual labour for viticultural winter pruning and canopy management. However, there is a clear lack of empirical studies on the effects of low-input training on viticultural costs. The aim of the present study was therefore to empirically assess the cost-saving potential of low-input training systems taking into account single or total viticultural processes on both flat terrain and steep slope sites. More than 1,500 working time records from 36 German vineyard observations of five different regions were used to estimate viticultural costs. Such cost benchmarks are of interest to wine growers in order to make cost-effective viticultural decisions. In addition, public agricultural policy could benefit from insights into how to reduce costs and hence the subsidies required to preserve steep slope viticulture.

### 1. Training of vines with vertical shoot positioning (VSP) systems

Growing vines on a trellis with VSP is the most common training system in German viticulture (Müller *et al*., 2000); vines are either cane or spur pruned in winter, leaving one or two canes intact and tied to a wire prior to budburst. This is a labour-intensive process, in which the pruning of vines, removal of canes from the wireframe and tying of the remaining canes are all done manually. Such intensive labour (total labour demand of approximately 100 h/ha/year) entails high costs of 1,520 € per hectare, or 26 % of the total cost of manual labour at VSP sites (Strub *et al.,* 2021). Because pruning requires skilled workers who are becoming increasingly scarse (Botelho *et al*., 2020), their labour is likely to become even more costly in the future.

Attempts have been made to mechanise winter pruning, at least in part. Mechanisation is commonly used to pre-cut the very top of canes and to shred the removed parts. Canepruner® or vinestripper® have recently started to be used to remove canes from their wireframe. However, because these machines are very expensive and prone to malfunction (Walg, 2016a, Walg, 2016b), they are not widely used. For cordon systems, which is a special kind of VSP pruning system, specific mechanisation options are available for winter pruning and cane removal. However, these systems are primarily employed in countries bordering the Mediterranean Sea, as well as in countries in the Southern and Western Hemispheres, and they are rarely used in Germany.

After winter pruning, in most VSP systems canes need to be tied manually. In the summer, all VSP systems involve shoot thinning and shoot positioning, whereby excessive shoots are removed and the remaining shoots are positioned upright and disentangled between pairs of wires or strings. While shoot removal and shoot positioning can be partly mechanised, such mechanisation has not become firmly established in Germany. The processes of tying canes, thinning shoots, lowering wires and positioning shoots jointly account for 32 % of the total viticultural costs on flat terrain sites (Strub and Loose, 2021). This cost does not differ significantly on steep slope sites because, like flat terrain sites, viticultural processes are mainly performed manually (Strub and Loose, 2021).

## 2. Training of vines in low-input systems

In low-input systems, vines are also trained to a trellis, but they are grown in the form of hedges and are cut using a mechanical trimmer. Because the canopy persists as a hedge, the process steps of cane tying, shoot thinning, wire lowering and shoot positioning are usually not required.

Low-input systems were first developed in the 1970s in Australia in the form of a minimal pruning (MP) system. In MP vineyards, the hedges are only trimmed at the bottom to prevent the canes from touching the ground, but otherwise they are left unpruned, resulting in very wide canopies which become bare inside. For MP, vineyards with wide inter-row distances of approximately 3 m are needed to allow a wide canopy to develop and a tractor to pass through. Currently, 65 % of all viticultural sites in Australia are managed using MP systems, particularly in warm and well-irrigated regions conducive to vigorous vine growth (Clingeleffer *et al*., 2005).

Since the beginning of the 21st century, low-input systems have become increasingly employed in European viticulture as well as in Australia, due to climate change and the corresponding increases in average temperatures. Furthermore, in Europe, low-input trained vineyards are often created through the conversion of an existing VSP system with a standard 2 metre inter-row distance. Such SMPH systems combine features of traditional VSP-type trellising systems with the concept of minimal pruning (Intrieri *et al*., 2011), whereby instead of canes from the previous vegetation period being pruned in the winter, they are tied to a wireframe and mechanically pruned in winter into a hedge shape using normal grapevine hedging machines. Consequently, in spring, a high number of buds will burst all over the canopy, creating a green hedge. During the vegetation period mechanical leaf trimming is required two to three times per season. Because of their identical inter-row distance and heavily trimmed canopy, SMPH vineyards look similar to VSP vineyards once the canopy has developed; the only obvious difference is that grapes in SMPH are distributed over the entire canopy, rather than within a defined grape zone, and such vines differ widely in their leaf area to fruit weight range (Molitor and Junk, 2019).

For low-input systems, all pruning and canopy management processes are performed mechanically. While the cost savings from mechanical canopy management are obvious, there is limited empirical research on the effect of such management on the total viticultural cost. So far, only the costs for selected processes have been analysed. Archer and van Schalkwyk (2007), for example, reported that MP decreased labour hours by 100 % for pruning and 85 % for canopy management. Likewise, Bates and Morris (2009) reported that mechanical pruning and fruit thinning led to a cost reduction of 80 %. No such research, however, has been conducted on the effect of different training systems on all viticultural processes or on total viticultural cost.

The cost benefits of low-input systems cannot be assessed without considering the potential drawbacks of these systems; for example, the possibility of lower wine quality resulting from higher yields (Deloire *et al*., 2016), increased demand for water for MP, and compulsory machine harvesting. Compared to VSP systems, low-input systems generate canopies that produce a considerably higher number of buds and shoots, generally resulting in higher yields. This effect is strongest in the first years after conversion if no counter measures, such as thinning, are taken. Regarding non-thinned SMPH systems, Molitor *et al*. (2019) reported an average yield increase of 78 % for the second to sixth years after conversion, when the self-regulation of vines occurs. Particularly in the first years after conversion, yield regulation is essential in low-input systems to achieve a satisfactory leaf area to fruit ratio and to enhance phenolic maturation (Schultz *et al*., 2000).

For yield regulation in low-input systems grape harvesters mainly are used (Walg, 2013). However, the intensity of yield reduction generated by a grape harvester is difficult to control and can range from subtle to extreme reduction with the same machine and in identical settings (Molitor *et al.*, 2019). Alternative thinning measures in low-input systems, such as bioregulators, have been found to frequently produce unsatisfying results (Weyand and Schultz, 2006), while rotating brush systems may cause too much damage to the vine (Walg, 2013).

Moderate yield increases can be desirable for producers and can reduce cost per litre through economies of scale. Depending on the availability of water, the intensity of hedging and the thinning measures used, long-term yields can increase by 35 % to 74 % when VSP systems are converted to SMPH systems (Intrieri *et al.*, 2011; Molitor *et al.*, 2019). Similar average yield increases of between 25 % to 56 % were reported for MP systems (Schultz *et al.*, 2000; Zheng *et al.*, 2017). A different long-term study at Geisenheim University that directly compared MP and VSP training in the same vineyard revealed average yields of 75 hl/ha for VSP and 145 hl/ha for MP, as well as different average must weights (TSS: 21 % Brix (VSP) compared to 18,5 % Brix (MP); data not shown; Stoll *et al.,* unpublished). The effect of yield on cost per litre thus represents an important economic consideration.

Besides yield and quality issues, low-input systems require further viticultural considerations, in particular the suitability of the variety. In Germany, for example, SMPH is mostly recommended for white varieties (DLR Rheinpfalz, Research Institute Geisenheim, 2011). Under such climatic conditions, MP for red varieties often results in unsatisfactory ripening and higher incidences of bunch rot. However, in SMPH, due to a lower leaf area to fruit weight ratio, phenological stages and thus ripening are delayed, and the looser bunch architecture is less susceptible to bunch rot (Molitor *et al.*, 2019).

Due to the larger canopy associated with low input systems, they also entail increased water demand, MP in particular (Schultz *et al.*, 2000). Without irrigation, the potentially higher incidence of drought caused by climate change can become more problematic at MP sites than at VSP or SMPH sites, particularly on steep slopes (Hofmann and Schultz, 2015).

Low-input systems require compulsory machine harvesting, because grapes do not grow in a delimited grape zone, but rather all over the canopy (Archer and van Schalkwyk, 2007). This implies that low-input sites must be accessible to a standard harvester on flat terrain or a steep slope harvester on steep slopes (Strub and Loose, 2021). Traditional selective manual harvesting is impossible at low-input trained sites and must instead be accomplished by modern sorting technology, such as optical sorting tables (Weber *et al.*, 2020). The potential disadvantages and limitations of low-input systems must therefore be taken into account well in advance of conversion, because reverting back to a manual pruning system is difficult, if not impossible (Molitor, 2010).

The conversion of a VSP to a MP system requires about 50 labour hours per hectare. This includes the fastening of canes and the reinforcement of the trellis system to withstand the pressure of the large canopy. In MP training systems in particular, every second row has to be removed, because the space between rows is usually too narrow (Molitor, 2010). To convert VSP into SMPH systems, the labour demand is therefore lower, because the same number of rows is kept and the trellis does not need to be reinforced.

**3. Research questions**

The aim of this study was to analyse the cost structures of the management processes in vineyards which apply VSP and low-input training (MP and SMPH) to determine their cost-saving potential. The study focused on how low-input training affects the costs of particular viticultural processes, as well as the total annual viticultural costs for either standard flat terrain sites or two different types of steep slope sites. Because low-input systems can differ with respect to yield, it was also important to analyse the cost per litre differences between the training systems.

- RQ1: What is the cost advantage of low-input training compared to VSP training on flat terrain sites?
- RQ2: What is the cost advantage of low-input training compared to VSP training on steep slope sites?
- RQ3: How do differences in yield impact cost differences between low-input and VSP systems?

## MATERIALS AND METHODS

The underlying framework of this study comprised the definition of specific vineyard site types and their optimal degree of mechanisation, as well as all process steps executed throughout the vegetation period. The viticultural costs were determined from labour and machine costs, whereas cost estimates were assigned to labour and machine hours (for details, see Strub *et al.*, 2021).

**1. Site types**

The six site types analysed in this paper are a sub-selection from a complete vineyard typology derived from Strub *et al.* (2021).

**TABLE 1.** Framework of three pairs of vineyard site types with VSP and low-input training under optimal mechanisation of viticultural processes dependent on external factors and corresponding sample sizes (modified based on Strub and Loose, 2021).

| External factors | | | Mechanisation of viticultural processes | | | Site types | Sample sizes | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Determined by nature | Determined by winegrower | | | | | | | | | |
| Slope and access to vineyard sites | Orientation of rows towards the slope | Training system | Pruning | General manage-ment | Harvesting | | n 2017 | n 2018 | n 2019 | n total |
| No limitation | - | VSP | Manual | Unsupp. | SH | 1a VSP SH | 3 | 5 | 6 | 14 |
| | | LI (SMPH) | Mechanical | Unsupp. | SH | 1b LI (SMPH) SH | 2 | 2 | 2 | 6 |
| Limited access for machines | DSS | VSP | Manual | Unsupp. | SSH | 2a VSP unsupp SSH | — | 2 | 3 | 5 |
| | | LI (SMPH) | Mechanical | Unsupp. | SSH | 2b LI (SMPH) unsupp SSH | — | 1 | 1 | 2 |
| | | VSP | Manual | Rope | SSH | 2c VSP Rope | 1 | 4 | 3 | 8 |
| | | LI (MP) | Mechanical | Rope | SSH | 2d LI (MP) Rope | — | 1 | — | 1 |
| | | | | | | Sum | 6 | 15 | 15 | 36 |

DSS = direction of steepest slope; VSP = vertical shoot positioning; LI = low-input system (referred to as MP in Strub *et al.* (2021)); MP = minimal pruning; SMPH = semi-minimal pruned hedge; Unsupp. = unsupported; SH = standard harvester; SSH = steep slope harvester. Corresponding site types in Strub *et al.* (2021): 1a = 1b; 1b = 1a; 2a = 2c; 2b = 2a; 2c = 2f; 2d = 2b.

The site types were characterised by external factors (Columns 1 to 3 in Table 1) and, consequently, by corresponding levels of mechanisation (Columns 4 to 6 in Table 1). The six site types cover flat terrain sites (types 1a and 1b) and steep slope sites, with both unsupported mechanisation (types 2a and 2b) and rope support (types 2c and 2d).

The comparison of production costs between VSP and low-input systems was conducted pairwise per site type, with VSP and low-input trained sites differing in degree of mechanisation of all processes related to pruning (Column 4 in Table 1). The sample size per site type reflects prevailing German viticulture methods; since low-input training is still relatively uncommon, there were less sampled low-input trained sites than sampled VSP sites. Likewise, because steep slope mechanisation is a recent development (Strub and Loose, 2021), low-input trained sites on steep slopes are still exceedingly rare, and therefore only one site was available for MP (type 2d). Differences per site type between the distinct low-input forms MP and SMPH cannot be analysed from the available data.

Pair 1 (site type 1a versus site type 1b): vineyards on flat terrain managed using standard narrow-track tractors and standard grape harvesters (SH). Type 1a: manual pruning for VSP; type 1b: mechanical pruning for low-input systems (SMPH).

Pair 2 (site type 2a versus site type 2b): vineyards with slopes above a 35 % to 40 % gradient, depending on soil structure and infrastructure, in which standard narrow-track tractors can be used for mechanical pruning and general management. However, an SSH consisting of a crawler tractor equipped with a harvesting head is needed for harvesting on the slope (Walg, 2007). Type 2a: manual pruning for VSP; type 2b: mechanical pruning for low-input systems (SMPH).

Pair 3 (site type 2c versus site type 2d): vineyards with a slope above 40 %. Standard narrow-track tractors must be replaced by crawler tractors secured with winch-and-rope support systems that prevent the machines from sliding down the hill (Grečenko, 1984; Walg, 2007; Yisa *et al.*, 1998). The crawler tractors are used for general management and harvesting, as described above, in combination with a harvester head. Type 2c: manual pruning for VSP; type 2d: mechanical pruning with a crawler tractor for low-input system (MP).

The details of the low-input sites included in the sample are listed in Table 2. All but one vineyard was planted with white grape varieties, which were considered to be more suitable for low-input systems in cool to moderate climate. All the sites were converted from VSP to SMPH or MP several years ago and have since adjusted to the new training system. None of the sites were irrigated, nor are there any plans to irrigate them in the future. At all sites, except for site type 2d, the initial VSP row spacing was retained and the low-input system now in place is the SMPH. During transformation to MP, every second row was removed for the site type 2d observation, because the initial inter-row spacing of 1.6 m prevented mechanised vineyard management. The wines produced from these sites were all designated for lighter-style market entry and mid-level wines.

## 2. Database of labour and machine time records

The dataset for this study consisted of 1,519 working time records from 20 different vineyards representing the six vineyard types shown in Table 1. The labour and machine times were recorded in daily diaries throughout 2017, 2018 and 2019 in five management-led wine estates comprising between 50 and 230 hectares of vineyards from five different German wine-growing regions. The data collection was based on an extensive list of number-coded viticultural activities (Strub and Loose, 2021). For comparability, the time records were standardised to per-hectare values.

## 3. Selection of process steps for analysis

Out of all viticultural activities (Strub and Loose, 2021), only those that are performed on a regular, annual basis were selected for the comparative cost analysis. The viticultural processes *Mineral fertilisation*, *Organic fertilisation*, *Straw application*, *Replanting of missing vines*, *New planting*, *Maintenance work* and *Irrigation* were exempted, because they are less frequently performed. In this sample, these seven processes only represent about 1 % of the total viticultural cost, because they were rarely ever performed.

Instead of including process steps *Under-vine cultivation (code 1500)* and *Chemical weed control (code 1600)* separately, they were combined to make a single process: *Weed removal* (code 1500+). This was a sensible choice, because these two initial processes are complementary for removing weeds from underneath the vines and are rarely performed jointly. The process steps considered for the comparative cost analysis are shown in Table 3, along with the corresponding sample sizes per site type.

## 4. Transformation of labour and machine hours into cost estimates

The original working time records were prized with cost estimates for labour and machine hours, full details of which are provided in Strub *et al.* (2021). For labour costs, union wage agreements and federal minimum wage provisions, including non-wage labour costs, were used based on the process type and the qualifications of the workers employed (AGV Hessen e.V. and IG BAU, 2010; Federal Ministry of Labour and Social Affairs Germany, 2019). The machine cost was calculated according to Walg (2016a), Becker and Dietrich (2017) and ÖKL (2020), and was based on expenditure for depreciation, interest for tied-up capital, maintenance, repair and storage as well as fuel consumption and insurance and taxes. Pest control by helicopter and harvesting by SSH is usually performed by contractors, and therefore the cost of these machines was calculated from contractor prices, which include personnel costs and the expected profit margin.

As this study focused on costs associated with the external conditions of vineyards, the total viticultural cost only took into account labour and machine costs. Costs of materials, capital costs of the vineyards and the cost of transporting workers to the vineyards were therefore excluded. For more details on other cost components, see Strub and Loose (2021).

**TABLE 2.** Details of the low-input sites included in the study.

| Site type | Years observed | Grape variety | Planting year | Year of conversion | Low-input system | Row spacing [m] | Yield [hl/ha] |
|---|---|---|---|---|---|---|---|
| 1b | 2017 / 2018 / 2019 | Riesling | 2007 | 2016 | SMPH | 2.0 | 68 - 80 |
| 1b | 2018 / 2019 | Riesling | 1985 | 2008 | SMPH | 2.0 | 110 |
| 1b | 2017 | Müller-Thurgau | 1989 | 2015 / 2010 | SMPH | 2.0 | 95 - 111 |
| 2b | 2018 / 2019 | Pinot Noir | 1978 | 2016 | SMPH | 1.8 | 106 |
| 2d | 2018 | Riesling | 1976 | 2007 | MP | 3.2 | 111 |

None of the sites were irrigated, nor is irrigation planned; all sites were used for the production of basic wines.
SMPH = semi-minimal pruned hedge; MP = minimal pruning. (Site types modified based on Strub *et al.*, 2021).

  

**TABLE 3.** Viticultural processes – number of observations per vineyard site type (1a to 2d).

| Code | Process | Site types | | | | | | N Total |
|---|---|---|---|---|---|---|---|---|
| | | 1a | 1b | 2a | 2b | 2c | 2d | |
| | | VSP SH | LI (SMPH) SH | VSP unsupp SSH | LI (SMPH) unsupp SSH | VSP Rope | LI (MP) Rope | |
| | n | 14 | 6 | 5 | 2 | 8 | 1 | 36 |
| 100 | Winter pruning | 14 | 5 | 5 | - | 8 | - | 32 |
| 200 | Tying | 14 | - | 5 | - | 8 | - | 27 |
| 300 | Shoot thinning | 13 | - | 5 | - | 6 | - | 24 |
| 400 | Lowering the wires | 3 | - | 1 | - | - | - | 4 |
| 500 | Shoot positioning | 14 | - | 5 | - | 8 | - | 27 |
| 600 | Trimming | 14 | 5 | 5 | 2 | 8 | 1 | 35 |
| 700 | Defoliation | 12 | - | 4 | - | 6 | - | 22 |
| 800 | Yield regulation | 3 | 3 | 2 | 2 | - | - | 10 |
| 900 | Harvesting | 14 | 6 | 5 | 2 | 8 | 1 | 36 |
| 1000 | Pest control | 14 | 6 | 5 | 2 | 8 | 1 | 36 |
| 1300 | Cultivation | 12 | 5 | 5 | 2 | 8 | 1 | 33 |
| 1400 | Cover crop management | 13 | 5 | 5 | 2 | 6 | 1 | 32 |
| 1500+ | Weed removal | 14 | 6 | 5 | 2 | 8 | 1 | 36 |

VSP = vertical shoot positioning; SH = standard harvester; LI = low-input system; SMPH = semi-minimal pruned hedge; MP = minimal pruning; SSH = steep slope harvester. (Site types modified based on Strub *et al*., 2021).

### 5. Statistical analysis to determine cost effects of low-input and VSP training (RQ 1+2)

The dataset contained related observations from five wine estates across three vintages. To account for this interrelatedness, univariate analysis of variance with fixed and random effects was conducted for flat terrain site types 1a and 1b, for which sufficient observations were available. *Site type* served as a fixed effect, while *Year* and *Estate* served as random effects. A series of univariate models of variance with fixed and random effects were estimated in SPSS for relevant process steps to test whether the dependent variables, total viticultural cost and process-related costs, differed significantly between site types. The limited observations for steep slope sites types 2a to 2d did not provide sufficient degrees of freedom, and therefore only a descriptive analysis was conducted in these cases.

### 6. The effect of yield on cost per litre (RQ 3)

The limited observations did not provide sufficient data to empirically model the effect of yield on cost per litre. Therefore, the effect of yield on costs per litre was analysed hypothetically by dividing the total cost per hectare of every site type by plausible yield levels of between 50 hl/ha and 150 hl/ha. It was assumed that process costs do not depend on yield levels. The absolute values in €/L and relative factor multiples were analysed descriptively comparing the site types. Here, a factor of 2 represented a 100 % higher cost per litre. The analysis did not take into account planting density, which is lower for MP sites with wider row spacing.

## RESULTS

### 1. Cost differences between low-input and VSP systems on flat terrain (RQ1)

The results of the statistical analysis for the comparison of type 1a and 1b flat terrain sites are given in Table 4. Columns III to V show the $F$-statistics and significance levels of the univariate model of variance. Columns VI to IX contain the mean values and absolute and percentage differences.

When analysing the cost differences for viticultural processes and the total viticultural costs, the univariate model of variance revealed five strongly significant effects for the fixed factor *Site type*. Low-input (SMPH) training significantly reduced the costs of the *Tying*, *Winter pruning*, *Shoot positioning* and *Defoliation* processes by -80 % to -100 % on average. The high cost reductions of -100 % for *Shoot thinning* and *Lowering the wires* (rarely performed on the sampled VSP sites) were not significant. Similarly, the cost reduction of -82 % for *Yield regulation* was not significant, probably because few cases were conducted on VSP sites. The cost for *Pest control* increased significantly by an average of 146 %. The cost for *Trimming* increased by 158 % for low-input (SMPH) trained sites, although this increase was not statistically significant. Small, insignificant increases in *Cultivation*, *Cover crop management* and *Weed removal* costs of between 26 % and 47 % were identified.

*Total cost* was on average 46 % lower for flat terrain low-input (SMPH) trained sites, although this difference was only marginally significant ($p$ = 0.051). In total, the *Tying, Shoot thinning, Lowering the wires, Shoot positioning* and *Defoliation* processes - which did not have to be performed at low-input trained sites - represented 35 % of the total viticultural cost of VSP sites. Because of mechanisation, the high cost for *Winter pruning* (32 % of the total cost on VSP sites) could be substantially reduced at low-input (SMPH) trained sites by 80 %. The cost savings of 2,860 € for these six processes more than compensated for the higher costs of *Pest control* and *Trimming* (700 €) at low-input (SMPH) trained sites. Further information on the data distribution of the total viticultural cost are provided in Appendix 1 and Appendix 2.

In total, there were seven significant effects for the random factor *Estate*. Of these, the cost variance related to individual viticultural decisions by the wine businesses was highest for *Harvesting, Shoot thinning* and *Cover crop management*.

Only two significant effects for *Cover crop management* and *Yield regulation* could be observed for the random factor *Year*. These were related to strong annual differences in external factors (e.g., precipitation, which was low, with drought risk in 2018) and low yields due to a spring frost event in 2017. Overall, the weak effect of the random factor *Year* suggests that cost estimates are only slightly affected by annual differences.

**TABLE 4.** Univariate model of variance with fixed and random effects and mean values to analyse the cost effect of the training systems for flat terrain sites (site type 1a and 1b).

| I | II | III | | IV | | V | | VI | VII | VIII | IX |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Univariate model of variance | | | | | | Means | | | |
| | Process steps | Site type (F) | | Estate (R) | | Year (R) | | 1a VSP SH | 1b LI (SMPH) SH | Δ absolute 1a vs 1b | Δ relative 1a vs 1b |
| | | $F^+$ | | F | | F | | in €/ha | in €/ha | in €/ha | in % |
| 100 | Winter pruning | 17.9 | **** | 1.2 | | 1.0 | | 1,520 | 307 | -1,213 | -80% |
| 200 | Tying | 25.2 | **** | 1.0 | | 2.9 | * | 271 | 0 | -271 | -100% |
| 300 | Shoot thinning | 0.9 | | 9.1 | **** | 0.4 | | 465 | 0 | -465 | -100% |
| 400 | Lowering the wires | 0.3 | | 0.7 | | 0.6 | | 168 | 0 | -168 | -100% |
| 500 | Shoot positioning | 13.3 | *** | 6.7 | *** | 1.3 | | 622 | 0 | -622 | -100% |
| 600 | Trimming | 2.6 | | 2.6 | * | 1.6 | | 130 | 336 | 206 | 158% |
| 700 | Defoliation | 12.7 | *** | 0.3 | | 0.9 | | 121 | 0 | -121 | -100% |
| 800 | Yield regulation | 0.6 | | 3.4 | ** | 3.9 | ** | 501 | 88 | -413 | -82% |
| 900 | Harvesting | 2.1 | | 10.8 | **** | 1.1 | | 608 | 428 | -180 | -30% |
| 1000 | Pest control | 37.8 | **** | 4.3 | ** | 1.0 | | 338 | 832 | 494 | 146% |
| 1300 | Cultivation | 2.5 | | 6.4 | *** | 2.2 | | 159 | 233 | 74 | 47% |
| 1400 | Cover crop management | 1.1 | | 8.4 | *** | 5.0 | ** | 163 | 206 | 43 | 26% |
| 1500+ | Weed removal | 1.5 | | 0.2 | | 0.0 | | 264 | 358 | 94 | 36% |
| | Total cost | 4.7 | * | 4.8 | ** | 0.7 | | 4,720 | 2,559 | -2,161 | -46% |

F = fixed effects; R = random effects; LI = low-input system; SMPH = semi-minimal pruned hedge; SH = standard harvester; VSP = vertical shoot positioning; Columns C–E: univariate model of variance with fixed effect (Site type) and random effects (Estate, Year); Columns F–I: mean values for dependent variable 'total cost per process step' per site type; **** $p \leq 0.001$; *** $p \leq 0.01$; ** $p \leq 0.05$; * $p \leq 0.1$. (Site types modified based on Strub *et al.*, 2021).

  

### 2. Cost differences between low-input and VSP systems on steep slopes (RQ2)

Because of the limited number of observations, only descriptive average cost values could be analysed for steep slope sites. Differences in the impact of *Estate* and *Year* could not be separated, and therefore the analysis could only provide explorative results. The results for the type 2d site should be interpreted with caution, as they were based on a single MP observation.

Generally, cost differences similar to those of flat terrain sites can be observed for steep slope sites (Table 5). The six process steps that are not required for low-input trained sites result in a similarly strong cost reduction of 34 % (type 2b) and 46 % (type 2d). The absolute cost savings from low-input MP training were higher for type 2d, where limited mechanisation requires rope support. Similar to flat terrain sites, *Winter pruning* was the process demonstrating the highest absolute cost savings. Also similar to flat terrain sites, the costs for *Pest control* and *Trimming* increased for type 2b low-input trained sites, although not as much. Aside from flat terrain sites, the costs for *Cultivation, Cover crop management* and *Weed removal* decreased slightly for type 2b low-input training, which could be related to *Estate* and *Year* effects.

The single MP observation for type 2d is different from all other types, as low-input training reduced the costs for *Pest control* and *Trimming* compared to VSP. This reduction could be related to MP training and the wider row spacing of 3 m on the type 2d site versus 2 m on the type 2c site, which leads to a significantly lower number of vines per hectare and hence reduces the distance covered when carrying out vineyard management. In addition, the absolute cost values for type 2d differed from those for type 2b, with *Pest control* being less expensive and *Cultivation, Cover crop management* and *Weed removal* being more expensive. The reduction in the cost of *Pest control* could be related to the annual effect of low precipitation, while cost increases in the latter three can be clearly attributed to the higher machine cost for rope-supported systems (Strub and Loose, 2021). The single available observation for type 2d MP training resulted in a similar total cost to type 2b (5,137 € versus 4,944 €). The observations available here, albeit limited, suggest that a change from VSP to low-input systems can reduce the total cost of limited mechanisation on steep slope sites to an amount similar to the absolute cost of flat terrain VSP sites (4,720 €/ha in Table 4).

### 3. Influence of yield level on cost per litre (RQ3)

The analysis of the effect of yield on cost per litre took into account the generally higher yield of low-input trained sites compared to VSP sites which was mainly due to the higher number of buds. Table 6 provides cost per litre for the six site types analysed for a yield range between 50 hl/ha and 150 hl/ha. Cost per litre decreased with higher yield when the total viticultural cost was assumed to be independent of yield. In the selected yield range, the total cost was reduced from the maximum value of 1.90 €/L for type 2c to 0.17 €/L for type 1b.

Table 6 and Figure 1 show the effect of low-input training on cost per litre. The average German yield of 90 hl/ha (Federal Statistical Office Germany, 2015-2019) resulted in a total cost of 0.52 €/L for the most common site, type 1a (VSP with SH). At this average German yield level, compared to standard type 1a, the cost per litre for low-input trained sites was 46 % lower for the flat terrain site (type 1b) and only 5 % and 9 % higher for steep slope types 2b and 2d respectively. At a constant yield, this cost per litre difference is identical to the cost per hectare difference. If yields at steep slope low-input trained sites were to be increased slightly to 100 hl/ha cost per litre would be similar to that of the flat terrain VSP. Further increases in yield will reduce the cost per litre accordingly. For VSP at steep slope sites, a similar cost reduction can only be achieved by substantial yield increases to 140 hl/ha (type 2a) and 190 hl/ha (type 2c), which, however, will almost certainly have a negative effect on quality.

The y-axis indicates the factor multiple, by which cost increases compared to the reference value of 0.52 €/L. For instance, with a factor of 2.02 at the reference yield the costs of the VSP rope-supported steep slope site are almost double. Two effects become obvious from Figure 1: first, introducing low-input training on flat terrain can provide a significant cost savings potential indicated by the distinctly lower per litre cost curve. Second, both dotted steep slope low-input curves (type 2b and 2d) are very close to the common flat terrain VSP (type 1a) curve, supporting the notion that a change in the viticultural system can overcome steep slope cost disadvantages. The cost curves for traditional VSP systems on steep slopes are clearly

**TABLE 5.** Mean values and percentage differences for all processes for low-input training and VSP steep slope sites with limited mechanisation.

| I | II | III | IV | V | VI | VII | VIII | IX | X |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean values | | Δ absolute 2a vs 2b | Δ % 2c vs 2a | Mean values | | Δ absolute 2c vs 2d | Δ % 2d vs 2b |
| | | 2a | 2b | | | 2c | 2d | | |
| | | VSP unsupp SSH | LI (SMPH) unsupp SSH | | | VSP Rope | LI (MP) Rope | | |
| Code | Process step | cost/ha in € | | in € | | cost/ha in € | | in € | |
| 100 | Winter pruning | 1,858 | 0 | -1,858 | -100% | 1,951 | 0 | -1,951 | -100% |
| 200 | Tying | 289 | 0 | -289 | -100% | 353 | 0 | -353 | -100% |
| 300 | Shoot thinning | 326 | 0 | -326 | -100% | 206 | 0 | -206 | -100% |
| 400 | Lowering the wires | 168 | 0 | -168 | -100% | 0 | 0 | 0 | 0% |
| 500 | Shoot positioning | 389 | 0 | -389 | -100% | 609 | 0 | -609 | -100% |
| 600 | Trimming | 258 | 414 | 156 | 60% | 734 | 661 | -73 | -10% |
| 700 | Defoliation | 343 | 0 | -343 | -100% | 474 | 0 | -474 | -100% |
| 800 | Yield regulation | 454 | 103 | -351 | -77% | 0 | 0 | 0 | 0% |
| 900 | Harvesting | 2,250 | 2,250 | 0 | 0% | 2,250 | 2,250 | 0 | 0% |
| 1000 | Pest control | 1,069 | 1,803 | 734 | 69% | 1,683 | 706 | -977 | -58% |
| 1300 | Cultivation | 152 | 85 | -67 | -44% | 506 | 673 | 167 | 33% |
| 1400 | Cover crop management | 161 | 123 | -38 | -24% | 407 | 526 | 119 | 29% |
| 1500+ | Weed removal | 203 | 167 | -36 | -18% | 617 | 321 | -296 | -48% |
| | Total cost [€/ha] | 7,446 | 4,944 | -2,502 | -34% | 9,519 | 5,137 | -4,382 | -46% |

VSP = vertical shoot positioning; unsupp = unsupported; SSH = steep slope harvester; LI = low-input system; SMPH = semi-minmal pruned hedge; MP = minimal pruning. Cost for harvesting is based on contractor invoicing and is therefore identical across all four site types. (Site types modified based on Strub *et al*., 2021).

above and only cut the horizontal 1.0-cost factor-line at very high yields.

## DISCUSSION

This paper provides the initial results of a field study on the effects of low-input training systems on viticultural costs of individual processes and the total viticultural costs of both flat terrain and limited mechanisation steep slope sites. These findings thereby contribute to identifying options for increasing the economic sustainability of the wine industry (Corbo *et al.*, 2014; Falcone *et al.*, 2015; Martins *et al.*, 2018; Pannell and Glenn, 2000).

### 1. Cost advantage of low-input training on flat terrain sites

Total viticultural costs can be reduced by using low-input training systems without further investment just based on savings made in certain management processes, such as *Tying, Shoot thinning, Lowering the wires, Shoot positioning and defoliation*, as well as by implementing the full mechanisation of otherwise labour-intensive process steps, such as *Winter pruning*. For flat terrain sites, low-input SMPH training can result in average cost savings of 2,161 €/ha or 46 % of the total cost.

The labour and machine costs of the pest control and trimming processes consistently increased for low-input SMPH training, although only significantly for pest control. While thus far not reported elsewhere in the literature, this effect could be related to slower-paced machinery operating in larger and unordered canopies. To verify this, however, further research is required. In this study, differences in material costs, such as pesticide cost, were not taken into account. Due to the larger canopy, it is likely that a higher amount of pesticides for MP training would

**TABLE 6.** Per litre costs in €/Litre for the different site types at yield levels between 50 hl/ha and 150 hl/ha.

| | 1a VSP SH | 1b LI (SMPH) SH | 2a VSP unsupp SSH | 2b LI (SMPH) unsupp SSH | 2c VSP Rope | 2d LI (MP) Rope |
|---|---|---|---|---|---|---|
| Total cost per ha | 4,720 € | 2,559 € | 7,446 € | 4,944 € | 9,519 € | 5,137 € |
| Yield | | | | | | |
| 50 hl/ha | 0.94 | 0.51 | 1.49 | 0.99 | 1.90 | 1.03 |
| 60 hl/ha | 0.79 | 0.43 | 1.24 | 0.82 | 1.59 | 0.86 |
| 70 hl/ha | 0.67 | 0.37 | 1.06 | 0.71 | 1.36 | 0.73 |
| 80 hl/ha | 0.59 | 0.32 | 0.93 | 0.62 | 1.19 | 0.64 |
| 90 hl/ha | 0.52 | 0.28 | 0.83 | 0.55 | 1.06 | 0.57 |
| 100 hl/ha | 0.47 | 0.26 | 0.74 | 0.49 | 0.95 | 0.51 |
| 110 hl/ha | 0.43 | 0.23 | 0.68 | 0.45 | 0.87 | 0.47 |
| 120 hl/ha | 0.39 | 0.21 | 0.62 | 0.41 | 0.79 | 0.43 |
| 130 hl/ha | 0.36 | 0.20 | 0.57 | 0.38 | 0.73 | 0.40 |
| 140 hl/ha | 0.34 | 0.18 | 0.53 | 0.35 | 0.68 | 0.37 |
| 150 hl/ha | 0.31 | 0.17 | 0.50 | 0.33 | 0.63 | 0.34 |

VSP = vertical shoot positioning; SH = standard harvester; LI = low-input system; SMPH = semi-minimal pruned hedge; MP = minimal pruning; SSH = steep slope harvester; grey shaded areas indicate yield levels for which the cost of site types are close to identical to the reference type 1a VSP SH (0.52 €/Litre). (Site types modified based on Strub *et al*., 2021).

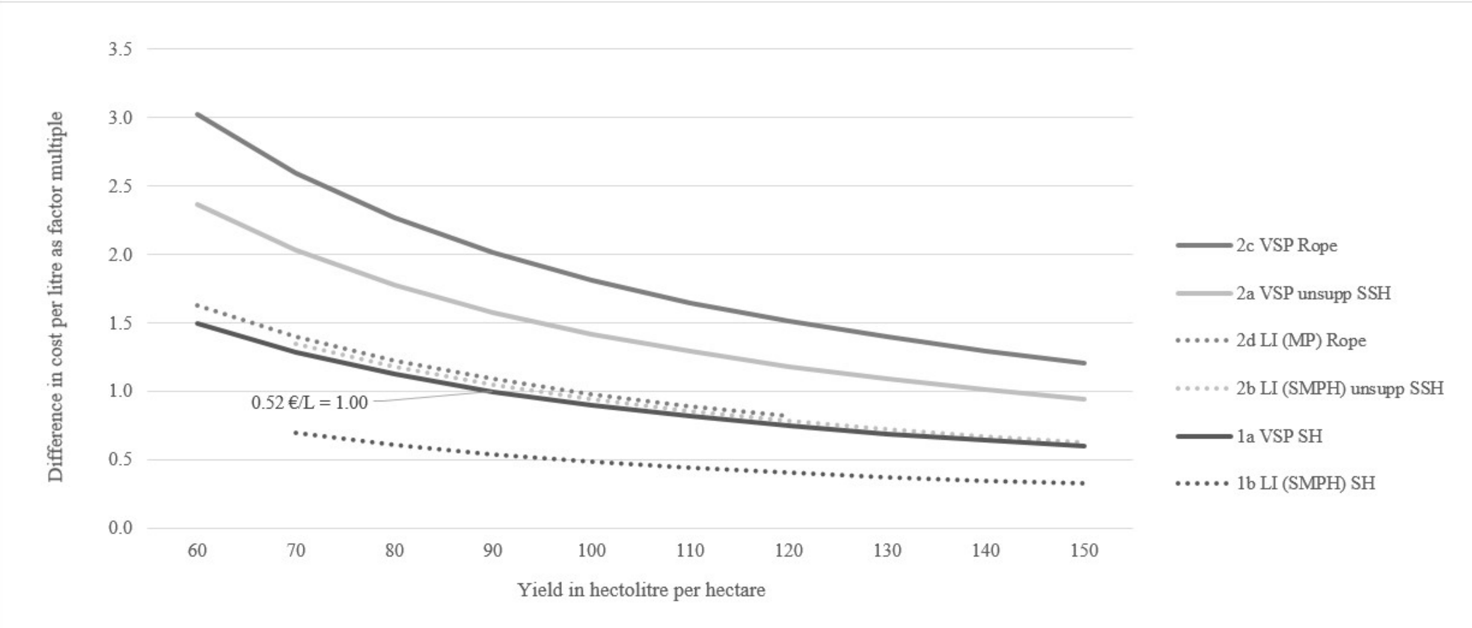


**FIGURE 1.** Per litre cost differences per site type at different yield levels expressed as a factor multiple (1.0 cost equal type 1a).

VSP = Vertical shoot positioning; unsupp = unsupported; SSH = steep slope harvester; LI = low-input system; MP = minimal pruning; SMPH = semi-minimal pruned hedge; site types used (1a to 2d). (Site types modified based on Strub *et al*., 2021).

be required, which could further increase costs for pest control. The sample was dominated by older, less vigorous vineyards, which might explain why only a half of them required yield regulation. The limited availability of water in 2018 and 2019 due to drought, coupled with the inability to irrigate these sites, might also explain why less than expected yield regulation was conducted. The total viticultural cost might be slightly higher when extensive yield regulation is required directly after conversion to low-input training (Molitor, 2010; Schultz *et al*., 2000; Weyand and Schultz, 2006).

The cost of labour for converting sites from an existing training system to an MP system (about 627 €, less for conversion to SMPH) must be added for new conversions. This cost, however, is more than compensated for by the cost reduction achieved during the first year post-conversion.

The large number of significant *Estate* effects suggests that further research is required to better understand the complexity of the influencing parameters. On the one hand, differences in vineyard management between the estates could be related to external viticultural factors (Bramley, 2010; Bramley and Hamilton, 2004), such as differences in soil conditions, differences in precipitation (van Leeuwen *et al.*, 2016), differences in the age of the vineyards, and differences in site topography (e.g., longer or shorter rows impacting processing or distances covered during site management); on the other hand, the observed variance could be related to internal factors within the estates, such as management decisions (Mesiti and Vanclay, 2006), personnel management, risk aversion and the estate's philosophy in terms of product quality (Mota *et al.*, 2021; Sharp, 1991). More information about the impact of these factors could help wine estates to correctly benchmark their viticultural costs and improve their economic performance.

**2. Cost advantage of low-input training on steep slopes**

The limited number of observations only permitted an exploratory descriptive analysis of the total cost for mechanisable steep slope low-input trained sites. The overall findings largely agree with those for flat terrain sites. Total cost could be reduced to a similar extent by about 34 % (SMPH) to 46 % (MP), and thus result in absolute cost values similar to those of flat terrain VSP systems (type 1a). The preliminary findings suggest that a change in the viticultural training system can overcome a major share of the cost disadvantage of mechanisable steep slopes. While mechanisation on its own cannot – at least thus far – sufficiently improve the economic sustainability of steep slopes (Strub and Loose, 2021), the conversion to low-input training could further reduce manual labour and expensive machine time of specialised steep slope equipment. Further research is required to substantiate these preliminary findings.

**3. Cost effects of higher yield**

Low-input trained sites generally result in higher yields (Intrieri *et al.*, 2011; Molitor *et al.*, 2019; Schultz *et al.*, 2000; Zheng *et al.*, 2017) that reduce the per litre cost of wine. This represents a second cost-saving factor besides the generally lower absolute viticultural cost of low-input trained sites. The advantage of higher yields and lower total cost are of particular interest for market entry to medium-level producers, as well as bulk wine producers that represent a substantial share of the wine market (Loose and Pabst, 2018). Wine estates have to determine optimal yield levels by designating their vineyards to certain wine profile targets (Mora, 2006; Spawton, 1990). For steep slope wine growers, the cost effect of higher yields may provide a second important opportunity to reduce cost disadvantages compared to common VSP flat terrain sites, if the availability of water is sufficient. The analysis did not include the effect of different planting densities, which differ between low imput systems SMPH and MP.

**4. Outlook**

The findings of this study are related to current wine market conditions *ceteris paribus* that are unaffected by decisions made by individual wine growers. That said, it should be noted that overall market prices will fall, if many or all producers convert to low-input training and produce higher yields at lower cost. This would further escalate the global oversupply of wine (Loose and Nelgen, 2021). In the end, production costs are lowest on warm, flat terrain sites that can be easily irrigated and for which low-input training is suitable, cementing their advantage in terms of viticultural cost efficiency (Archer and van Schalkwyk, 2007; Clingeleffer *et al.*, 2005). Economic history shows that producers can only temporarily benefit from innovations like low-input training systems, as any advantages are eventually offset by their wider adoption (van der Veen, 2010).

The current analysis was limited to monetary costs; it did not consider potential positive and negative external effects. True cost accounting (Falcone *et al.*, 2015) that also prices external effects, such as the full cost of water usage and irrigation, biodiversity, pesticide use and soil carbonisation, as well as the benefits for biodiveristy and tourism from steep slopes (Cox and Underwood, 2011; Job and Murphy, 2006; Tafel and Szolnoki, 2020) would be required to make a cost-efficient decision for society at large. Irrigation costs were not included in this study because the analysed sites were not irrigated. Fungus-resistant grape varieties (i.e., progressive vines; so called PiWi), would not only reduce pesticide use, but would also further decrease viticultural costs by reducing the pest management process and improve the overall sustainable developmental goals (Loose and Remaud, 2013; Pomarici and Vecchio, 2019).

Climate change could both favour or penalise the wide adoption of low-input training systems. Due to its capacity for delaying maturation, low-input training has been identified as a possible strategy for reducing the velocity of ripening processes caused by climate change (Molitor *et al.*, 2019; Zheng *et al.*, 2017). The higher demand for water (Schultz *et al.*, 2000) in MP trained systems can be problematic in many wine-growing regions in which precipitation patterns frequently change, thereby necessitating irrigation to sustain viticulture in these areas (Costa *et al.*, 2019). The breeding and adoption of drought-resistant rootstocks may be one possible medium- to long-term solution to this problem (Duchene, 2016; Cornelis van Leeuwen and Destrac-Irvine, 2017).

### 5. Limitations and future research

Even though the data for this study were limited to Germany, field data were obtained from five different growing regions. However, the number of observations for low-input trained steep slope sites did not allow for a robust statistical inferential analysis. Because of data limitations the cost differences between SMPH and MP low-input training could not be sufficiently separated for the different site types. More data must be collected to better differentiate both systems, to generate more precise cost estimates for steep slope sites and to empirically validate the effect of yield on cost with actual yield observations, thereby also taking into account the planting density. Whilst SMPH and VSP have the same planting density, it is reduced by approximately 25 % in MP compared to the other training systems. In the future, digital SmartFarming software, such as Vineyard Cloud®, will likely provide more extensive datasets with features to better organise work tasks. Furthermore, the cost analysis should be extended to other wine-growing regions and growing conditions. The effect of water availability, as well as vine water status, on resulting wine quality and yield should ideally be included in the analysis to better understand the limitations and constraints of low-input systems.

## CONCLUSION

This study showed that low-input training systems increase the degree of mechanisation in viticulture and reduce production costs, even in cool to moderate climates such as Germany. The adoption of low-input systems could constitute an important contribution to improving the economic sustainability of growers for the substantial market volume of entry- and medium-level wines, as well as steep slope sites.

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## REFERENCES

AGV Hessen e.V., & IG BAU. (2010). General collective agreement for viticulture in Hesse (in German). Germany.

Archer, E., & van Schalkwyk, D. (2007). The Effect of Alternative Pruning Methods on the Viticultural and Oenological Performance of Some Wine Grape Varieties. *South African Journal of Enology and Viticulture*, 28(2), 107–132. https://doi.org/10.21548/28-2-1466

Bates, T., & Morris, J. (2009). Mechanical Cane Pruning and Crop Adjustment Decreases Labor Costs and Maintains Fruit Quality in New York 'Concord' Grape Production. *HortTechnology*, 19(2), 247–253. https://doi.org/10.21273/HORTSCI.19.2.24

Becker, A., & Dietrich, J. (2017). Viticulture and Enology: Data for operational planning (16th revised edition). KTBL data compilation (in German). Board of Trustees for Technology and Construction in Agriculture e.V. (KTBL).

Botelho, M., Cruz, A., Silva, E. B., Mexia, A., Ricardo-da-Silva, J., Castro, R., & Ribeiro, H. (2020). Mechanical pruning in non-irrigated vineyards: effects on yield and grape composition of cultivar 'Syrah' (*Vitis vinifera* L.). *Acta Horticulturae* (1276), 125–130. https://doi.org/10.17660/ActaHortic.2020.1276.18

Bramley, R., & Hamilton, R. P. (2004). Understanding variability in winegrape production systems. *Australian Journal of Grape and Wine Research*, 10(1), 32–45. https://doi.org/10.1111/j.1755-0238.2004.tb00006.x

Bramley, R. (2010). Precision Viticulture: Managing vineyard variability for improved quality outcomes. In A. G. Reynolds (Ed.), *Managing wine quality: v. 1. Viticulture and wine quality*, 445–480. Woodhead Pub. Ltd. https://doi.org/10.1533/9781845699284.3.445

Capitello, R., Agnoli, L., & Begalli, D. (2015). Chinese import demand for wine: evidence from econometric estimations. *Journal of Wine Research*, 26(2), 115–135. https://doi.org/10.1080/09571264.2015.1014547

  

Clingeleffer, P. R., Petrie, P. R., & Ashley, R. M. (2005). Suitability of minimal pruning and other low-input systems for warm and cool climate grape production. In GiESCO (Ed.), *XIV International GiESCO Viticulture Congress: 23-27 August, 2005, Geisenheim, Germany* (pp. 2–9).

Corbo, C., Lamastra, L., & Capri, E. (2014). From Environmental to Sustainability Programs: A Review of Sustainability Initiatives in the Italian Wine Sector. *Sustainability*, 6(4), 2133–2159. https://doi.org/10.3390/su6042133

Costa, R., Fraga, H., Fonseca, A., García de Cortázar-Atauri, I., Val, M. C., Carlos, C., Reis, S., & Santos, J. A. (2019). Grapevine Phenology of cv. Touriga Franca and Touriga Nacional in the Douro Wine Region: Modelling and Climate Change Projections. *Agronomy*, 9(4), 210. https://doi.org/10.3390/agronomy9040210

Couderc, J.P., & Marchini, A. (2011). Governance, commercial strategies and performances of wine cooperatives. *International Journal of Wine Business Research*, 23(3), 235–257. https://doi.org/10.1108/17511061111163069

Cox, R. L., & Underwood, E. C. (2011). The importance of conserving biodiversity outside of protected areas in mediterranean ecosystems. *PloS One*, 6(1), e14508. https://doi.org/10.1371/journal.pone.0014508

Deloire, A., Carbonneau, A., López, F., Suarez, S., Pérez, C., Domergue, P., & Samson, A. (2016). Interaction «training system x vigour» on Merlot. Comparison between vertical trellis and minimal pruning. First results. *OENO One*, 38(1), 59. https://doi.org/10.20870/oeno-one.2004.38.1.933

DLR Rheinpfalz, Research Institute Geisenheim. (2011). Minimal pruning - List of suitable varieties DLR Rheinpfalz and Research Institute Geisenheim (in German). http://www.wetter-bw.de/Internet/global/themen.nsf/ALL/A5B577F545B29AC1C12573E1002AEB5F/$FILE/Sorteneignung_bei_Minimalschnitt.pdf.

Duchene, E. (2016). How can grapevine genetics contribute to the adaptation to climate change? *OENO One*, 50(3). https://doi.org/10.20870/oeno-one.2016.50.3.98

Falcone, G., Strano, A., Stillitano, T., De Luca, A. I., Iofrida, N., & Gulisano, G. (2015). Integrated sustainability appraisal of wine-growing management systems through lca and lcc methodologies. *Chemical Engineering Transactions*, 44, 223–228. https://doi.org/10.3303/CET1544038

Federal Ministry of Labour and Social Affairs Germany. (2019). Minimum wage (in German). https://www.bmas.de/DE/Themen/Arbeitsrecht/Mindestlohn/mindestlohn.html

Federal Statistical Office Germany. (2015-2019). Agriculture, Forestry and Fishery - Growth and Yield - wine must - 2014-2018 (Technical series 3 sequence 3.2.1). Germany.

Grečenko, A. (1984). Operation on steep slopes: State-of-the-art report. *Journal of Terramechanics*, 21(2), 181–194. https://doi.org/10.1016/0022-4898(84)90020-X

Hofmann, M., & Schultz, H. R. (2015). Modeling the water balance of sloped vineyards under various climate change scenarios. *BIO Web of Conferences*, 5, 1026. https://doi.org/10.1051/bioconf/20150501026

Intrieri, C., Filippetti, I., Allegro, G., Valentini, G., Pastore, C., & Colucci, E. (2011). The Semi-Minimal-Pruned Hedge: A Novel Mechanized Grapevine Training System. *American Journal of Enology and Viticulture*, 62(3), 312–318. https://doi.org/10.5344/ajev.2011.10083

Job, H., & Murphy, A. (2006). Germany's Mosel Valley: Can Tourism Help Preserve Its Cultural Heritage? *Tourism Review International*, 9(4), 333–347. https://doi.org/10.3727/154427206776330526

Loose, S. M., & Nelgen, S. (2021). State of the German and International Wine Markets. *German Journal of Agricultural Economics*, 70(5), 87-102. https://doi.org/10.30430/70.2021.5.87-102

Loose, S. M., & Pabst, E. (2018). Current State of the German and International Wine Markets. *German Journal of Agricultural Economics*, 67(Supplement), 92–101.

Loose, S. M., & Remaud, H. (2013). Impact of corporate social responsibility claims on consumer food choice. *British Food Journal*, 115(1), 142–166. https://doi.org/10.1108/00070701311289920

Loose, S. M., Strub, L., & Kurth, A. (2021). Economic sustainability of wine estates: First insights and a roadmap for future research. *12th* Conference of the Academy of Wine Business Research*, Dijon*.

Martins, A. A., Araújo, A. R., Graça, A., Caetano, N. S., & Mata, T. M. (2018). Towards sustainable wine: Comparison of two Portuguese wines. *Journal of Cleaner Production*, 183, 662–676. https://doi.org/10.1016/j.jclepro.2018.02.057

Mesiti, L., & Vanclay, F. (2006). Specifying the farming styles in viticulture. *Australian Journal of Experimental Agriculture*, 46(4), 585. https://doi.org/10.1071/EA05103

Molitor, D. (2010). Minimal pruning - Tipps for the conversion (in German). *Das Deutsche Weinmagazin,* (9), 18-19.

Molitor, D., & Junk, J. (2019). Climate change is implicating a two-fold impact on air temperature increase in the ripening period under the conditions of the Luxembourgish grapegrowing region. *OENO One*, 53(3). https://doi.org/10.20870/oeno-one.2019.53.3.2329

Molitor, D., Schultz, M., Mannes, R., Pallez-Barthel, M., Hoffmann, L., & Beyer, M. (2019). Semi-Minimal Pruned Hedge: A Potential Climate Change Adaptation Strategy in Viticulture. *Agronomy*, 9(4), 173. https://doi.org/10.3390/AGRONOMY9040173

Mora, P. (2006). Key factors of success in today's wine sector. *International Journal of Wine Marketing*, 18(2), 139–149. https://doi.org/10.1108/09547540610681112

Mota, J., Moreira, A., Costa, R, Serrão, S., Pais-Magalhães, V., & Costa, C. (2021). Performance indicators to support firm-level decision-making in the wine industry: a systematic literature review. *International Journal of Wine Business Research*, 33(2), 217-237. https://doi.org/10.1108/IJWBR-06-2020-0027

Müller, E., Schulze, G., & Walg, O. (2000). Pocketbook of viticulture (11.th ed.). (in German). Fraund Publishing House.

ÖKL (2020). ÖKL standard values for machines for fruit and wine growing (in German). Austrian Board of Trustees for Agricultural Engineering and Rural Development. https://oekl.at/gruppe/maschinen-fur-den-garten-obst-und-weinbau/

Pannell, D. J., & Glenn, N. A. (2000). A framework for the economic evaluation and selection of sustainability indicators in agriculture. *Ecological Economics*, 33(1), 135–149. https://doi.org/10.1016/S0921-8009(99)00134-2

Pomarici, E., & Vecchio, R. (2019). Will sustainability shape the future wine market? *Wine Economics and Policy*, 8(1), 1–4. https://doi.org/10.1016/j.wep.2019.05.001

Schreieck, P. (2016). Viticulture in terraced steep slopes (in German). *Landinfo,* (1), 11–15.

Schultz, H. R., Kraml, S., Werwitzke, U., Zimmer, T., & Schmid, J. (2000). Adaptation and Utilization of Minimal Pruning Systems for Quality Production in Cool Climates. *American Journal of Enology and Viticulture*, 51(5), 185–190.

Sharp, B. (1991). Marketing Orientation: More than Just Customer Focus. *International Marketing Review*, 8(4). https://doi.org/10.1108/EUM0000000001540

Spawton, T. (1990). Marketing Planning for Wine. *International Journal of Wine Marketing*, 2(2), 2–49. https://doi.org/10.1108/eb008580

Strub, L., Kurth, A., & Loose, S. M. (2019). Added value pays off (in German). *Rebe and Wein,* (01), 40-42.

Strub, L., Kurth, A., & Loose, S. M. (2021). The effects of viticultural mechanization on working time requirements and production costs. *American Journal of Enology and Viticulture*, 72(1), 46-55. https://doi.org/10.5344/ajev.2020.20027

Strub, L., & Loose, S. M. (2021). The cost disadvantage of steep slope viticulture and strategies for its preservation. *OENO One,* 55(1), 49–68. https://doi.org/10.20870/oeno-one.2021.55.1.4494

Tafel, M., & Szolnoki, G. (2020). Estimating the economic impact of tourism in German wine regions. *International Journal of Tourism Research,* 22(6), 788–799. https://doi.org/10.1002/jtr.2380

van der Veen, M. (2010). Agricultural innovation: invention and adoption or change and adaptation? *World Archaeology*, 42(1), 1–12. http://www.jstor.org/stable/25679724

van Leeuwen, C., & Destrac-Irvine, A. (2017). Modified grape composition under climate change conditions requires adaptations in the vineyard. *OENO One*, 51(2), 147–154. https://doi.org/10.20870/oeno-one.2017.51.2.1647

van Leeuwen, C., Trégoat, O., Choné, X., Bois, B., Pernet, D., & Gaudillère, J.P. (2016). Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes? *OENO One*, 43(3), 121. https://doi.org/10.20870/oeno-one.2009.43.3.798

Walg, O. (2007). Pocketbook of viticulture technology (2nd edition) (in German). Fraund Publishing House.

Walg, O. (2013). Minimal pruning in trellis - problems in practical viticulture (in German). *Landwirtschaftliches Wochenblatt,* (26), 37–40.

Walg, O. (2016a). Kobold, Vine Stripper, and Co.: Mechanisation of pruning - Cane strippers, part 3 (in German). *Das Deutsche Weinmagazin,* (1), 14–19.

Walg, O. (2016b). Tips for the use of cane strippers (in German). *Der Deutsche Weinbau,* (3), 20–23.

Weber, D., Rudy, H., & Porten, M. (2020). Cleanly sorted (in German). *Der Deutsche Weinbau,* (22), 20–23.

Weyand, K. M., & Schultz, H. R. (2006). Regulating yield and wine quality of minimal pruning systems through the application of gibberellic acid. *J. Int. Sci. Vigne Vin*, 40(3), 151–163. https://doi.org/10.20870/oeno-one.2006.40.3.871

Yisa, M. G., Terao, H., Noguchi, N., & Kubota, M. (1998). Stability criteria for tractor-implement operation on slopes. *Journal of Terramechanics*, 35(1), 1–19. https://doi.org/10.1016/S0022-4898(98)00008-1

Zheng, W., del Galdo, V., García, J., Balda, P., & Martínez de Toda, F. (2017). Use of Minimal Pruning to Delay Fruit Maturity and Improve Berry Composition under Climate Change. *American Journal of Enology and Viticulture*, 68(1), 136–140. https://doi.org/10.5344/ajev.2016.16038.