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## **Cost Efficiency and Sustainability of Steep Slope Viticulture**

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## **Declaration of Originality**

I declare that I have prepared the submitted thesis independently and without unauthorised third-party help and that no data other than that available in thesis-listed facilities have been used. All text passages that are quoted literally or analogously from other published papers, and all information that is based on verbal statements, are identified as such.

I observed the principles of safeguarding good scientific practice as defined in the statutes of Hochschule Geisenheim University and Justus-Liebig-University Gießen when carrying out the analyses of my research as detailed in this thesis.

Geisenheim, March 2021

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Larissa Sylva Michaela Strub

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## Summary

The first viticultural plantations in Europe were established on sloping terrain to take advantage of their good microclimatic conditions. In recent decades, however, a significant decrease in vineyard acreage on steep slopes has occurred, particularly in Germany. The elevated labour demand at these sites together with stronger international competition and the overall diminished profitability of the sites for wine estates have been implicated as drivers behind this decrease. However, a sound cost assessment of different vineyard setups in terms of general growing conditions and corresponding mechanisation options has thus far not been performed.

This doctoral thesis contributes to explaining the abandonment of steep slope vineyard sites from an economic perspective using the example of Germany. To enable a substantiated cost assessment, a transparent framework of viticultural site types was developed. Using this framework, working time records were collected at five management-led wine estates in Germany over three years for 30 reference sites, resulting in 82 observations and over 3,400 single records for labour and machine hours. After valuing the working time records with appropriate cost rates, the cost dataset was analysed using analysis of variance (ANOVA) with fixed and random effects to estimate the influence of different external factors on the structure of viticultural costs.

The analysis revealed that three types of external factors significantly influence the cost of viticultural management. These factors are the slope of and access to vineyard sites, the orientation of rows towards the slope, and the training system. The cost differences between the vineyard site types are attributable to differences in mechanisation intensity and the types of machines used. While flat terrain allows the mechanisation of most viticultural processes with very efficient machinery, such as standard narrow-track tractors and standard grape harvesters, sites with limited mechanisation require specialised machinery, such as crawler tractors and steep slope harvesters (SSHs), to overcome the gradient. The sites with the most difficult conditions inhibit the mechanisation of single or all processes. The more mechanisation is limited, the higher the demand for manual labour will be. In addition to this, specialised steep slope machinery usually entails higher capital costs and operates more slowly, mostly due to additional securing by rope, necessitating the double passing of every row.

The cost disadvantage of sites with limited mechanisation compared to fully mechanised sites ranges from 2,748 €/ha to 7,713 €/ha, depending on the degree of limitation. In addition to these per hectare disadvantages, vineyards planted on slopes are more often affected by water scarcity, which has intensified in recent years and is expected to further intensify due to the impacts of climate change.

Water scarcity causes drought issues that lead, among other negative effects, to below-average yield levels, thereby exacerbating the cost disadvantage of steep slope sites on a per litre level.

Certain viticultural practices can help to decrease viticultural costs at sites with limited mechanisation. The construction of transversal terraces to replace vertically planted vineyards can result in a cost reduction of 3,595 €/ha for crawler-operated steep slope vineyards and 6,093 €/ha for manual sites, consequently decreasing the cost disadvantage compared to flat terrain sites to 1,507 €/ha on average. However, the construction of transversal terraces requires high investments and is accompanied by certain climate- and water supply-related problems, thus requiring a careful consideration of the economic advantages of such construction with respect to the initial situation. The introduction of low-input training systems instead of vertical shoot positioned (VSP) trellis systems at sites permitting mechanical harvesting by SSHs supersedes the manual pruning necessary at VSP sites, thereby reducing the viticultural costs of steep slope sites with limited mechanisation to levels commensurate with those of fully mechanised VSP sites on flat terrain. The downside of low-input systems is the often increased water demand, which requires a secured water supply. In addition, as low-input systems do not allow for manual quality-improvement processes or manual harvesting, they are suitable mainly for wines of a basic quality level.

The results of the research discussed in this thesis indicate that there are substantial cost disadvantages at vineyard sites that are impeding full mechanisation with standard machinery. Viticultural costs at the most disadvantaged manual sites are more than 1.6 times those at fully mechanised flat terrain sites. That said, sub-standard yield levels were not included into this figure. These cost disadvantages usually cannot be covered by price premiums, thus leaving a gap between elevated costs and stable prices.

These findings raise serious concerns about the future of steep slope viticulture, especially given the prospects of adverse environmental impacts driven by climate change. Worse, most consumers are not willing to pay higher prices for steep slope wines. As such, additional costs cannot be expected to be offset by price premiums. The only possibility for the sustained cultivation of steep slope sites lies in financial support by the public sector. To justify public support, the overall value of steep slope viticulture created by the additional ecosystem services (ES) they provide under certain conditions and with respect to potential social costs must be assessed. The current practice of support payments (e.g. government subsidies) for steep slope viticulture in Germany is decidedly untargeted insofar as it only considers the gradient of these sites as a criterion for eligibility. The distribution scheme could be improved by including the influential factors identified within the framework of this thesis as well as the overall value of steep slope sites for society into the eligibility assessment.

## **Zusammenfassung**

Die ersten Weinberge in Europa wurden in Steillagen angelegt, um die dortigen vorteilhaften mikroklimatischen Bedingungen auszunutzen. In den letzten Jahrzehnten konnte in Deutschland ein starker Rückgang der Anbauflächen in Steillagen beobachtet werden. Der erhöhte Arbeitsaufwand in diesen Lagen zusammen mit der insgesamt sinkenden Rentabilität und dem starken internationalen Wettbewerb, die die Weingüter vor wirtschaftliche Herausforderungen stellen, werden als Treiber dafür gesehen. Eine fundierte Kostenbewertung verschiedener Weinbergs-Setups unter Berücksichtigung der allgemeinen Anbaubedingungen und entsprechender Mechanisierungsoptionen fehlte bisher.

Ziel dieser Dissertation ist es, eine Erklärung für die Aufgabe von Steillagen aus ökonomischer Sicht am Beispiel Deutschlands zu finden. Für eine fundierte Kostenabschätzung wurde ein Schema zur Kategorisierung von Weinbergstypen entwickelt. Darauf basierend wurden in fünf deutschen, managementgeführten Weingütern über den Zeitraum von drei Jahren in 30 Referenzlagen Arbeitszeiterfassungen durchgeführt, in Summe 82 Beobachtungen und über 3.400 Einzelaufzeichnungen von Arbeits- und Maschinenstunden. Nach der Bewertung der Arbeitszeitaufzeichnungen mit entsprechenden Kostensätzen wurde der Datensatz mittels Varianzanalyse (ANOVA) mit fixen und zufälligen Effekten analysiert, um den Einfluss verschiedener externer Faktoren auf die Struktur der Weinbaukosten zu ermitteln.

Die Analyse ergab, dass drei Arten von externen Faktoren einen signifikanten Einfluss auf die durch die Bewirtschaftung der Weinberge verursachten Kosten haben. Diese Faktoren sind die Hängigkeit und der Zugang zu den Weinberglagen, die Ausrichtung der Rebzeilen zum Hang und das Erziehungssystem. Die Kostenunterschiede zwischen den Weinbergstypen sind auf Unterschiede in der Mechanisierungsintensität und den eingesetzten Maschinen zurückzuführen. Während flaches Gelände die Mechanisierung der meisten Weinbauprozesse mit sehr effizienten Maschinen wie Schmalspurtraktoren und Standard-Traubenvollerntern erlaubt, erfordern Lagen mit begrenzter Mechanisierung Spezialmaschinen wie Raupenschlepper und Steillagenvollernter, um die Steigung zu überwinden. Die Lagen mit den schwierigsten Bedingungen verhindern die Mechanisierung einiger oder aller Prozesse. Je stärker die Mechanisierung eingeschränkt ist, desto höher ist der Bedarf an Handarbeit. Hinzu kommt, dass die spezialisierten Maschinen für Steillagen in der Regel höhere Kapitalkosten verursachen und langsamer arbeiten, vor allem wegen der zusätzlichen Sicherung durch Seilwinden, die das doppelte Überfahren jeder Reihe erforderlich machen.

Der Kostennachteil von Standorten mit begrenzter Mechanisierbarkeit im Vergleich zu vollmechanisierten Standorten liegt je nach Grad der Begrenzung zwischen 2.748 €/ha und 7.713 €/ha. Zusätzlich zu diesen Hektar-Nachteilen sind Weinberge in Hanglagen häufiger von Wassermangel



betroffen, die durch den Klimawandel bereits in den letzten Jahren in höherem Maße im Vergleich zu Flachlagen aufgetreten ist und sich wohl weiter verstärken wird. Wassermangel verursacht Dürreprobleme, die unter anderem zu unterdurchschnittlichen Erträgen führen und damit den Kostennachteil in Steillagen aus Pro-Liter-Sicht weiter verstärken.

Bestimmte Weinbaupraktiken können helfen, die weinbaulichen Kosten in Lagen mit begrenzter Mechanisierung zu senken. Die Anlage von Querterrassen anstelle von Weinbergen in Falllinie führt zu einer Kostenreduzierung von 3.595 €/ha in raupenbefahrenen Steillagen und 6.093 €/ha bei manuellen Lagen, wodurch sich der Kostennachteil im Vergleich zu flachem Gelände auf durchschnittlich 1.507 €/ha reduziert. Allerdings ist der Bau von Querterrassen mit hohen Investitionen und gewissen klima- und wasserwirtschaftlichen Problemen behaftet, so dass eine sorgfältige Abwägung der wirtschaftlichen Vorteilhaftigkeit basierend auf der Ausgangssituation erforderlich ist. Die Einführung von Minimalschnitt-Erziehungssystemen anstelle von Spalierziehung in Lagen, die eine maschinelle Ernte mit dem Steillagenvollernter erlauben, macht den in Spalieranlagen notwendigen manuellen Rebschnitt überflüssig und senkt damit die Weinbaukosten in begrenzt mechanisierten Steillagen auf das Niveau von vollmechanisierten Spalieranlagen im Flachland. Der Nachteil von Minimalschnittsystemen ist der oft erhöhte Wasserbedarf, der eine gesicherte Wasserversorgung erfordert. Darüber hinaus erlaubt die Erziehung in Minimalschnittsystemen keine manuellen qualitätsverbessernden Prozesse oder Handlese und ist daher hauptsächlich für Weine im Basissegment geeignet.

Die Ergebnisse dieser Dissertation zeigen, dass Weinbergsflächen, in denen keine Vollmechanisierung mit Standardmaschinen möglich ist, mit einem erheblichen Kostennachteil behaftet sind. Die Weinbaukosten in den am stärksten benachteiligten, manuellen Lagen betragen mehr als das 1,6-fache der Kosten in vollmechanisierten Flachlagen. Das unterdurchschnittliche Ertragsniveau ist in dieser Betrachtung noch nicht berücksichtigt. Diese Kostennachteile können meist nicht durch Preisaufschläge gedeckt werden, so dass eine Lücke zwischen erhöhten Kosten und stabilen Preisen entsteht.

Dieser Befund wirft ein düsteres Licht auf die Zukunft des Steillagenweinbaus, die durch den Einfluss des fortschreitenden Klimawandels noch verschlechtert wird. Die Verbraucher zeigen keine erhöhte Zahlungsbereitschaft für Steillagenweine, die einen Beitrag zur Deckung der erhöhten Kosten leisten würde. Die einzige Chance für die nachhaltige Bewirtschaftung von Steillagen liegt in der öffentlichen Förderung. Um diese zu rechtfertigen, muss der Gesamtwert des Steillagenweinbaus unter Berücksichtigung zusätzlicher Ökosystemleistungen und möglicher gesellschaftlicher Kosten ermittelt werden. Die derzeitige Förderpraxis für den Steillagenweinbau in Deutschland ist durch die hauptsächlichliche Berücksichtigung der Hangneigung als Kriterium für die Förderwürdigkeit eher ungerichtet. Das Verteilungsschema könnte optimiert werden, indem die im Rahmen dieser Dissertation

identifizierten Einflussfaktoren sowie der gesamtgesellschaftliche Nutzen in die Bewertung der Förderfähigkeit einbezogen würden.

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## List of Abbreviations

€/ha	Euro per hectare
€/L	Euro per litre
ANOVA	Analysis of variance
BfN	Bundesamt für Naturschutz
BMEL	Bundesministerium für Ernährung und Landwirtschaft
CAP	Common Agricultural Policy
CES	Cultural ecosystem services
DI	Deficit irrigation
DLR RLP	Dienstleistungszentrum Ländlicher Raum Rheinland-Pfalz
DSS	Direction of steepest slopes
EMS	Environmental management system
ES	Ecosystem services
ha	hectare
HMUKLV	Hessisches Ministerium für Umwelt, Klimaschutz, Landwirtschaft und Verbraucherschutz
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal rate of return
L	litre
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LI	Low-input systems
MLR BW	Ministerium für Ländlichen Raum und Verbraucherschutz Baden-Württemberg
MP	Minimal pruning
MWVLW RLP	Ministerium für Wirtschaft, Verkehr, Landwirtschaft und Weinbau Rheinland-Pfalz
NPV	Net present value
OIV	International Organisation of Vine and Wine
SH	Standard harvester
SMPH	Semi-minimal pruned hedge
SSH	Steep slope harvester
TT	Transversal terraces
UAV	Unmanned aerial vehicle
UBA	Umweltbundesamt
UGV	Unmanned ground vehicle
VSP	Vertical shoot positioned
WUE	Water use efficiency

# 1 General Introduction

## 1.1 Problem statement

Vines planted on steep slopes have shaped viticulture in Europe for centuries. Besides providing space for grape production, sloping vineyard sites lining rivers form landscapes that attract a constant flow of tourists (Job and Murphy, 2006; Tafel and Szolnoki, 2020) and offer invaluable habitats for numerous plants and animals (Cox and Underwood, 2011). In Germany, between 7,700 and 14,192 hectares, equivalent to 8 % to 14 % of the total viticultural area, depending on the source, are officially classified as steep slope vineyards (Strub and Loose, 2016). However, in recent decades, the vineyard acreage on steep slopes in Germany has decreased considerably. For example, the viticultural acreage in Rhineland-Palatinate, the state with the largest wine-growing region in Germany, has declined by 28 % since 1999 (Statistisches Landesamt Rheinland-Pfalz, 2016).

It is generally agreed that the amount of work required on steep slopes is significantly greater than that on flat terrain. The gap in labour demand between flat terrain and steep slopes has widened since the 1950s due to rapid technological progress on flat terrain. Although crawler tractor systems and steep slope harvesters (SSHs) have significantly simplified work on steep slopes, too, mechanisation on flat terrain is much more advanced. Today, the labour demand at steep slope sites is estimated to be two to six times higher than that at flat terrain sites (Schrieck, 2016).

The long-proclaimed climatic advantages of planting vines on steep slopes rather than on flat terrain have been undermined by climate change. Formerly, the improved inclination of the sun towards the ground on steep slopes, especially during spring and autumn, allowed viticulture in marginally climatic zones (Hoppmann *et al.*, 2017). Rising temperatures and drought issues attributable to climate change have, however, neutralised this benefit (Fraga, 2020), posing additional challenges for the cultivation of vines on steep slopes.

A survey administered in 2016 amongst German wine estates engaged in the cultivation of steep slope vineyards revealed that the estates viewed these vineyards as part of their identity and that they were accordingly obliged to perpetuate the heritage of their ancestors despite the higher labour demand that doing so entailed. At the same time, these estates expressed how difficult it was to communicate to consumers the myriad challenges they faced in cultivating vines on steep slopes and the unique qualities of the resulting wines (Loose and Strub, 2017). A survey conducted with wine consumers confirmed that consumers did not consider the unique properties of steep slope wines to be a justification for their

higher price, lending credence to the claim by wine producers that marketing these wines was decidedly challenging (Loose *et al.*, 2017). A second administration of the survey in 2021 (not yet published) revealed that steep slope wine producers have become increasingly distressed. Faced with mounting challenges, such as high labour intensity and increasing labour costs as well as a scarcity of seasonal workers and unsatisfactory public support schemes, these wine producers have cast doubt on the future of steep slope viticulture. The survey responses indicated that the closer the wine estates come to handing over their companies to the next generation, the more critical the situation will become. This is because whereas the older generation is prepared to endure a more difficult business environment for want of income alternatives, the younger generation is freer to choose alternate career paths and realise different life purposes. In simpler terms, for the younger generation, abandoning the family business is a feasible option.

The general situation of the viticultural sector in Germany as well as internationally is marked by a highly competitive globalised wine trade, an annual overproduction of wine, which has been occurring for years (OIV, 2019), and challenges associated with climate change, which threaten the prosperity of wine estates themselves. The survey responses showed that while some producers are ready to accept economic hardship in order to sustain steep slope viticulture, others are less optimistic and have considered giving up on steep slope sites or on wine production as a whole. For their part, consumers appear to have little appreciation for the efforts made to sustain steep slope viticulture. The low cost efficiency and resulting economic unsustainability of steep slope sites, together with the challenging market environment, are generally perceived to be the main reason for the abandonment of steep slope sites.

Even though it is clear that labour intensity is considerably elevated at steep slope sites and that more capital-intensive machinery arrangements are needed at these locations compared to flat terrain sites, reliable figures on the actual impact of higher labour input and elevated capital costs on viticultural expenses are unavailable.

Likewise, the actual factors underlying the cost disadvantages of steep slope sites remain unclear. The official definition of steep slope vineyards in Germany is based on the slope gradient. Depending on the state in which viticultural regions are situated, steep slope vineyards are defined by a gradient exceeding 30 % or 40 % or by the determination that they can only be managed by hand (Loose and Strub, 2017). Importantly, this simple definition serves as the basis for the payment of subsidies. And yet, no data currently exist to confirm whether this definition sufficiently describes the true cost disadvantages of steep slope vineyards.



This thesis thus seeks to address knowledge deficiencies with regard to the economic costs of steep slope viticulture and their impact on business performance and to thereby provide a point of departure for future research on the development of steep slope sites in the context of economic sustainability.

## 1.2 Literature review

### 1.2.1 Economic sustainability of viticulture

The concept of *sustainability* has attained increased importance in recent years in both viticultural practice and research on the viticultural sector. In 1987, the World Commission on Environment and Development emphasised the salience of sustainable development in three critical dimensions – environment, society and economy – to ensure that not only present but also future needs can be met (World Commission on Environment and Development, 1987). Elkington (1997) subsumed these three dimensions under the so-called *triple bottom line* that companies should follow in their business strategies and practices in order to operate in a sustainable manner.

In both general awareness and perceptions by those in the wine industry, sustainability is often associated foremost with the environmental dimension (Szolnoki, 2013). This association is reflected in many studies on environmental sustainability in the wine sector (Hughey *et al.*, 2005; Santini *et al.*, 2013; Cichelli *et al.*, 2016; Moggi *et al.*, 2020). However, in light of strong international competition in the globalised wine market, the constant oversupply of wine (OIV, 2019), the disproportionate rate at which costs are increasing compared to market prices, thereby reducing profitability (Nicholson, 2019; Strub *et al.*, 2019), and the adverse effects of climate change, which require costly adaptations and financial buffers to compensate for yield losses, the economic dimension of sustainability is of utmost concern to wine producers (Loose and Pabst, 2019). The lack of profitability is especially threatening to the economic sustainability – and therefore the survival – of the global wine sector (Sellers-Rubio, 2010; Pappalardo *et al.*, 2013; Loose and Pabst, 2020). Consequently, any strategy aimed at fostering environmental sustainability will only be worthwhile if the economic sustainability – and, as such, the long-term survival – of the wine industry is secured. At present, however, knowledge about the impact of socially and environmentally sustainable practices on economic performance in the wine industry is limited (Pomarici and Vecchio, 2019).

Historically, different approaches have been taken to review the economic sustainability of wine companies. Atkin *et al.* (2011), for instance, saw a clear economic advantage in the form of cost leadership and differentiation strategies for those wine estates that had environmental management systems (EMS) in place. Borsellino *et al.* (2016) used a case study to highlight the positive socio-economic impacts of implementing the *triple bottom line* approach to sustainability. Yet, these and other

studies that have analysed elements of economic sustainability (Flint and Golcic, 2009; Gabzdylova *et al.*, 2009) have been based mainly on surveys, and as such little sound quantification of economic sustainability using transparent criteria has thus far been performed.

To quantify the environmental and economic sustainability of the viticultural dimension of wine production, Pannell and Glenn (2000) developed an assessment scheme based on Bayesian decision theory, ranking available information according to its relative importance for decision making. Similarly, other researchers have successfully deployed Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) to rate and compare different production options with respect to environmental and ecological sustainability (Strano *et al.*, 2013; Falcone *et al.*, 2015; Martins *et al.*, 2018). Other studies have focused on more specific aspects of sustainability, such as agro-energy (Zambon *et al.*, 2018) or strategic differentiation through tourism and marketing (Dawson *et al.*, 2011). For their part, Torquati *et al.* (2015) used case studies of three wine estates in Italy that had restored traditional cultural landscapes to analyse their economic performance. Torquati and colleagues' approach was based on a cost assessment of the estates' restoration activities and on the evaluation of the net present value (NPV), internal rate of return (IRR) and breakeven point of the investment. However, this approach did not permit the assessment of the economic performance of the three businesses as a whole.

Current schemes aimed at measuring sustainability at the farm level in different wine-producing countries focus mostly on environmental issues and goals (Klohr *et al.*, 2013; Corbo *et al.*, 2014; Flores, 2018; Merli *et al.*, 2018). The economic indicators included in these sustainability schemes target the evaluation of business strategies and regional impacts rather than the measurement of business performance *per se*. To provide a more transparent measurement of the economic sustainability of companies as a whole, Loose *et al.* (2021) suggested the use of a system of economic key figures based on quantitative business data, with profit after the remuneration of family labourers as the central criterion.

The impact of steep slopes on the overall economic sustainability of wine estates that practice steep slope viticulture in comparison to the overall economic sustainability of flat terrain wine estates has not yet been investigated.

### 1.2.2 The assessment of steep slope viticulture from different perspectives

Historically, steep slope viticulture has been analysed from very different angles depending on the research field. Therefore, the state of the science in different disciplines will be outlined in the following paragraphs.

#### *Technological aspects of steep slope viticulture*

To date, a major focus of research on steep slope agriculture and viticulture has been technical in nature. Towards the end of the 1950s and into the 1960s many researchers studied the effect of mechanisation in agriculture and the influence of slopes on farmability (Huber, 1959; Meimberg *et al.*, 1962). In the 1980s, the first studies on optimising viticultural management on steep slopes were conducted. Grečenko (1984), Hunter (1993) and Yisa *et al.* (1998) assessed the physics of driving tractors on sloping terrain by describing the physical limits of stability of tractors on sloping terrain, thereby laying the foundation for mechanisation in this context. Steinmetz (1985) studied the ways in which marginal zones could be developed on sloping terrain to identify technical solutions to prevent the continued falling fallow of steep slope vineyards. Steinmetz concluded that vineyard infrastructure and the shear strength of the soil were critical factors for determining mechanisability. Leimbrock (1984) investigated the feasibility of strengthening cultivation through cross-terracing. This research was motivated by Leimbrock's observation that the lack of profitability of steep slope sites could pose a threat to the sustained cultivation of these areas. Leimbrock ultimately identified three core problems in this context: costs, performance and farm structures. Similarly, Pla and Nacci (2002) examined the potential for cross-terracing to enable mechanisation and thus decrease production costs. In this regard, they identified a number of threats to soil properties that were associated with these new plantation systems. Schwarz and Vollmer (2010) assessed the practicability of and costs associated with different winch-and-rope systems in order to improve the economic efficiency of cultivating vineyards on steep slopes. In a study by Huber (2015), the cultivation of vertically oriented steep slope vineyards was compared to that of vineyards on transversal terraces from both a technical and economic perspective, the latter of which was based on a full cost approach. However, the database for the cost comparison was not transparent, consequently limiting the validity and reliability of Huber's study. A number of more current studies on steep slope cultivation in the field of viticulture technology, which were published in specialist publications in Germany, such as *der deutsche weinbau* or *das deutsche weinmagazin*, focused primarily on the technical assessment of innovations. One very recent example of such research, which was intensively covered in the specialist media, was on the development of the steep slope harvester (SSH), which was tested for practical use for the first time during 2015 and 2016 in Germany. Despite such

research efforts, economic cost assessments of viticulture on steep slopes has been either limited to very specific underlying conditions or outright omitted.

#### *Low-input training systems for steep slope viticulture*

Low-input training systems can reduce labour demand in viticultural management because the manual processes necessary in VSP trellis systems – pruning, removal of cut canes, tying and removal of shoots – become superfluous (Archer and van Schalkwyk, 2007; Bates and Morris, 2009). Low-input training was originally developed and remains very common in warmer climates, such as Australia, often implemented in combination with irrigation to compensate for the elevated water demand of the more massive canopies (Clingeffer *et al.*, 2005). In the moderate climate of middle Europe, low-input training was first implemented around the start of the new millennium. In low-input systems, vines grow in a hedge-like manner and are only trimmed with a hedging machine. Thus, vine canes are not removed every year (Clingeffer *et al.*, 2005; Intrieri *et al.*, 2011). Due to this difference in canopy structure, grape growth is scattered over the whole height of the canopy instead of in a designated grape zone (Molitor and Junk, 2019), as in VSP trellis systems. This is why mechanical harvesting is obligatory when working with low-input training systems. Thus, thanks to the recent development of SSHs, low-input training has been introduced at sites where SHs cannot be used. The effect of the viticultural cost of low-input training at steep slope sites has not yet been analysed.

#### *The assessment of viticultural costs of flat terrain and steep slope sites*

In the past, working time records and cost calculations were carried out for individual wine estates and selected cultivation systems on both flat and steep slopes. These studies using individual wine estates as research object referred to defined cultivation conditions and problems. However, as the database was very company-specific, direct comparisons were inhibited and not all aspects of steep slope viticulture were covered. These studies are not publicly available for privacy reasons, too.

The labour demand of different training systems was the object of analysis in studies conducted by Brazsil and Somogyi (2001) and Vollmer and Schwarz (2013). Brazsil and Somogyi evaluated working time records for different training systems and row spacing taking into account different weather conditions. Vollmer and Schwarz analysed the labour demand of different training systems using GPS-based documentation systems but did not consider the effects of terrain. A cost assessment was also not conducted in either case.

Cost calculations for machinery, which can be found mainly in the trade literature, were limited to specific machines, i.e. they were not comprehensive for all machinery used in viticulture during the vegetation cycle.

The Board of Trustees for Technology and Construction in Agriculture (Kuratorium für Technik und Bauwesen in der Landwirtschaft) publishes data from working time assessments and machine costs (Becker and Dietrich, 2017), which are updated frequently. However, the validity of working time data for cost assessments of steep slope sites is limited, as highly generalised statements are made that do not adequately reflect the existence of different types of steep slopes. These data and corresponding assessments can therefore only be used as an initial orientation aid, not as a reliable database. The data for machine costs, however, are very comprehensive and can thus be reliably used in the further assessment of total viticultural cost.

In summary, although cost assessments for specified growing conditions exist, neither a coherent assessment of steep slope viticulture in its various forms with respect to labour demand nor a comparison to growing conditions and attendant costs of flat terrain viticulture has yet been conducted.

#### *The impact of climate change on steep slope viticulture*

When viticulture first arrived in Europe, steep slopes were the preferred sites for planting vines. This is because the sunwards inclination of these sites greatly enhanced the absorption of solar radiation by vines, especially in the spring and summer (Hoppmann *et al.*, 2017). As a consequence, even in moderate climate zones, such as Germany, grapes typically reached full ripeness even in difficult years, while grapes grown on flat terrain often remained unripe.

Climate change has increased temperatures in recent decades (IPCC, 2014; UBA, 2019). Today, grapes usually reach full ripeness on both sloping and flat terrain (Palliotti *et al.*, 2014; van Leeuwen and Darriet, 2016). Thus, steep slopes are no longer needed to provide high-quality grapes. As a result of increasing temperatures, water evaporation from the ground has also accelerated (Schultz *et al.*, 2009), and long periods with very low levels of soil humidity during the summer have become more common in Germany (UBA, 2019). These changes have generated more frequent drought conditions, especially at steep slope sites, which have less water retention capacity, thereby reducing yields (Hofmann and Schultz, 2015; van Leeuwen and Darriet, 2016). As the length of the growing season and hence the timing of the harvesting period are closely linked to the annual average temperature (Jones and Alves, 2012), it is likely that the expected continued increase in temperatures will be accompanied by shifts in the harvest period, particularly at steep slope sites, towards earlier dates. This means that harvesting will occur at higher temperatures alongside overall elevated sugar levels in grape must (Bock *et al.*, 2013),

which could potentially have a detrimental effect on aroma composition (Medrano *et al.*, 2003; van Leeuwen and Darriet, 2016). Thus, the previous advantage of steep slopes will be neutralised, providing additional justification for the abandonment of steep slope viticulture.

#### *Ecosystem services (ES) of steep slope viticulture*

Even though wine produced from steep slope viticulture is not perceived to be particularly special, as the survey responses from wine consumers demonstrated, steep slope vineyards in themselves are held in high regard in the public eye as multifunctional agricultural systems that provide a wide range of ecosystem services (ES) apart from serving as areas for grape production (Winkler *et al.*, 2017). The most notable contribution of these sites is likely cultural ecosystem services (CES), which are linked to the preservation of traditions, the conservation of nature and the promotion of environmental attractions (Winkler and Nicholas, 2016). A number of cultural landscapes associated with steep slope viticulture – namely the Wachau Valley in Austria, the Upper Middle Rhine Valley in Germany, the Colline del Prosecco di Conegliano e Valdobbiadene in Italy, and the Alto Duoro wine region in Portugal – have been acknowledged as UNESCO World Heritage Sites (UNESCO, 2021). Moreover, several studies have confirmed the important role these sites play in the promotion of tourism (Job and Murphy, 2006; Lourenço-Gomes *et al.*, 2015; Tafel and Szolnoki, 2020). More precisely, Dawson *et al.* (2011) highlighted the salience of place marketing with regard to economic differentiation strategies, especially for small wine estates, for improving the economic situation, which is inherently connected to the attractiveness of the marketed landscapes.

Steep slope vineyards, if properly managed, can greatly contribute to the preservation of biodiversity as well. As perennial crops, vines provide comparatively stable ecosystems and habitats for species adapted to xerothermal conditions (Maixner *et al.*, 2012). Assandri *et al.* (2018) demonstrated that low-intensive agricultural landscapes, such as small-scale viticultural terraces, which can only be cultivated by hand, support a wider variety of bird species. Transversal terraces with high embankments provide habitats for numerous insect and other species if the embankments are planted with a diverse assortment of cover crops intermixed with bare spots to encourage sun-basking and provide resting places (Jäger and Porten, 2018). On these embankments, a significantly greater number of species and individual members of species can typically be found compared to vineyards planted in vertical direction. In addition, terraces that follow the contours of hills are naturally aligned with the movements of flying insects. Put differently, terraces serve as pathways between habitats and foster the intermixing of populations, thereby encouraging the maintenance of genetic diversity (Jäger and Schmidt, 2021).

Cover crops on the embankments of terraced vineyards and between vineyard rows also aid in the prevention of erosion and soil degradation (Jäger and Porten, 2018; Schütte *et al.*, 2020). Agricultural

plots planted with perennial crops, such as grape vines, can serve as carbon sinks and can facilitate carbon dioxide fixation as well – if managed properly (Brunori *et al.*, 2016; Galati *et al.*, 2016; Williams *et al.*, 2020).

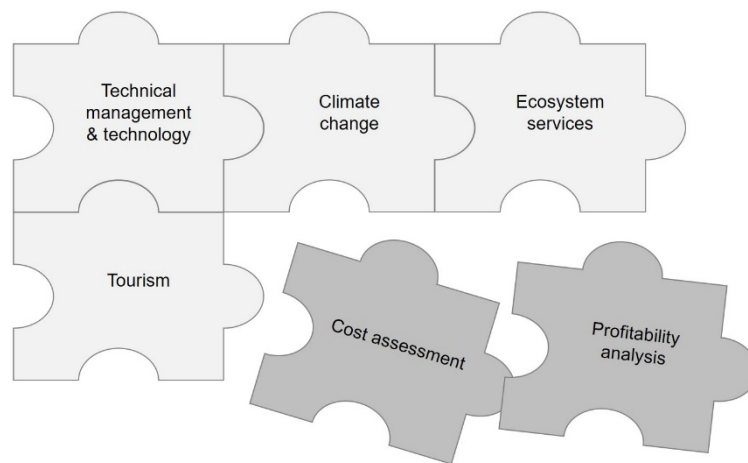
Amidst the contradictory forces of the continuing abandonment of steep slope vineyards and the growing recognition of their general socio-cultural value, several state authorities in Germany and other European nations have expressed interest in preserving these vineyards and a willingness to support those wine growers who continue to cultivate them (MLR BW, 2016; BfN, 2019; MWVLW RLP, 2021). Such support includes eligibility for subsidies, both for the cultivation of these sites and for their restructuring (European Union, 2013). However, the extent to which these subsidies compensate for the economic costs of managing steep slope vineyards compared to their flat terrain counterparts is as of yet unclear.

### 1.3 Outline of the thesis and research approach

To date, the extant research has approached the topic of steep slope viticulture from different angles. Such multifarious approaches have culminated in a thorough understanding of the technical and technological possibilities and limitations of steep slope viticulture as well as the various effects of climate change on the surrounding local and regional landscapes and their features. Further, research on ES for steep slope viticulture has developed relatively recently with a number of research projects having been either just completed or currently underway. The results of these projects, including their implications and applications, are expected to be published and practically implemented in the next few years. Lastly, the place-marketing role of steep slope vineyards, particularly for promoting tourism, has also been addressed in recent years.

Despite the variety of research angles taken towards steep slope viticulture, a comprehensive evaluation of its economic dimensions and future prospects, especially for wine growers and their estates, continues to be neglected. The question of the extent to which steep slope viticulture exerts a substantive economic impact is as practically relevant as it is academically compelling. Steep slope vineyards constitute the economic basis for the perpetuation of many wine-growing families and their estates, particularly in remote areas devoid of substantial tracts of flat terrain. They also, as noted above, contribute to environmental conservation by fostering biodiversity and to the tourism industry via their inherent natural beauty.

That labour demand in steep slope viticulture is elevated, and that the machinery needed for steep slope cultivation and harvesting is markedly different from that used in flat terrain viticulture, is not disputed. Accordingly, it goes without saying that the production costs associated with steep slope viticulture are considerably greater as well. And yet, it would be unreasonable to expect state authorities to change their distribution practices of subsidies for steep slope vineyards based solely on assumptions. What is needed, then, is a comprehensive economic analysis of viticultural management with a sound cost assessment of steep slope compared to flat terrain vineyards as well as their relative profitability.



*Figure 1: Research angles towards steep slope viticulture and knowledge deficiencies.*

*Source: own illustration*

### 1.3.1 Research questions

Based on evident knowledge deficiencies in the current state of research, this doctoral thesis aims to answer the following questions:

RQ1: Which factors determine the structure of labour and the cost of machinery at flat terrain and steep slope vineyards?

RQ2: What are the actual cost disadvantages of steep slope vineyards compared to flat terrain vineyards?

RQ3: How do yield levels impact the cost structure of flat terrain versus steep slope vineyards?

RQ4: Which measures could help to improve the cost efficiency of steep slope viticulture and thereby help to sustain the practice?

This thesis is based on three papers, of which Papers I and II have already been published. Paper III is currently under review.



### 1.3.2 Systematic typology of vineyard types based on mechanisation intensity

To address the research questions outlined above, viticulture in Germany, which has seen a decline in steep slope cultivation and acreage, constituted the research focus. As discussed previously, the current definition of steep slope viticulture in Germany is based mainly on their gradient, with the exception of one state, in which the necessity for mechanisation is also considered. Reports provided by the wine industry itself, however, have foregrounded several other factors that should be considered when defining steep slope viticulture, particularly at the threshold between flat terrain and steep slopes. These factors include labour demand and the amount of capital invested, especially with regard to the purchase, installation and operation of machinery, as well as the relative intensity of mechanisation. At steep slope sites, mechanisation intensity and the types of machines used vary widely, as does labour intensity. Paper I aimed to systematically outline the external factors influencing mechanisation intensity, choice and use of machinery, machine hours and labour demand for the three main sets of processes comprising viticultural management. Based on these factors, a typology of vineyard types was derived stratified by machinery setup and mechanisation intensity. In the second part of the paper, this typology was applied to a dataset developed from fieldwork on working time records, including machine hours, which were assessed with respect to cost estimates for machinery and labour. The research sample consisted of five wine estates, each managing between 50 and more than 200 hectares of vineyards. Each wine estate is located in a different wine-growing region of Germany. The data collection period extended over three years and resulted in over 3,400 single data points.

Figure 2 depicts the data collection process, which served as the basis for the statistical analysis undertaken to answer the research questions. To estimate the cost of labour and machine hours, cost rates were determined for each piece of machinery and level of experience of the staff. For the harvesting example, no machinery was needed for manual harvesting and non-skilled workers were employed at minimum wage. In contrast, harvesting accomplished by machines required the purchase of harvesters and the employment of tractor operators at a higher wage level, resulting in different harvesting costs per hour. In this way, every process was valued as cost per hour, depending on the relative combination of required machinery and staff.

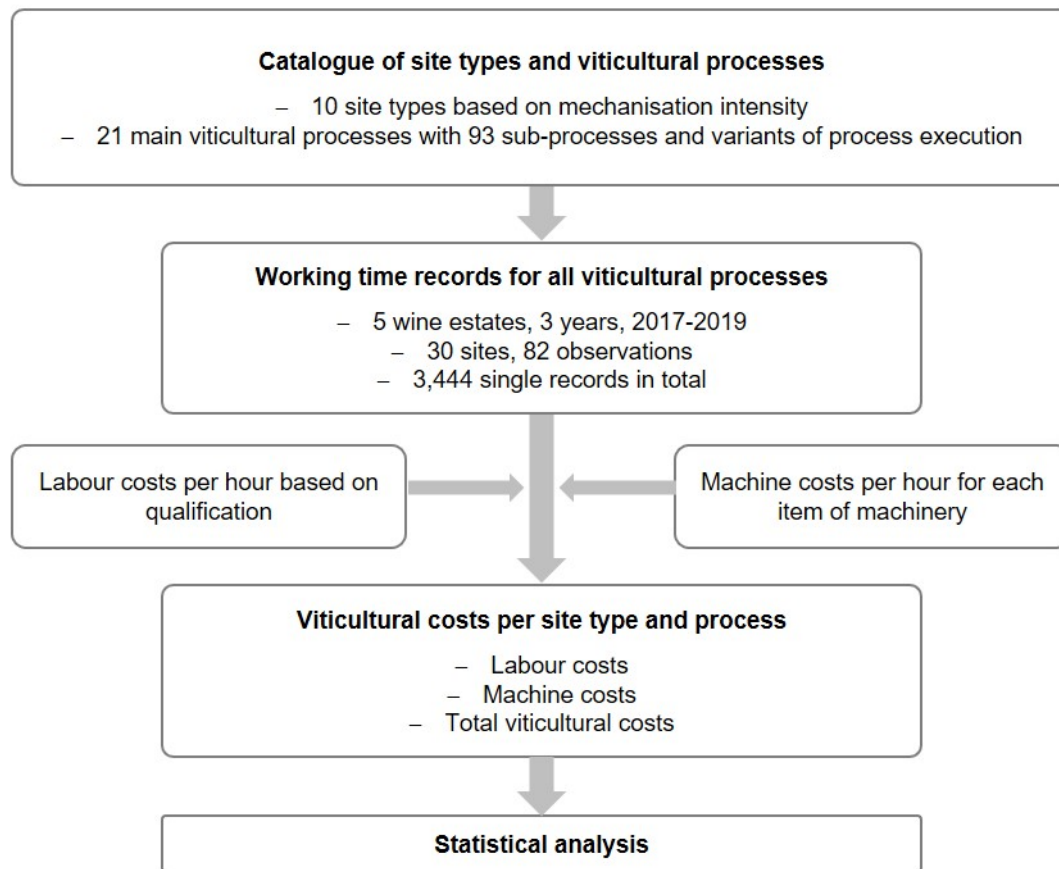


Figure 2: Methodology for data collection and statistical analysis.  
Source: own illustration.

The inclusion of wine estates from different regions and their observation for three years served to control for the influence of random factors, such as annual variability in and managerial decisions concerning viticultural costs, and thereby generate more robust results for the ultimate estimation of the influence of mechanisation. Analysis of variance (ANOVA) with fixed and random effects was conducted to determine the relative influence of mechanisation intensity with respect to the three sets of viticultural processes examined in this research: labour costs, machine costs and total viticultural cost.

### 1.3.3 Cost analysis

In Paper II, the vineyard site typology developed in Paper I was applied to determine the actual difference in costs between vineyard sites with limited mechanisation and those with full mechanisation as well as to identify the costs driving viticultural processes. Furthermore, whether the conversion of vineyard sites with limited mechanisation and with rows planted in the direction of the steepest slope into transversal terraces could potentially be profitable and thus improve the feasibility and variety of mechanisation options and the cost structure of the viticultural management of steep slope vineyards

was also evaluated. The assessment of the cost differences between sites with limited and optimal mechanisation was conducted by ANOVA. The analysis of the profitability of transversal terraces was based on the calculation of the NPV.

In Paper III, the effect of the introduction of low-input training systems on viticultural costs at sites with either full or limited mechanisation was determined by ANOVA with fixed and random effects, as well as by a descriptive comparison of mean values.

For the statistical analyses discussed in Papers II and III, sub-samples of the full sample described in Paper I were used.

## **2 Results**

### 2.1 Paper I: Effects of viticultural mechanization on working time requirements and production costs

This chapter is based on an article published by the author of the present work, with Simone Mueller Loose and Andreas Kurth as co-authors. Any reference to the chapter should be cited as follows:

Strub, Larissa, Kurth, Andreas and Loose, Simone Mueller (2021). Effects of viticultural mechanization on working time requirements and production costs. *American Journal of Enology and Viticulture*, No. 72 (1), 46–55. DOI: 10.5344/ajev.2020.20027

**Declaration of co-authorship  
for doctoral theses based on published or submitted co-authored articles**




This declaration form has to be submitted together with the thesis.  
Please use one form for each publication.

Name of the candidate:  Larissa Strub
Title of the article: Effects of viticultural mechanization on working time requirements and production costs
Submitted to  or  accepted for publication or <u>published in</u>  American Journal of Viticulture and Enology

Authors contributed to the work according to the following categories  
(max. 100 % per column):

A - more than 75 % B- 51 to 75 % C - 26 to 50 % D- up to 25 % 0 - no contribution

*Please insert the appropriate letter/zero for each contributing author in the resp. column*

Name	Literature review	Development of theoretical model/frame work	Concept and design of the study/ analysis	Execution, choice and development of methods	Evaluation and interpretation of results	Concept and writing of the article	Signature of the author
Strub, Larissa	A	A	A	A	A	B	
Kurth, Andreas	0	0	D	0	0	D	
Loose, Simone	0	0	D	D	D	D	

Please use an additional sheet if more authors contributed.

# Effects of Viticultural Mechanization on Working Time Requirements and Production Costs

Larissa Strub,<sup>1\*</sup> Andreas Kurth,<sup>1</sup> and Simone Mueller Loose<sup>1,2</sup>

**Abstract:** The purpose of this study was to empirically estimate machine and labor costs for mechanization of viticultural processes and to assess the relative effect of mechanization options on viticultural costs. By identifying three external factors that determined the degree of optimal mechanization of three major viticultural processes, we developed a systematic typology of 12 unique vineyard types. To estimate the effects of the factors and processes on production costs, we analyzed the variance of more than 3400 single working time records of five German wine estates across three years with fixed and random effects. Mechanization of general viticultural processes, harvesting, and pruning strongly affected viticultural costs. Minimal pruning provided a cost savings potential of 58% for vineyards that permitted mechanized harvesting. Very steep slopes suffered significant cost disadvantages of up to 164% that could only partially be compensated by mechanization. We identified opportunities for wine producers to improve their economic profitability by increasing viticultural mechanization. The methodological framework developed can be applied to other wine regions with different cost settings and the analysis of big data sets from digitalization of viticulture. The results can aid wine producers and policymakers to choose cost-efficient viticultural systems and provide benchmarks to compare labor intensity.

**Key words:** economic sustainability, mechanization, production costs, steep slope viticulture, training systems, viticultural practice

Profitability and economic sustainability pose major threats and challenges to wine estates globally (Sellers-Rubio 2010, Pappalardo et al. 2013, Loose and Pabst 2020). The profits of more than half of German wine estates are estimated to not fully cover family members' working time nor to enable interest payments for the equity employed (Strub and Loose 2018). For New Zealand wineries, profits have declined, while costs have significantly increased through rising wages and higher costs of energy and materials (New Zealand Wine and Ministry for Prime Industries 2019). Options to limit or reduce production costs, of which vineyard management is a major share, are urgently needed.

There is a long history of cost reduction by replacing manual work with mechanization in agriculture in general (Huber 1959) and viticulture in particular. In flat terrain vineyard sites, labor hours have reportedly decreased by 90% since 1950 through viticultural mechanization (Schreieck 2016). Recently, the total working time in flat terrain sites have only marginally been reduced, while wages have continued to increase. Options that could further reduce labor hours and total production costs and increase economic sustainability are therefore of particular research interest. Although feasible options such as minimal pruning (MP) systems were already introduced more than 30 years ago (Clingeffer 1983, Clingeffer and Possingham 1987), their implications on viticultural costs remain poorly understood.

Growing grapevines on steep slope sites still requires substantial manual work compared to flat terrain sites. In some areas, production costs have been reduced by reshaping the landscape into transversal terraces (TTs), which permits some degree of mechanization (Pla and Nacci 2002). Examples include parts of the Douro Valley in Portugal, the Penedès and Priorat regions in Spain (Lourenço-Gomes et al. 2015), and the Baden Kaiserstuhl area in Germany.

In many countries, a substantial area of vineyards located on steep slopes is planted in the direction of the steepest slope (DSS) or on small single terraces. Examples are the Upper Middle Rhine Valley in Germany, Prosecco di Conegliano e Valdobbiadene in Italy, and the Wachau in Austria, which form unique cultural landscapes that attract tourists (Lourenço-Gomes et al. 2015, Winkler and Nicholas 2016, Winkler et al. 2017), and some of these are listed as UNESCO World Heritage Sites. Winegrowers themselves can often only partially utilize these positive economic externalities. For instance, steep slope winegrowers in Germany do not receive a sufficient price premium for their products to cover additional

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costs (Loose and Strub 2017, Loose et al. 2017). Steep slope areas have, therefore, increasingly been abandoned in Germany because of insufficient profitability despite public subsidies (Strub and Loose 2016).

Over recent decades, some progress in mechanization has been achieved in steep slope viticulture, depending on the degree of the slope and access for machinery. Examples include rope and winch-supported tractor or crawler tractor systems and a steep slope harvester that was introduced to the market in 2016. Because of the required support systems for machinery to overcome the slope, these systems require larger investments and are less time-efficient than standard flat terrain systems. It is therefore of particular interest for winegrowers to investigate the cost savings potential of different mechanization options for steep slope viticulture. In addition, public policy aiming to sustain steep slopes through subsidies can benefit from valid information about cost disadvantages that remain after new mechanization options have been used.

This study aimed to determine the relative effect size of different mechanization options to reduce viticultural costs, the degree to which viticultural costs are reduced by MP systems, and the degree to which various mechanization options can reduce viticultural costs in steep slope sites.

**Systematic typology of vineyard types.** The degree to which viticultural processes can be mechanized depends on multiple external factors. In combination, the external factors and degree of mechanization of the main viticultural processes resulted in distinct vineyard types. These vineyard types build the systematic framework for a subsequent cost analysis.

**External factors affecting vineyard management.** Vineyard management is largely influenced by three main external factors (F): F1, slope and access to vineyard sites; F2, orientation of rows toward the slope; and F3, the training system (Grečenko 1984, Steinmetz 1985, Hunter 1993). The first factor (slope and access to vineyard sites) is mainly determined by a vineyard's topography and therefore is imposed by nature. In contrast, the two other factors (row orientation and training system) depend on winegrowers' decisions and affect vineyard management and mechanization options over the long term (Table 1).

*F1, slope and access to vineyard sites.* Three broad categories of vineyard steepness can be distinguished: flat to moderate slope (<40% slope), steep slope (>40% slope), and very steep slope vineyards (>60% slope). Flat to moderate slopes do not limit the use of machinery for vineyard management. Slopes >40% require additional supporting measures to permit mechanization, while very steep slopes make mechanization nearly impossible and mainly require manual labor.

*F2, orientation of rows towards the slope.* Vines on sloping terrain are either planted in DSS, so they run vertically down the slopes, or on TTs. Historically, vines have often been planted on small single terraces supported by dry stone walls (Coombe and Dry 1992, Petit et al. 2012), which do not permit the use of machinery (Stanchi et al. 2012, Torquati et al. 2015). To permit mechanization, terraces supported by massive embankments that are broad enough for narrow track tractors or crawler tractors have been constructed over the last 50 years in many areas (Leimbrock 1984). To construct such terraces out of the hill slope, extensive shifting of soil is necessary, and such a massive intervention to the topography requires specific soil conditions. Examples of the recent adoption of TTs are the regions of Priorat and Penedès in Spain (Ramos et al. 2007, Stanchi et al. 2012) and the Kaiserstuhl area in Germany.

*F3, training systems.* Vertical shoot positioning (VSP) is an internationally common training system, in which vines are planted in rows supported by wire frames (Zoecklein et al. 2008). The MP training system was developed in the late 1970s in Australia to economize the labor-consuming manual winter pruning required for VSP. Instead, the vines grow as hedges that are only cut in form with a mechanical trimmer (Clingeffer 1983, Clingeffer and Possingham 1987). MP systems require grape picking by a mechanical harvester, because the grapes grow throughout the whole canopy. Therefore, MP systems are generally recommended for the production of basic quality wines, for which no manual selection of grapes or other quality-improving measurements are required (Archer and van Schalkwyk 2007, Morris and Main 2010, Gatti et al. 2011). Because MP systems are ideally planted with wider row distances, the strategic decision between VSP and MP usually binds the winegrower to one system over the mid- to long-term.

**Table 1** Systematic framework of external factors and degrees of mechanization of viticultural processes.

<b>External factors (F)</b>	<b>Levels</b>
Slope and access to vineyard sites (F1)	No limitation Limited access for machines No access for machines
Orientation of rows toward the slope (F2)	Direction of steepest slope Transversal terraces
Training system (F3)	Trellis system combined with vertical shoot positioning Trellis system combined with minimal pruning <sup>a</sup>
<b>Mechanization of viticultural processes (P)</b>	<b>Levels</b>
General viticultural management (soil/canopy management and pest control) (P1)	Unsupported narrow track tractor/crawler tractor without winch Rope and winch-supported systems No mechanization (manual labor)
Harvesting (P2)	Standard harvester Steep slope harvester Manual harvesting
Pruning (P3)	Mechanical pruning Manual pruning

<sup>a</sup>Minimal pruning as synonym for low-input training systems (Strub et al. 2021).

Another factor strongly influencing both mechanization and yield is the planting density of vines. Similar to the training system, planting density is determined by the winegrower at the time of vineyard planting and binds the winegrower to this density over the life of a vineyard. However, planting density was not analyzed in this study.

**Mechanization of viticultural processes.** In their combination, the three external factors determined the optimal degree of mechanization of the three main viticultural processes (P) listed in the bottom half of Table 1: P1, general viticultural management including canopy and soil management and pest control of vines and grapes; P2, grape harvesting; and P3, pruning of the vines.

*P1, mechanization of general viticultural management.* The mechanization level of general viticultural management largely depends on the external factor of slope and access to vineyards (F1). It determines if agricultural vehicles, such as tractors and harvesters, can operate without support, if additional measures such as ropes and winches have to be applied, or if mechanization at the site cannot be employed. For flat terrain, the narrow track tractor is the most common vehicle that can also be employed in DSS-oriented vineyards with slopes up to 40%, depending on soil structure and greening (Grečenko 1984, Yisa et al. 1998, Walg 2007). Crawler tractors with higher traction can overcome steeper slopes in DSS vineyards. For even steeper slopes, additional support by rope and winch systems that prevent tractors from sliding down hills are required (Grečenko 1984, Walg 2007). Rope and winch systems reduce labor input compared to manual work but demand more time compared to standard narrow track tractors because the rope requires each row to be passed twice (Schrieck 2016). Furthermore, an additional tractor is necessary to pull the carrier, which transports the rope and winch system. In TTs, unsupported narrow track tractors or crawler tractors can be used with the advantage of passing a row only once (Leimbrock 1984).

Because of the high frequency of general viticultural management during the growing season, soil and canopy management and pest control are the most common and foremost mechanized processes in viticulture. If general management cannot be mechanized, harvest and pruning also must be manually performed. Certain conditions still prevalent in the Prosecco region or the Middle Rhine Valley require manual vineyard management. These are, for instance, extreme slopes, slopes without access for rope and winch systems, and small terraces completely inaccessible for machinery. At these sites, pesticides can be dispersed by helicopter. This tactic, however, requires costly employment of a service provider and special permits by authorities.

*P2, mechanization of harvesting.* Because of the high labor intensity of harvesting, mechanization of grape harvesting is the next logical step after mechanization of general viticultural management. A standard harvester (SH) can climb slopes up to 35% under optimal soil and greening conditions (Walg 2007). Wet conditions can prevent its use. In 2016, dedicated steep slope harvesters (SSHs), designed as an attachment to a crawler tractor, were used for the first time outside of experimental

trials. In steep slope vineyards planted in the DSS, the harvesting crawler tractor was secured by a rope and winch system. Whenever crawler tractors can operate in terraced vineyards, SSHs can also be used without additional security measures.

*P3, mechanization of pruning.* The mechanization of pruning is identical to that of the factor training system, as detailed above. The two factors were, therefore, combined (i.e., training) in the later analysis. Training systems, such as VSP, require manual winter pruning, shoot-thinning, and shoot positioning. Only MP systems do not require winter and summer pruning, except for hedging every second year for canes facing the ground. Independent of row orientation and slope, both training systems can be applied as long as general viticultural management and harvesting can be mechanized. MP systems are not feasible for sites such as small terraces that are inaccessible to tractors. MP systems are compatible with steep slopes as long as the employment of SSHs is feasible.

**Classification of vineyard types.** The external factors and the viticultural processes (Table 1) were combined to establish a classification of nine different vineyard types with different optimal mechanization levels, whereby both manual DSS and TT vineyards without mechanization were merged into one type (Table 2). The combination considers the partial interrelation of the three external factors. The orientation of rows toward the slope is negligible on flat terrain because there is no slope. Similarly, sites without access for machines do not permit MP training.

It is a deliberate decision by the vineyard not to use optimal mechanization if the advantages of manual work outweigh its cost. Selective grape harvesting required for premium wines is one reason. Accordingly, there are three additional vineyard types for manual harvesting, although mechanical harvesting would technically be feasible. For these three types, the applied level of mechanization has suboptimal technical efficiency. These types are marked with asterisks in Table 3.

The systematic analysis of the mechanization options for viticultural processes resulted in 12 practically relevant vineyard types that may differ in labor and machine costs. This universal framework can be applied internationally to the majority of existing viticultural settings.

## Materials and Methods

The methodological framework developed in the previous section was applied to analyze viticultural costs for 10 of the 12 vineyard types in Germany.

**Definition of viticultural process steps and time recordings.** At the start of the project, the researchers compiled and systematically number coded all viticultural process steps into 20 major categories with several subcategories (Supplemental Table 1). The categories of new planting, planting of missing vines, and maintenance of training systems do not occur on a regular annual basis and therefore are not considered here. Each viticultural process step is distinctly related to the appropriate machinery equipment, permitting an unambiguous allocation of machinery and its cost (Supplemental Table 2).

On a daily basis, vineyard workers entered their process steps (number codes), the vineyard site (number code), the



labor hours, and the machine hours into a Microsoft Excel spreadsheet prepared by the researchers. Harvesting time records only covered the process of picking the grapes and transporting them from the vineyard site to a grape wagon or onto a truck parked next to the vineyard. The harvesting time did not include the grape transport to the cellar, which is largely determined by the distance between the vineyard and the processing plant, a factor outside the scope of this study. Information on breaks and preparation times were separately recorded and were not included in the net-value work time records.

**Data collection.** The data were based on working and machine time records from five larger and management-led wine estates from five different winegrowing regions in Germany. Each of the participating wine estates identified several individual vineyards that differed in their viticultural typology and permitted a clear delimitation when recording working times. The vineyards represented 10 of the 12 possible combinations of viticultural mechanization (Table 3).

Data collection was performed for three years, from 2017 through 2019. In the far right columns of Table 3, the num-

ber of observations per vineyard type differed between the years because the wine estates changed viticultural practices (e.g., manual instead of machine harvesting) or they did not record a year because of personnel shortages. A total of 3444 diary entries were recorded and analyzed across 82 different vineyard site observations. Each observation was based on an average of 42.2 individual annual diary records per vineyard site (standard deviation [SD] 11.6). Differences in the number of observations in the last column reflect the relative rarity of some viticultural practices, such as MP or TTs, which are still rather uncommon in Germany.

The first two types, 1a and 1b, can be characterized as flat terrain sites; their accessibility and topography allow full mechanization, including the usage of an SH. All other types were somehow restricted in mechanization. Type 1b represents the standard vineyard type in Germany and many other countries and was, therefore, used as a reference for the cost estimates for the other types.

Type 2 sites were ordered by decreasing level of mechanization beginning with 2a, which had the least limitations in

**Table 2** Framework of vineyard types with optimal mechanization of viticultural processes dependent on external factors.

External factors (F)			Mechanization of viticultural processes (P)				
Determined by nature	Determined by winegrower		P1 General management	P2 Harvesting <sup>a</sup>	P3 Pruning	Type	
F1 Slope and access to vineyard sites	F2 Orientation of rows towards the slope <sup>a</sup>	F3 Training system <sup>a</sup>					
No limitation	—	MP	Unsupported	SH	Mechanical	1a	
		VSP	Unsupported	SH	Manual	1b	
Limited access for machines	DSS	MP	Unsupported	SSH	Mechanical	2a	
		MP	Rope	SSH	Mechanical	2b	
		VSP	Unsupported	SSH	Manual	2c	
		VSP	Rope	SSH	Manual	2f	
		TT	MP	Unsupported	SSH	Mechanical	2h
			VSP	Unsupported	SSH	Manual	2i
No access for machines	DSS/TT	VSP	Manual	Manual	Manual	3	

<sup>a</sup>DSS, direction of steepest slope; TT, transversal terraces; MP, minimal pruning; VSP, vertical shoot positioning; SH, standard harvester; SSH, steep slope harvester.

**Table 3** Framework of all vineyard types (optimally and suboptimally mechanized) and sample sizes included in the study.

F1 Slope and access to vineyard sites	Type	F2 Orientation of rows toward the slope <sup>a</sup>	F3 Training system <sup>a</sup>	P1 General management	P2 Harvesting <sup>a</sup>	n <sub>2017</sub>	n <sub>2018</sub>	n <sub>2019</sub>	n total
No limitation (flat terrain)	1a	—	MP	Unsupported	SH	2	2	2	6
	1b <sup>b</sup>	—	VSP	Unsupported	SH	3	5	6	14
Limited access for machines (mainly steep slopes)	2a	DSS	MP	Unsupported	SSH	—	1	1	2
	2b	DSS	MP	Rope	SSH	—	1	—	1
	2c	DSS	VSP	Unsupported	SSH	—	2	3	5
	2d <sup>c</sup>	DSS	VSP	Unsupported	Manual	8	6	4	18
	2e <sup>c</sup>	TT	VSP	Unsupported	Manual	1	1	1	3
	2f	DSS	VSP	Rope	SSH	1	4	3	8
2g <sup>c</sup>	DSS	VSP	Rope	Manual	7	4	5	16	
No access for machines (very steep slopes)	3	DSS / TT	VSP	Manual	Manual	3	4	2	9
Sum	—	—	—	—	—	25	30	27	82

<sup>a</sup>DSS, direction of steepest slope; TT, transversal terraces; MP, minimal pruning; VSP, vertical shoot positioning; SH, standard harvester; SSH, steep slope harvester.

<sup>b</sup>Reference site type.

<sup>c</sup>Suboptimally mechanized sites with manual harvesting, although mechanical harvesting might have been technically possible; no empirical observations were available for types 2h and 2i.

mechanization. These type 2 sites were coherently referred to as “steep slope sites”. Nevertheless, the cost estimates for type 2 sites were also applicable to flat terrain sites in which harvesting was manually conducted for quality reasons to allow selected picking of grapes even though the sites were suitable for mechanical harvesting. Type 3 sites required all work to be manually performed because the external factor F1 allows no access for machinery to the sites, which were characterized as very steep slope sites.

At the end of each year, the diary data were aggregated by the researchers and discussed among the wine estates’ managers. Through this comparison, outliers and data entry errors were identified, and the raw data were cleaned and corrected accordingly before analysis. Prior to the cost analysis, time records were standardized to per hectare values.

**Labor and machine cost approach.** Costs were derived by multiplying recorded times by the cost estimates for machinery and labor hours. The cost estimates for machinery were mainly based on detailed data collection for viticulture by the German Board of Trustees for Technology and Construction in Agriculture (KTBL). The total machine costs included seven components of fixed costs and three components of variable costs (Supplemental Table 3). Detailed fixed and variable cost components for all viticultural machinery employed are compiled in Supplemental Table 2. Two process steps were usually performed by external service providers who charged on a per-hectare basis. These per-hectare costs were entered as machine costs for process steps 905 “Main harvesting by steep slope harvester” and 1004 “Pest control–Helicopter.”

The cost estimates for labor input consisted of wage costs and minimum nonwage labor costs, which were based on union wage agreements, federal minimum wage provisions for Germany, and legally required social security contributions, as detailed in Supplemental Table 4. The total viticultural costs were calculated by summing the labor and machine costs. The costs of materials and consumables, such as fertilizers, pesticides, and other materials for integrated viticulture, were outside the scope of this study. The data for Germany suggest that these additional costs amount to ~997 €/ha (Euro/hectare) (Becker and Dietrich 2017, p. 121), which would have to be added to viticultural costs considered here if the full costs of grape production were to be assessed.

For the descriptive analysis, the averages and SD of labor costs, machine costs, and total costs were calculated per hectare. The calculations for the average cost per liter were initially based on an average German grape yield of 11.5 tons/ha (equivalent to 9002 L/ha) (our own calculation based on the Federal Statistical Office Germany 2015 to 2019). Subsequently, the effect of yield differences on the cost per liter are detailed. Potential quality differences among the mechanization options were outside the scope of this analysis.

**Analysis of variance (ANOVA) with fixed and random effects.** Observations among the five different wine estates and three vintages were partially related. To account for vintage and estate effects, univariate models of variance with fixed and random effects were estimated. Costs were the dependent variables; the external factors and processes were the independent,

fixed effects variables; and estate and vintage served as random effects variables to correctly model the interrelatedness of observations. Because of the limited number of observations, only the main effects of factors and processes could be considered. The partial  $\eta^2$  value was used as a measure of the effect size to assess the relative impact of the fixed effects on cost. It measured the cost variance share explained by a factor of that variance, which remained after the variance explained by other factors was excluded. Representing different residual explained variances, the partial  $\eta^2$  values did not sum to one. Post-hoc differences between the factor levels were estimated in SPSS software (SPSS, Inc.) with Tukey-B.

## Results

First, the descriptive results of the labor, machine, and total costs are detailed for the 10 vineyard types included in this study. Then, the results of the ANOVA are presented to answer the research questions.

**Descriptive analysis.** The labor costs, machine costs, total costs, relative share of labor costs, and costs per liter in €/ha and €/L are shown in Table 4. The total costs relative to the standard vineyard type, 1b, in column 15 show strong differences among the vineyard mechanization systems.

For flat terrain sites, the labor costs for MP sites were considerably lower than those for VSP sites, but the whiskers of the box plots in Figure 1 marginally overlap. For MP systems at flat terrain sites, the average total cost advantage of 2129 €/ha resulted in cost savings of 44% or 0.24 €/L for an average German grape yield.

There was a trending cost increase with more limited mechanization, shown in Figure 2. Despite this evident trend, overlapping standard deviations indicate that small sample sizes and the combination of the different factors resulted in non-significant differences among the eight systems from 2a to 3.

Steep slope vineyards that did not permit any form of mechanization had the highest average total cost of 12,410 €/ha or 1.38 €/L. These results represent a cost disadvantage of 164% and 0.86 €/L, respectively, compared to mechanized VSP flat terrain sites (3 versus 1b in Table 4). These nonmechanized steep slope sites required an average of 3.4 times as many labor hours as mechanized flat terrain sites, and the total costs were 2.6 times higher. There was a large SD from the nine observations, which suggested considerable differences. Changing steep slopes, which allow mechanization with rope and winch systems, from VSP to MP training systems reduced the total costs to 4944 €/ha and 5137 €/ha (lines 2a and 2b in Table 4), respectively, which was a decrease of 34% and 46%, respectively. In both cases, the machinery costs accounted for more than 80% of total costs, strongly reducing labor costs.

The costs per liter critically depended on grape yield per hectare, which has so far been held constant at the level of the German average of 90.02 hL/ha. The observed cost values can be transformed to different yields by dividing the total costs by the yield. The resulting costs per liter for a typical yield range are provided in Table 5.

**ANOVA.** The ANOVA estimated the main effects of the four fixed factors (i.e., F2, F3, P1, and P2) and two random

Table 4 Average values, standard deviations, shares, and differences for labor input and production costs of vineyard types compared to those of standard type 1b.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
		External factors (F) Viticultural processes (P)													Cost per liter <sup>a</sup>				
		Labor hours and costs						Machine hours and costs						Total costs					
Type	n	F3 Training <sup>b</sup>	F2 Row Orientation <sup>b</sup>	P1 General Management	P2 Harvesting <sup>b</sup>	Ø labor hours [hr/ha] <sup>b</sup>	Ø labor costs [€/ha]	SD labor costs [€/ha] <sup>bc</sup>	Ø machine hours [hr/ha]	Ø machine costs [€/ha]	SD machine costs [€/ha]	Ø total costs [€/ha]	SD total costs [€/ha]	Δ total costs [€/ha] vs reference 1b	% Δ total costs vs reference 1b	€/L	Δ €/L vs. reference 1b		
1a	6	MP	—	Unsupported	SH	49	991	199	46	1577	350	2568	523	-2129	-45%	0.29	-0.24		
1b	14	VSP	—	<b>Unsupported</b>	SH	218	3335	1060	32	1362	452	4697	1358	—	—	0.52	—		
2a	2	MP	DSS	Unsupported	SSH	39	611	390	34	4333	391	4944	676	+246	+5%	0.55	+0.03		
2b	1	MP	DSS	Rope	SSH	54	880	—	54	4257	—	5137	—	+440	+9%	0.57	+0.05		
2c	5	VSP	DSS	Unsupported	SSH	249	4148	512	39	3996	618	7446	991	+2748	+59%	0.83	+0.31		
2d	18	VSP	DSS	Unsupported	Manual	423	5947	1534	43	1089	402	7035	1713	+2338	+50%	0.78	+0.26		
2e	3	VSP	TT	Unsupported	Manual	311	4466	1182	47	2185	624	6651	1424	+1953	+42%	0.74	+0.22		
2f	8	VSP	DSS	Rope	SSH	283	4234	1268	63	5285	645	9519	1402	+4821	+103%	1.06	+0.54		
2g	16	VSP	DSS	Rope	Manual	506	7264	1502	67	3164	1303	10,428	2537	+5730	+122%	1.16	+0.64		
3	9	VSP	DSS/TT	Manual	Manual	735	10,081	3364	83	2329	1645	12,410	4585	+7713	+164%	1.38	+0.86		

<sup>a</sup>An average grape yield of 9002 L/ha was assumed for the calculation of the cost per liter. Type 1b in bold was the reference category for the calculations in columns 15, 16, and 18.

<sup>b</sup>DSS, direction of steepest slope; TT, transversal terraces; MP, minimal pruning; VSP, vertical shoot positioning; SH, standard harvester; SSH, steep slope harvester; Ø, average; SD, standard deviation.

<sup>c</sup>€, Euro.

factors across all 10 vineyard sites. The results in Table 6 indicate significant effects for mechanization of general viticultural management and harvesting technique on all three cost components and of the factor training system on labor costs and total costs.

The mechanization of general viticultural management (P1) significantly and very strongly affected all cost components. The partial effect size indicated that mechanization of general viticultural management explained between 37% and 45% of the remaining variance in labor, machine, and total costs not explained by other factors. The results of the post-hoc tests in Table 7 indicate significant differences for all three factor levels for labor and total costs and a differentiation between unsupported and manual versus rope mechanization for machine costs. Rope support required on steep slopes results in 1.5 times higher labor costs and 2.3 times higher machine costs compared to unsupported mechanization of general viticultural management. The labor costs for manual viticulture were 2.5 and 1.7 times as high as unsupported and rope-supported mechanization of general viticultural management, respectively. Because of the high costs of helicopter spraying (1400 €/ha/season; Supplemental Table 2), the machine costs for manual viticulture did not significantly differ from those of unsupported mechanization. The total costs for manual viticulture were 2.2 and 1.3 times higher than for unsupported and rope-supported mechanization, respectively.

The training system (F3) significantly and strongly affected labor costs but not machine costs and therefore, had a small to medium effect on the total costs (Table 6). The training system was the third most important factor for labor costs after general viticultural management and harvesting. Across the entire sample, on average, the total costs for MP systems were 59% lower than for VSP systems (Table 8). This cost advantage resulted from 6.4 times lower labor costs for MP systems, which were 15% of those for VSP systems (Table 8).

The harvesting technique (P2) significantly and strongly affected labor and machine cost and had a small to medium effect on total cost. It was the most important factor for machine costs (52% residual variance explained) and the second most important factor for labor costs (Table 6). Its strong influence was driven by high labor costs for manual harvesting and high machine costs for SSHs (Table 9). Manual harvesting requires ~37 times the working hours and 22 times the labor costs of an SH. The machine hours for an SSH were 1.9 times higher as an SH because the machine must pass the row twice. This difference was statistically significant. A direct comparison of individual cost components between SSHs and other levels was not possible because service providers were employed for SSH harvesting and charged a fee per hectare that was accounted for in machine hours. The total harvest costs for SSHs were 4.1 times higher than those for harvesting with an SH but not significantly different from those for manual harvesting.

Few observations of TTs in this study resulted in low test power, and no significant effects were observed for the fixed effect factor of row orientation (F2). The random factor of estate had a significant, medium-sized effect on labor costs and total costs. Although the three vintages included in this study remarkably differed from each other with regard to pest control, yields,

and harvesting conditions, the random effect of year did not significantly affect costs.

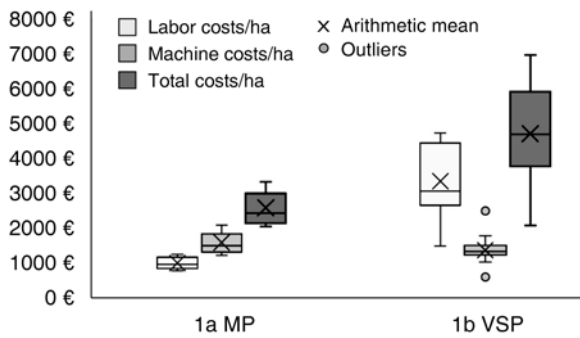
**Future projection of harvesting cost.** To assess whether future market developments might lead to a cost advantage for the SSH over manual harvesting, price developments and changes in ownership were projected over the next five years. Because the SSH is still a new technology, it is usually not yet part of the wine estates' machinery but is sourced out to service providers who mark up costs by a profit margin. Further refinement, larger-scale production, and positive experiences for winegrowers will likely result in ownership of these machines by wine estates that invest in the harvester head to be mounted on existing crawler tractors. In addition to individual ownership, cooperation or collective ownership are also feasible future options. Expert estimates of labor costs and machine costs were used for the SSH harvest costs projected for 2024. Past wage and machinery price increases of 8% each

since 2014 (Federal Statistical Office Germany 2019a, 2019b) were extrapolated five years into the future to 2024 (Table 9).

The total costs for harvesting with an SH and manual harvesting were both assumed to increase by 8%. Because of cost reduction and changes in ownership, the total cost of the SSH declined by 49%. These results assumed contrary price developments will result in a cost advantage for SSHs over manual harvesting by 2024.

### Discussion

Winegrowers have to base their decisions for viticultural alternatives on reliable full-cost information to keep their business profitable and economically sustainable. This study fills a research gap by providing wine producers with empirically measured information on the labor, machine, and total costs of different vineyard types.



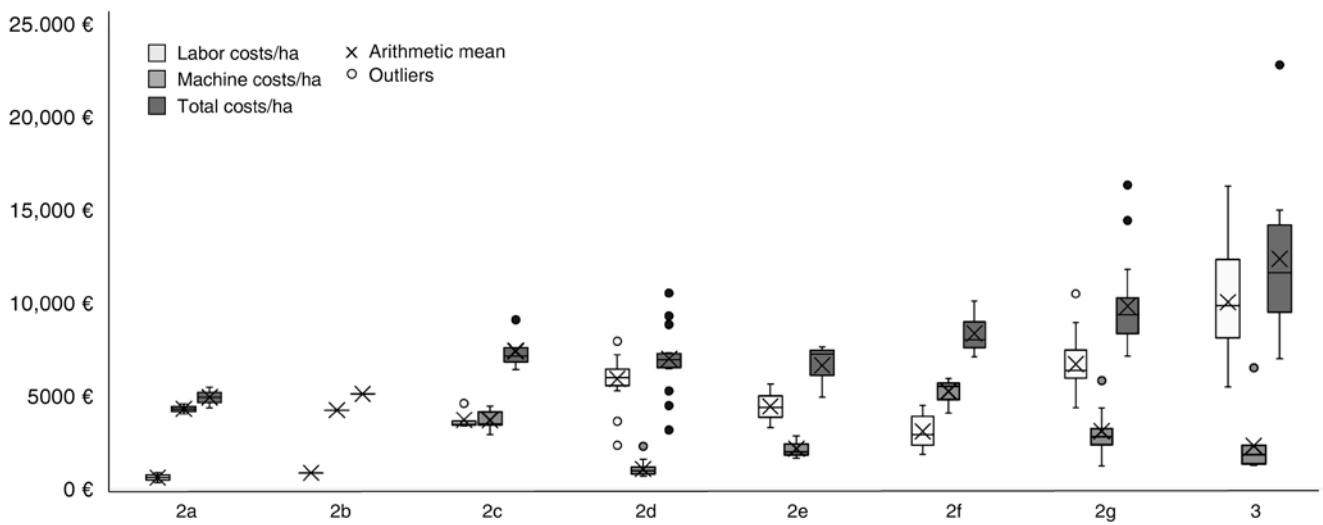
**Figure 1** Labor, machine, and total costs for training systems in flat terrain sites with no limitation of mechanization. MP, minimal pruning; VSP, vertical shoot positioning; €, Euro.

**Table 5** Total costs per liter for vineyard types at different yield levels.

Type	Ø total costs [€/ha] <sup>b</sup>	Yield <sup>a</sup>				
		50 hL/ha € cent/L	75 hL/ha € cent/L	100 hL/ha € cent/L	125 hL/ha € cent/L	150 hL/ha € cent/L
1a	2568	51	34	26	21	17
1b	4697	94	63	47	38	31
2a	4944	99	66	49	40	33
2b	5137	103	68	51	41	34
2c	7446	149	99	74	60	50
2d	7035	141	94	70	56	47
2e	6651	133	89	67	53	44
2f	9519	190	127	95	76	63
2g	10,428	209	139	104	83	70
3	12,410	248	165	124	99	83

<sup>a</sup>10 tons/ha grapes  $\pm$  78 hL/ha grape must (LWK RLP 2016).

<sup>b</sup>Ø, average; €, Euro.



Type	2a	2b	2c	2d	2e	2f	2g	3
Factor row orientation	DSS	DSS	DSS	DSS	TT	DSS	DSS	DSS/TT
Factor training system	MP	MP	VSP	VSP	VSP	VSP	VSP	VSP
Process general mechanization	Unsupported	Rope	Unsupported	Unsupported	Unsupported	Rope	Rope	Manual
Process harvesting	SSH	SSH	SSH	Manual	Manual	SSH	Manual	Manual

**Figure 2** Labor, machine, and total costs for site types with limited or no mechanization. DSS, direction of steepest slope; TT, transversal terraces; MP, minimal pruning; VSP, vertical shoot positioning; SSH, steep slope harvester; €, Euro.

**Table 6** Univariate model of variance for labor costs, machine costs, and total costs with fixed and random effects.<sup>a</sup>

Source <sup>c</sup>	df	Labor cost [€/ha] <sup>b</sup>			Machine cost [€/ha]			Total cost [€/ha]		
		F	p value	Part. $\eta^2$ <sup>d</sup>	F	p value	Part. $\eta^2$	F	p value	Part. $\eta^2$
Constant term	1	32.1	<0.001	0.40	81.2	<0.001	0.58	57.7	<0.001	0.54
P1 General management (F)	2	20.1	<0.001	<b>0.37</b>	28.6	<0.001	<b>0.45</b>	22.1	<0.001	<b>0.39</b>
P2 Harvesting (F)	2	15.0	<0.001	<b>0.30</b>	37.2	<0.001	<b>0.52</b>	5.2	0.008	0.13
F3 Training system (F)	1	18.2	<0.001	<b>0.21</b>	0.0	0.847	0.00	9.8	0.003	0.12
Estate (R)	4	2.9	0.028	<b>0.14</b>	1.8	0.140	0.09	2.8	0.033	<b>0.14</b>
Year (R)	2	0.6	0.550	0.02	1.1	0.351	0.03	0.5	0.580	0.02
F2 Row orientation (F)	1	3.8	0.054	0.05	1.2	0.283	0.02	0.9	0.342	0.01

<sup>a</sup>n = 82 observations.<sup>b</sup>€, Euro.<sup>c</sup>F, fixed effect; R, random effect.<sup>d</sup>Part.  $\eta^2$ , effect size partial eta-squared, sorted by decreasing effect size on total costs. Factors with a partial eta-squared value above 0.14 and 0.06 had a large and medium effect size on cost, respectively (Cohen 1988).**Table 7** P1 Mechanization of general viticultural management – Post-hoc Tukey-B test.

	Labor cost [€/ha] <sup>a</sup>	Machine cost [€/ha]	Total cost [€/ha]
Unsupported	4020 a <sup>b</sup>	1706 a	5726 a
Rope and winch	6039 b	3886 b	9925 b
Manual	10,081 c	2329 a	12,410 c
F-value	20.1	28.6	22.1
p value	<0.001	<0.001	<0.001

<sup>a</sup>€, Euro.<sup>b</sup>Different letters indicate significantly different values at  $p = 0.05$ .**Table 8** F3 Training system – F-statistics.

	Labor cost [€/ha] <sup>a</sup>	Machine cost [€/ha]	Total cost [€/ha]
VSP <sup>b</sup>	5844	2433	8278
MP <sup>b</sup>	894	2487	3382
F-value	18.2	0.0	9.8
p value	<0.001	0.847	0.003

<sup>a</sup>€, Euro.<sup>b</sup>VSP, vertical shoot positioning system; MP, minimal pruning system.**Table 9** P2 Harvesting technique: labor hours, machine hours, and costs for harvesting, current values, and future projection for the next five years – Post-hoc Tukey-B test.

Harvesting technique	Current labor intensity		Current harvest costs			Projected harvest costs		
	Labor hours harvest [hr/ha]	Machine hours harvest [hr/ha]	Labor costs harvest [€/ha] <sup>a</sup>	Machine costs harvest [€/ha]	Total costs harvest [€/ha]	Labor costs harvest [€/ha]	Machine costs harvest [€/ha]	Total costs harvest [€/ha]
SH <sup>b</sup>	4.0 a <sup>c</sup>	3.6 a	77 a	477 b	554 a	83 a	515 b	599 a
SSH <sup>b</sup>	6.7 a	6.7 b	0 a <sup>d</sup>	2250 c	2250 b	150 a	1006 c	1156 b
Manual	149.0 b	2.0 a	1868 b	55 a	1923 b	2018 b	57 a	2074 c
F-value	56.7	12.5	57.4	1352	32.1	52.5	101.7	8.5
p value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001

<sup>a</sup>€, Euro.<sup>b</sup>SH, standard harvester; SSH, steep slope harvester.<sup>c</sup>Different letters indicate significantly different values at  $p = 0.05$ .<sup>d</sup>For harvesting using an SSH, current labor costs were 0 €, which was attributable to the commissioning of service providers who did not differentiate between labor and machine costs in their invoices. For the projection, it was assumed that winegrowers owned and operated SSHs individually or in cooperation, incurring labor costs and machine costs. Projection by 2024: Labor and machine costs for SHs were +8% and costs for SSHs were -10%.

### Relative effects of mechanization on viticultural costs.

Because of its high frequency throughout the year, general viticultural management, including soil and canopy management and pest control, with standard or supported tractors had the largest cost-reducing effects compared to manual work across all three viticultural cost components. Thus, mechanization of general management in vineyards provided the largest cost reduction potential.

Harvesting was the second most important factor for labor costs and the most important factor for machine costs, which were partially offset at the total cost level. The training system strongly affected the total costs through a reduction in labor

costs, while the machine costs did not significantly increase. There were medium to strong, as well as significant differences in the average costs among the wine estates, which might have been related to general viticultural practices but could also have been caused by systematic differences in working time records. There were no systematic effects of vintage on costs suggesting generalizable results.

**Cost effects of MP.** For vineyard sites that were already optimally mechanized with unsupported tractors and SHs, labor intensity could only be further reduced by changing the training system to MP. The findings suggest a strong cost savings potential of 59% on average for the whole sample from

increasing mechanization of MP-trained vines. The average viticultural costs for flat terrain sites decreased from 0.52 €/L to 0.29 €/L, assuming an identical average yield per hectare. Usually, larger yields in MP systems of ~150 hL/ha in Germany result in a further cost advantage per liter.

The limited observations of steep slope sites also suggest strong cost savings potential for vineyards where SSHs can reliably be used for harvesting. Preliminary findings suggest a possible cost reduction to levels just above those for standard VSP flat terrain vineyards. MP training on steep slopes is only a feasible option if soil conditions and terrain allow the unrestricted use of an SSH for every vintage. Manual harvesting is not a feasible option for MP-trained vines, and the entire harvest is at risk when wet conditions restrict the use of SSHs.

Bulk wine producers face low profits or deficits (Strub et al. 2019) at German bulk wine prices of ~0.60 €/L to 0.80 €/L. For those producers, these cost savings offer strong potential to increase business viability. While MP training is already common in warmer climates like Australia, it is not yet standard in cooler climates like Germany. In light of continuously increasing wages and reduced availability of the labor force, MP is likely to increase in popularity. The required machine harvesting does not permit manual quality grape selection in difficult vintages, which might be required for top producers and high quality products. For the estimated 33,000 ha in Germany that are used to produce wines that are marketed as bulk wine, MP offers a viable chance for business survival because bulk wine usually does not receive a price premium for higher quality once minimum quality standards are met. However, introducing MP systems is a long-term commitment, because MP requires wider row spacing and cannot be immediately implemented. MP still has to overcome social prejudices in viticultural areas where winegrowers are considered lazy if their vineyards do not appear neatly combed. Sharing objective information about increased profitability might help overcome this preconception in the long term.

**Cost reductions through mechanization on steep slope sites.** Nonmechanized steep slope vineyards suffer from a cost disadvantage of an average 0.86 €/L compared to standard flat terrain sites. It is impossible to cover an average viticultural cost of 1.38 €/L excluding material costs, depreciation, or interest for equity plus overhead, and enological costs at current bulk wine prices of ~0.60 €/L to 0.80 €/L. Climate change-induced water stress on steep slopes further increases the cost per hectare by decreasing yield. Wine sold below costs results in incomplete coverage of personnel or machine costs, usually leading to abandonment of the company in the long term. Mechanization of steep slopes can help reduce, but not eliminate, their cost disadvantage.

The strongest cost savings potential lies in mechanization of general viticultural management. By introducing rope and winch assisted systems, the cost disadvantage reduces to an average of 0.64 €/L. Preliminary results from a few observations suggest that by further improving mechanization through restructuring vineyards to TTs, costs can be further reduced by 0.42 €/L. Public policymakers can compare these cost sav-

ings to the cost of establishing new transversal vineyards by large-scale landscape transformation.

Currently, the costs for manual harvesting and harvesting with an SSH are similar. Cost projections suggest that the relative advantage of the SSH will improve through investments of wine estates in their own SSH machinery and wage increases, scale-effects, and competition. More important than cost and wage considerations is the reduced availability of the workforce that is able to cope with the physically challenging labor on steep slopes. In addition, climate change has reduced the time window for harvesting (Loose and Pabst 2020), requiring more availability of workers to complete the harvest in less time. The shortage of labor and reduced harvest time windows will further increase the use of steep slope mechanization.

The limited data available thus far suggest the strongest cost reductions from MP in steep slopes if the vineyard allows access for machines. In addition to potential quality considerations for high range wines, the risk is considerably higher than in flat terrain regions, when wet weather conditions during autumn do not permit the usage of SSHs on steep slopes.

The results also provide empirical evidence about the required political support if steep slope viticulture should be preserved for reasons such as culture, tourism, or biodiversity. In cases where steep slope vineyards do not permit any mechanization, a cost disadvantage of an average 7713 €/ha has to be compensated by public funding. Current subsidies in Germany lie well below this value (Strub and Loose 2016).

**Limitations and future research.** After compiling working time records from 82 vineyard sites, the number of observations remained limited, particularly for the more unusual site types with MP and TTs. In the future, the methodology developed here should be applied to large data sets from digital vineyard management. Larger data sets also permit the modeling of interaction effects among factors, for instance, between steep slopes and MP, permitting more specific cost estimates. Viticulture will benefit from further penetration of digitization when programs such as Vineyard Cloud (Vineyard Cloud GmbH) automatically record and trace viticultural processes by geographic position, time, and process type. Large data sets from these applications will provide substantially more statistical power. The framework developed here to structure and assign vineyard types and viticultural processes can be a useful method for future assessment of digital big data and automatic analysis applications. Digitization and automation will also bring new technologies, such as spraying with multi-copters, to steep slope viticulture for which cost effects ought to be analyzed in the future.

This paper was limited to cost-efficient grape production. Interactions with a company's quality philosophy, market prices, resulting revenues, and business profitability were outside the scope of this analysis. Future research should also analyze the interaction between wine market returns and the various mechanization options. The data are, so far, limited to German wine estates and should be extended to other wine regions that differ in climate and viticultural practices, for instance, Mediterranean regions that require less pest control.

## Conclusion

The degree of optimal mechanization of viticultural processes is determined by three main external factors that can only be altered in the long term. Increasing mechanization of viticultural processes can improve economic sustainability of vineyards. MP can significantly reduce costs both in flat and steep terrain sites wherever mechanical harvesting is possible. Measures that permit mechanization and access for machinery can only partially offset cost disadvantages in steep slope viticulture.

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**Supplemental Data for:**

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**Supplemental Table 1** Process steps of vineyard management for working time recordings.

<b>Code</b>	<b>Process steps</b>	<b>Code</b>	<b>Process steps</b>
100	Winter pruning	902	Preharvesting by hand
101	Mechanical pruning	903	Main harvesting by hand
102	Manual main pruning without frost shoots	904	Main harvesting by standard harvester
103	Manual main pruning with frost shoots	905	Main harvesting by steep slope harvester
104	Pneumatic/electric main pruning without frost shoots	1000	Pest control
105	Pneumatic/electric main pruning with frost shoots	1001	Standard narrow track tractor
106	Manual removal of old canes without frost shoot	1002	Crawler tractor without winch
107	Manual removal of old canes with frost shoot	1003	Crawler tractor with winch/Steep slope mechanization system with winch
108	Mechanical removal of old canes	1004	Helicopter
109	Fasten and shorten of frost shoots	1005	Hose
110	Chopping of old canes	1006	Ampoules with pheromones
111	Removal of old canes from the vineyard	1100	Fertilization with mineral fertilizers
200	Tying	1101	Fertilization mineral, 0.1-0.2 t/ha
201	Tying - one cane/half arch	1102	Fertilization mineral, 0.3-0.5 t/ha
202	Tying - one cane/flat arch	1103	Fertilization mineral, 1.0 t/ha
203	Tying - two canes/half arch	1200	Fertilization with organic material
204	Tying - two canes/flat arch	1201	Fertilization organic, 20 m <sup>3</sup> /ha
300	Shoot-thinning, removal of excessive shoots	1202	Fertilization organic, 40 m <sup>3</sup> /ha
301	Shoot-thinning on the trunk manually	1203	Fertilization organic, 60 m <sup>3</sup> /ha
302	Shoot-thinning on the trunk mechanically	1300	Cultivation
303	Shoot-thinning chemically	1301	Ripper/disc harrow
304	Shoot-thinning near the head and along the canes, manually	1302	Rotary hoe/rotary harrow
400	Lowering the wires	1303	Deep plough
401	Lowering the wires manually	1400	Greening management
402	Lowering the wires mechanically	1401	Sowing of greening
500	Shoot positioning	1402	Mulching or milling of greening
501	Shoot position manually	1403	Mowing of edges by mulcher
502	Shoot positioning manually with wire spreaders	1404	Mowing of edges by motor scythe
503	Shoot positioning mechanically	1405	Mowing of trenches by mulcher
504	Removal of strings with reel on tractor	1406	Mowing of trenches by motor scythe
600	Trimming	1407	Mowing of embankments by mulcher
601	Trimming mechanically	1408	Mowing of embankments by motor scythe
602	Trimming manually using hedge trimmers	1500	Undervine cultivation
700	Defoliation	1501	Plough blade
701	Manual defoliation one-sided	1502	Intermediate axle disc plough
702	Manual defoliation two-sided	1503	Intermediate axis rolling hoe
703	Removal of first three leaves by hand	1504	Hoe (manually)
704	Defoliation with plucking machinery one-sided	1505	Motor scythe
705	Defoliation with plucking machinery two-sided	1600	Chemical weed control
706	Defoliation with blowing machinery one-sided	1601	Manually by hump sprayer
707	Defoliation with blowing machinery two-sided	1602	Mechanically
800	Yield regulation	1700	Straw application
801	Halving of compact clusters	...	
802	Halving of all clusters	2100	Irrigation
803	Removal of all grape clusters but one	2101	Installation of irrigation system
804	Loosing up of clenched clusters	2102	Irrigation
805	Removal of avarice grapes	2103	Maintenance of irrigation system
806	Yield regulation applying phytohormones		
807	Darwin brush		
900	Harvesting		
901	Negative selection by hand (e.g., before harvester)		



**Supplemental Data for:**

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**Supplemental Table 2** Composition of expenses for viticultural machinery.

	Purchase cost	Utilization potential [hr] <sup>a</sup>	Utilization duration [a]	Utilization [hr/a]	Fixed costs/a	Fixed costs/hr	Costs of repairs/hr	Fuel/h	Total costs /hr	Total costs/ha
Cane pruner	11,800 €	1000	8	125	1392 €	11.14 €	2.00 €	–	13.14 €	
Cane stripper <sup>b</sup>	24,675 €	1000	8	125	3356 €	26.85 €	2.00 €	–	28.85 €	
Cantilever arm	13,000 €	4000	6	667	2059 €	3.09 €	1.35 €	–	4.44 €	
Carrier for crawler tractor	15,000 €	15,000	15	1,000	1070 €	1.07 €	0.40 €	–	1.47 €	
Crawler tractor	69,000 €	5000	8	625	8142 €	13.03 €	6.70 €	6.77 €	26.50 €	
Console for under vine machinery	3300 €	350	10	35	323 €	9.23 €	0.80 €	–	10.03 €	
Darwin brush <sup>c</sup>	9000 €	500	10	50	24 €	0.48 €	1.50 €	–	1.98 €	
Deep plough 3 tines	6700 €	3330	10	333	712 €	2.14 €	4.00 €	–	6.14 €	
Defoliator one-sided	11,500 €	1000	8	125	1357 €	10.86 €	2.00 €	–	12.86 €	
Defoliator two-sided	19,000 €	1000	8	125	2242 €	17.94 €	2.00 €	–	19.94 €	
Fertilizer distributor	2850 €	1250	10	125	318 €	2.54 €	0.15 €	–	2.69 €	
Flat blade	3300 €	350	10	35	323 €	9.23 €	0.80 €	–	10.03 €	
Front sprayer frame	3400 €	5000	10	500	333 €	0.67 €	2.00 €	–	2.67 €	
Grape wagon 5000 L	23,000 €	12,000	10	1200	2489 €	2.07 €	0.40 €	–	2.47 €	
Helicopter for spraying, service provider <sup>d</sup>	–	–	–	–	–	–	–	–	–	1400 €
Intermediate axle disc plough	700 €	350	10	35	39 €	1,11 €	0.80 €	–	1.91 €	
Intermediate axle rotary hoe <sup>e</sup>	1200 €	350	10	35	118 €	3.36 €	0.80 €	–	4.16 €	
Manure distributor	10,500 €	12,000	10	1200	1131 €	0.94 €	0.40 €	–	1.34 €	
Mulcher	3900 €	900	8	113	460 €	4.09 €	5.10 €	–	9.19 €	
Mulcher for cantilever arm	7700 €	1000	8	125	943 €	7.54 €	5.90 €	–	13.44 €	
Narrow-track tractor 54 kW	70,500 €	8000	12	667	6417 €	9.63 €	3.80 €	5.47 €	18.90 €	
Ripper/ disc harrow	5500 €	1500	14	107	314 €	2.93 €	3.00 €	–	5.93 €	
Rotary brush	5500 €	800	8	100	649 €	6.49 €	1.50 €	–	7.99 €	
Rotary harrow	4900 €	1500	8	188	633 €	3.38 €	7.00 €	–	10.38 €	
Seed drill	3700 €	1125	14	80	314 €	3.91 €	2.50 €	–	6.41 €	
Sprayer mounted	9000 €	2000	10	200	913 €	4.57 €	2.20 €	–	6.77 €	
Sprayer pulled	14,500 €	2000	10	200	1452 €	7.26 €	2.40 €	–	9.66 €	
Spraying barrel 5000 L	2050 €	10,000	15	667	146 €	0.22 €	0.05 €	–	0.27 €	
Standard harvester 102 kW	195,000 €	1800	7	257	26,738 €	103.98 €	12.50 €	15.46 €	131.94 €	
Steep slope harvester, service provider <sup>f</sup>	–	–	–	–	–	–	–	–	–	2250 €
Steep slope harvesting head <sup>f</sup>	80,000 €	1800	7	257	10,583 €	41.16 €	64.00 €	–	105.16 €	
Trellising machine	21,000 €	1000	8	125	2478 €	19.82 €	2.00 €	–	21.82 €	
Vine trimmer one-sided over-row	9300 €	3000	8	375	1115 €	2.97 €	1.70 €	–	4.67 €	
Wire reel <sup>g</sup>	610 €	500	10	50	81 €	1.62 €	0.06 €	–	1.68 €	

<sup>a</sup>hr, hours; a, annum, year, based on Becker and Dietrich (2017).

<sup>b</sup>Estimation according to das deutsche weinmagazin 1/2016, p. 16.

<sup>c</sup>ÖKL; <https://oekl.at/richtwerte/>.

<sup>d</sup>Original invoice.

<sup>e</sup>Original offer.

<sup>f</sup>Based on information from Regnery, unpublished data, 2019.

### Supplemental Data for:

Strub L, Kurth A and Loose SM. 2021. Effects of viticultural mechanization on working time requirements and production costs. *Am J Enol Vitic* 72:46-55. doi: 10.5344/ajev.2020.20027.

**Supplemental Table 3** Machine full-cost components for vineyard management machinery.<sup>a</sup>

Fixed costs	Variable costs
Pro rata temporis depreciation	Performance-tied depreciation
Interest expenses for tied-up capital	Consumption of fuels at market prices
Expenses for liability insurance	Repair expenses
Expenses for technical inspection	
Motor vehicle tax	
Expenses for maintenance	
Expenses for storage	

<sup>a</sup>Based on Becker and Dietrich 2017, pp. 16–17.

**Supplemental Table 4** Database for labor costs.<sup>a</sup>

Wage Agreement Viticulture in Hesse, valid since 1 July 2017	Wage costs	Inclusive nonwage labor costs
<b>Vineyard and cellar workers for basic tasks</b>		
a) without training and work experience	10.41 €	14.21 €
b) after one year of employment and training	11.10 €	15.15 €
<b>Vineyard and cellar workers for heavy tasks</b>		
a) without training and work experience	11.80 €	16.11 €
b) after one year of employment and training	12.49 €	17.05 €
c) after three years of employment and training	13.88 €	18.95 €
<b>Winegrower</b>		
a) without corresponding, completed vocational training	13.88 €	18.95 €
b) with corresponding, completed vocational training	14.57 €	19.89 €
<b>Machine operator</b>		
a) Driver of motor-driven agricultural machines	14.57 €	19.89 €
b) Tractor driver	15.27 €	20.84 €
<b>Minimum wage provisions for Germany since 1.1.2018</b>	9.19 €	12.54 €
<b>Nonwage labor costs</b>		
Social security contributions	19.8% <sup>b</sup>	
Paid holidays	9.4% <sup>c</sup>	
Sick pay	7.3% <sup>d</sup>	
Sum	36.5%	

<sup>a</sup>No voluntary employer benefits included (such as training activities, health programs, or company pension schemes), based on: AGV Hessen e.V. and IG BAU 2010; Federal Ministry of Labor and Social Affairs Germany 2019.

<sup>b</sup>Techniker Health Insurance 2019.

<sup>c</sup>Own calculation based on 255 working days and 24 days of paid holidays.

<sup>d</sup>Rennert et al. 2019.

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## 2.2 Paper II: The cost disadvantage of steep slope viticulture and strategies for its preservation

This chapter is based on an article published by the author of the present work, with Simone Mueller Loose as a co-author. Any reference to the chapter should be cited as follows:

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**Declaration of co-authorship  
for doctoral theses based on published or submitted co-authored articles**



This declaration form has to be submitted together with the thesis.  
Please use one form for each publication.

Name of the candidate:  Larissa Strub
Title of the article: The cost disadvantage of steep slope viticulture and strategies for its preservation
Submitted to  or  accepted for publication or <u>published in</u>  OENO One

Authors contributed to the work according to the following categories  
(max. 100 % per column):

A - more than 75 % B- 51 to 75 % C - 26 to 50 % D- up to 25 % 0 - no contribution

*Please insert the appropriate letter/zero for each contributing author in the resp. column*

Name	Literature review	Development of theoretical model/frame work	Concept and design of the study/ analysis	Execution, choice and development of methods	Evaluation and interpretation of results	Concept and writing of the article	Signature of the author
Strub, Larissa	A	A	A	A	A	A	
Loose, Simone	0	D	D	D	D	D	

Please use an additional sheet if more authors contributed.

## The cost disadvantage of steep slope viticulture and strategies for its preservation

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### ABSTRACT

The falling fallow of steep slope vineyards is caused by cost disadvantages that have not been analysed so far. This study quantified the production costs of different types of steep slopes, identified cost drivers within viticultural processes and assessed the impact of grape yield on the production cost for vertical shoot positioning (VSP) systems. It also examined under what conditions the reshaping of steep slope vineyards into transversal terraces (TTs) is economically viable. Costs were derived from a dataset of 2321 working time records for labour and machine hours from five German wine estates over three years. The costs for standard viticultural processes were compared across five site types with different mechanisation intensities by univariate analysis of variance with fixed and random effects. The net present value (NPV) of reshaping slopes into horizontal terraces was also assessed. Manual management of steep slopes was determined to be 2.6 times more costly than standard flat terrain viticulture. The cost disadvantage of steep slopes mainly stems from viticultural processes with limited mechanisability that require specialised equipment and many repetitions. Current subsidies fall short of covering the economic disadvantage of manual and rope-assisted steep slopes. Climate change-related drought and yield losses further increase the economic unsustainability of steep slopes. Under certain conditions, the transformation of manual steep slope sites into TTs can be a viable economic option. Strategies to reduce the cost disadvantage are outlined. The estimated cost benchmarks provide critical input for steep slope wine growers' cost-based pricing policy. These benchmarks also give agricultural policy reliable indicators of the subsidies required for preserving steep slope landscapes and of the support needed to transform manual steep slope sites into TTs.

### KEYWORDS

steep slope viticulture, production costs, mechanisation, climate change, transversal terraces, economic sustainability, Germany

## INTRODUCTION

Planting vines on steep slopes has permitted viticulture in climatically marginal suitable zones. The practice has a long tradition in Europe, with the famous steep slope valley along the river Mosel dating back 2000 years to Roman times. The slopes provided climatic advantages for viticulture through improved insolation in spring and autumn based on the inclination of the slopes towards the sun, which was required to bring the grapes to ripeness (Hoppmann *et al.*, 2017). Historically, steep slope vineyards have made use of otherwise unsuitable agricultural land, as flat terrains have been reserved for the production of foodstuff.

### 1. Disadvantages from limited mechanisability and climate change

Nowadays, steep slope viticulture faces threats on two fronts: cost and climate. Viticulture on steep slopes has always been more burdensome than on flat terrain. While this extra effort was initially marginal when all viticulture involved manual work, its disadvantage increased sharply with the growing mechanisation of flat terrain sites starting in the 1950s (Schreieck, 2016; Strub *et al.*, 2021a).

Climate change has transformed the former climatic advantage of steep slopes for viticulture into a disadvantage. Dependent on the soil setting, intensified solar radiation often leads to problematic conditions on steep slopes. Reduced water retention capacity and high evapotranspiration often induce water stress that results in reduced yields (Hofmann and Schultz, 2015). Because of water scarcity, new plantations generally take up to three years longer to establish and bear fruit compared to flat terrain sites. Intense solar radiation can cause sunburn on the berries, which in turn alters the phenolic structure of wines and can negatively affect the sensory structure of white wines (Pons *et al.*, 2017; Ramos *et al.*, 2007; van Leeuwen and Darriet, 2016). These effects on the quantity and quality of wines have economic consequences for steep slope wine growers.

The ongoing decrease in the acreage of steep slope vineyards has been attributed to these detriments. For example, in Germany's largest wine-growing state, Rhineland-Palatinate, steep slopes have declined by 28 % between 1999 and 2015 (Strub and Loose, 2016). So far, there has been a lack of economic research on steep slope viticulture, particularly on the effects of limited mechanisation and yield losses on production costs. Although

viticulture has become increasingly mechanised in recent decades, the exact cost disadvantages for different types of steep slopes remain unknown. Reliable cost information is indispensable for wine producers' pricing decisions. Full costs must be covered if wine estates are to be economically sustainable (Strub *et al.*, 2021a). The intense price competition in the wine market (Loose and Pabst, 2019) and low consumer awareness and appreciation of steep slope wines (Loose *et al.*, 2017) pose significant challenges for steep slope wine producers in covering their full cost. The wine sector will therefore benefit from reliable empirical information about cost drivers, the economic impact of yield losses and strategies to reduce costs in steep slope viticulture.

### 2. Transformation of steep slope sites into transversal terraces (TTs)

The installation of transversal terraces (TTs) along the contours of a hill instead of rows running in the direction of steepest slopes (DSS) has been performed for decades in areas such as Baden in Germany and Priorat and Penedès in Spain to enable mechanisation in steep slope viticulture (Ramos *et al.*, 2007; Stanchi *et al.*, 2012). As a second advantage, TTs prevent rainwater from easily flowing down the hill, which is particularly important for strong rain events (Oliveira, 2001). However, so far there is no agreement whether terraced vineyards have a generally higher water retention capacity (Oliveira, 2001; Ramos *et al.*, 2007). The installation of TTs requires massive movements of soil, initiating a substantial intervention in the landscape (Cots-Folch *et al.*, 2006). Particular soil and topographic conditions must be met for the installation of TTs (Huber, 2015); which then require constant maintenance to prevent soil erosion and mitigate the risk of landslides (Tarolli *et al.*, 2014). Because a considerable share of the surface is used for the embankments carrying the terraces, the building of terraces leads to a decrease of the number of plants per hectare, depending on gradient and the embankment height (Huber, 2015).

### 3. Positive external effects of steep slopes for society

While steep slopes are no longer required to grow ripe grapes, they still provide positive external effects to society in the form of benefits for tourism and biodiversity (Cox and Underwood, 2011; Job and Murphy, 2006; Tafel and Szolnoki, 2020). European agricultural policy pays subsidies to steep slope wine growers to compensate for

the benefits of the public goods provided. Part of those subsidies is dedicated to increasing mechanisation by, for instance, transforming vertical steep slopes into TTs. To date, it remains unclear to what extent these subsidies cover the actual cost disadvantage. To make an informed decision, society in general and agricultural policy, in particular, depend on reliable information about the cost of subsidies required for the preservation of otherwise economically unsustainable steep slope viticulture.

#### 4. Research questions

This study aimed to analyse the cost structures in the management processes for steep slope viticulture with a focus on the cost effects of mechanisation and yields with respect to cost-saving potential. The study also examined the cost-saving potential of transforming vertical steep slopes into TTs.

The first set of research questions addressed the effects of mechanisability on cost differences between vineyard site types:

RQ1: What are the cost disadvantages of various steep slope viticultural systems compared to standard flat sites? (assuming identical yields)

RQ2: Which viticultural process increases costs most substantially on steep slope sites?

RQ3: How do differences in yields impact cost differences between viticultural systems?

The second set of research questions assessed whether transforming DSS steep slopes into TT sites is an economically viable option to overcome cost disadvantages and to sustain steep slope viticulture:

RQ4: To what degree can annual costs be reduced by reshaping steep slopes into TTs?

RQ5: When do annual cost savings pay off the cost of installing TTs?

### MATERIALS AND METHODS

The process steps of viticulture are first presented with their degree of possible mechanisation on flat terrain sites. External factors of terrain and the orientation of rows towards the slope resulted in a total of five different vineyard site types that differed in the degree to which specific viticultural processes could be mechanised. Total and single process step costs of these five site types will be compared in the analysis from a data set of labour and machine time records.

### 1. Processes of viticultural management

Viticultural management consists of different processes that are performed in a specific order throughout the vegetation period. The management cycle starts with pruning in winter and ends with picking the grapes in autumn. The cycle can be subdivided into three main complexes: winter pruning, general viticultural management and harvesting (modified based on Müller *et al.*, 2000; Strub *et al.*, 2021a). The required process steps and their execution vary depending on the training system of the vines. This study was limited to vineyard sites trained in a trellis with vertical shoot positioning (VSP). The standard processes performed on an annual basis in this system are listed in Table 1, together with their maximum degree of mechanisation at flat terrain sites and their required frequency within one year.

For flat terrain, almost all processes can be fully mechanised except for *Tying* (200), *Straw application* (1700), and particular methods of *Shoot positioning* (400, 500) and *Yield regulation* (800). These processes are all performed only once during the vegetation period (see Table 1). All processes that must be performed frequently (Pest management and Soil management) can be almost fully mechanised at flat terrain sites.

### 2. Site types

In the last section, the maximum degree of mechanisation of viticultural processes related to flat terrain sites was described. Three main external factors can limit mechanisability: “slope and access to vineyard sites”, “the orientation of rows towards the slope”, and “the training system” (Strub *et al.*, 2021a). As this paper is limited to vineyards with a VSP system, the factor training system is not relevant to the progress of the analysis. The “slope and access to vineyard sites” factor can be broken down into three levels: “no limitation”, “limited access for machines” and “no access to machines” (Column 1 in Table 2). Rows can be oriented in the DSS or on TTs (Column 2 in Table 2). The combination of the levels of both factors results in five different, optimally mechanised site types (last column in Table 2) that differ in the degree of mechanisation of the viticultural processes of “general management” and “harvesting” (Columns 3 and 4 in Table 2). These types will be detailed in the following.

	Process Complex	Code	Process	Description	Maximum degree of mechanisation *	Frequency [times per year]		
1	Winter pruning and tying	100	Winter pruning	Preparation of vines for the vegetation period; mechanical pre-pruning; manual pruning of vines resulting in one or two remaining canes as the basis for shoots to sprout in spring; removal of cut canes from wireframe, usually manually; mechanical chopping of cut canes or manual removal from vineyards	Partial	1		
		200	Tying	Remaining canes to be tied manually to wireframe to promote vines' growth as required	None	1		
		300	Shoot thinning	Removal of excessive shoots from trunk or cane – mechanically or manually, also in optimally mechanised sites	Full	2		
		400 500	Lowering the wires + Shoot positioning	Shoots to be brought in an upright position, either manually, also in optimally mechanised sites, between pairs of wire, or mechanically between pairs of strings, to provide ventilation of canopy and prevent damage in case of heavy wind; If shoot positioning with wires, wires need to be loosened and put down manually at the beginning of vegetation period	None: with wires Full: with string	3		
		600	Trimming (summer pruning)	Cutting of top and sides of canopy to support grape growth, hinder vegetative growth and improve ventilation and insolation – usually mechanically, by hand only steepest sites	Full	2-3		
		700	Defoliation	Removal of leaves to improve ventilation of grape zone and restrain the development of grapes to receive loosened grape clusters – mechanically or manually, also in optimally mechanised sites	Full	1		
		800	Yield regulation	Different options to reduce yield, either mechanically, by application of phytohormones or manually by removal of grapes or part of grapes	Full, depending on method	1		
		2	General viticultural management	1000	Pest control	Spraying of pesticides to prevent damage to vines, leaves and grapes, mainly by fungal diseases or insects – mechanically, in steepest sites, manually with a hose or by helicopter	Full	7-14
				1100 1200	Mineral or Organic Fertilisation	Biotechnological measures, such as the manual distribution of anapoules with insect pheromones, to prevent mating of the insects	None	1
				1300	Cultivation	Distribution of mineral or organic fertiliser in the vineyards to improve nutrient supply-mechanically, manually only steepest sites	Full	Every few years as required
1400	Cover crop management**			Breaking up of soil surface and composition to improve soil structure, ventilation, the release of nutrients and water holding capacity – mechanically, manually only steepest sites	Full	2-3		
1500	Under-vine cultivation			Sowing and managing cover crops to improve soil structure, provide nutrients, improve trafficability and prevent erosion-mechanically, usually no cover crops in steepest sites	Full	3-4		
1600	Chemical weed control			Removal of weeds between vines to decrease competition for water and improve ventilation between vines – mechanically, manually only steepest sites	Full	4-5		
1700	Straw application			Chemical removal of weeds by herbicides-mechanically, manually only steepest sites	Full	2		
2100	Irrigation			Manual distribution of straw on the surface to prevent erosion and evaporation – usually only in steep sites	None	1		
3	Harvesting			900		Additional water supply to prevent reduced yields and damaged wines due to drought-drip irrigation, if installed; otherwise mechanically, manually with a hose only in steepest sites	Full	As required
						Picking of grapes in autumn-mechanically or manually, also in optimally mechanised sites	Full	1



◀ **TABLE 1.** Standard processes of viticultural management in VSP systems (modified based on Müller *et al.*, 2000).

Notes: VSP-vertical shoot positioning; \*maximum degree of mechanisation at flat terrain sites; \*\*referred to as “Greening management” in Strub *et al.* (2021a).

The codes in the fourth column in Table 1 were created to simplify and structure the recording of working times and will be referred to throughout the paper. Aligning process steps to main process complexes causes codes to not be ordered strictly numerically.

**TABLE 2.** Framework of five vineyard site types with VSP under optimal mechanisation of viticultural processes dependent on external factors (modified based on Strub *et al.*, 2021a).

External Factors		Mechanisation of Viticultural Processes			Site Type	
Determined by Nature	Determined by Winegrower	Pruning*	General Management	Harvesting		
Slope and Access to Vineyard Sites	Orientation of Rows Towards the Slope					
No limitation	-	Manual	Unsupported	SH	1	Standard
Limited access for machines	DSS	Manual	Unsupported	SSH	2a	SSH
	TT	Manual	Rope	SSH	2b	Rope
No access to machines	DSS/TT	Manual	Unsupported	SSH	2c	TT
		Manual	Manual	Manual	3	Manual

Notes: VSP-vertical shoot positioning; DSS-direction of steepest slope; TT-transversal terrace; SH-standard harvester; SSH-steep slope harvester.

\*The degree of mechanisation of the pruning process step depends on the training system, which is outside the scope of this study. For VSP training systems, pruning is generally performed manually. In contrast, low-input training systems require mechanical pruning.

Corresponding site types in Strub *et al.* (2021a): 1 = 1b / 2a = 2c / 2b = 2f / 2c = 2i / 3 = 3.

*Site type 1-Standard:* In flat terrain, standard narrow track tractors and standard (grape) harvesters (SHs) can be used for viticultural management and harvesting (as detailed in Table 1).

*Site type 2a-SSHs:* For slopes with a gradient above 35 % to 40 %, depending on soil conditions, SHs must be replaced by steep slope harvesters (SSHs) or manual labour for the harvesting process (Walg, 2007).

*Site type 2b-Rope:* For slopes with a gradient above 40 %, standard tractors can no longer operate (Grečenko, 1984; Walg, 2007; Yisa *et al.*, 1998). Instead, for general viticultural management, crawler tractors, in combination with winch-and-rope systems, are used to prevent the tractor from sliding down the hill (Grečenko, 1984; Walg, 2007). These systems permit the mechanisation of most processes, which are also mechanised for flat terrain. However, the use of a crawler tractor critically depends on good soil structure. In the case of rainfall, it can be impossible to enter a steep slope vineyard with machinery. Moreover, once the crawler tractor is secured with a rope, every row needs to be passed twice (downwards and upwards in the same row), resulting in more

working and machine hours compared to standard tractors (Schrieck, 2016).

*Site type 2c-TTs:* Rows are planted on TTs that permit the use of a standard narrow or crawler tractor for general viticultural management in combination with an SSH for harvesting. The TTs created today are usually wide enough for one row of vines, which are planted towards the edges of the terraces with enough space between the row and the embankment for a narrow track tractor or a crawler tractor to pass. The tractors do not need any additional securing by winch and rope because they drive on flat terrain. Thus, the disadvantage of winch-and-rope systems, double-passing rows, is eliminated (Leimbrock, 1984).

*Site type 3-Manual:* On the most challenging steep slope sites, no access for machinery is possible, due to either the gradient or the location. This restriction necessitates manual labour for most processes. Although requiring special permits and at a high cost, pest management at these extreme sites can be mechanised using helicopter spraying.

### 3. Database of work and machine time records

This study’s data set consisted of 2321 working time records from 28 different vineyards that represented the five vineyard site types.

**TABLE 3.** Observations per site type, year and number of total observations.

Slope and Access to Vineyard Sites	Orientation of Rows Towards the Slope	General Management	Harvesting	n <sub>2017</sub>	n <sub>2018</sub>	n <sub>2019</sub>	n <sub>total</sub>	Site Type
No limitation	-	Unsupported	SH	3	5	6	14	1* Standard
	DSS	Unsupported	SSH	-	2	3	5	2a SSH
Limited access for machines	DSS	Rope	SSH / Manual	8	8	8	24	2b** Rope
	TT	Unsupported	Manual	1	1	1	3	2c** TT
No access for machines	DSS / TT	Manual	Manual	3	4	2	9	3 Manual
Sum				15	20	20	55	

Notes: DSS-direction of steepest slope; TT-transversal terrace; SH-standard harvester; SSH-steep slope harvester. \*reference site type \*\* in deviation from Table 2, for some observations, harvest was suboptimally mechanised but did not affect the cost because there was no significant cost difference between SSHs and manual harvesting (Strub et al., 2021a); hence, cases can be jointly analysed. Site type 2c is only analysed descriptively because of the small number of observations.

**TABLE 4.** Number of observations per site type and process step.

Code	Process	Site types					n <sub>total</sub>
		1	2a	2b	2c	3	
		Standard	SSH	Rope	TT*	Manual	
100	Winter pruning	14	5	24	3	8	54
200	Tying	14	5	24	3	9	55
300	Shoot thinning	13	5	22	3	9	52
400	Lowering the wires	3	1	4	1	3	12
500	Shoot positioning	14	5	24	3	9	55
600	Trimming	14	5	24	3	9	55
700	Defoliation	12	4	17	3	9	45
800	Yield regulation	3	2	4	1	3	13
900	Harvesting	14	5	24	3	9	55
1000	Pest control	14	5	24	3	9	55
1300	Cultivation	12	5	20	2	5	44
1400	Cover crop management	13	5	22	3	5	48
1500+	Weed removal	14	5	24	3	8	54

SSH-steep slope harvester; TT-transversal terraces.

\* Observations for descriptive analysis.

This set was part of a more extensive data set (Strub *et al.*, 2021a). The data were collected throughout 2017, 2018 and 2019 at five larger, management-led wine estates located in five different German wine-growing regions. Not all sites were sampled in all three years. For all number-coded viticultural activities (see Table 1 and Appendix I), workers recorded labour and machine hours in daily diaries. For comparability, the time records were standardised to per hectare values. Details of the sample are shown in Table 3.

The relative share of site types represents the typical distribution within the five wine estates as well as in Germany overall and therefore differs in the number of observations.

Detailed information on the sites analysed in this study are provided in Appendix II. Because of limited observations, those vineyard characteristics could not be included in the cost models. All sites were managed according to integrated principles, no site was cultivated by organic principles.

The sites were predominately planted with white varieties, mainly Riesling. The planting patterns mostly reflected standard German row distances of about 2 metres and common plant distances of around 1.2 metres. Row distances deviated partially in steep slope sites. Here also the previously common narrower distance of 1.6 metres was observed as well as very wide distances that resulted when the middle row was taken out to permit access of crawler tractors. The planting years were widely distributed between 1979 and 2014.

#### 4. Selection of process steps for analysis

Out of the complete list of 21 viticultural activities recorded (see Appendix I and Table 1), only those activities that are performed on a regular, annual basis were selected for analysis. Seven activities that are performed less frequently were exempted: (1100) *Mineral fertilisation*, (1200) *Organic fertilisation*, (1700) *Straw application*, (1800) *Replanting of missing vines*, (1900) *New planting*, (2000) *Maintenance work* and (2100) *Irrigation*. Although the costs for these steps were not included in the total cost, they only represented about 1 % of the total cost in this sample. The process steps (1500) *Under-vine cultivation* and (1600) *Chemical weed control* are two substitutive options for removing weeds and are rarely performed jointly by one estate. Therefore, it is sensible to analyse them jointly as a single process: *Weed removal* (code 1500+).

All process steps included in the comparative cost analysis are listed with corresponding sample sizes per site type in Table 4. The number of observations differs across single process steps. The majority of steps are imperative for viticulture and are performed at each vineyard site, while a few process steps are not compulsory and are thus performed in fewer cases (e.g., *Lowering the wires* and *Yield regulation*).

#### 5. Valuing time with cost

The per hectare working time records were valued with cost estimates for labour and machine hours (for full details, see Strub *et al.* (2021a)). The labour cost was based on union wage agreements as well as federal minimum wage provisions, depending on the type of process and the required workers' qualifications, and included non-wage labour costs (AGV Hessen e.V. and IG BAU, 2010; Federal Ministry of Labour and Social Affairs Germany, 2019). The machine cost included costs for depreciation, interest for tied-up capital, expenses

for maintenance, repair and storage, as well as fuel consumption, insurance and taxes based on Walg (2016), Becker and Dietrich (2017) and ÖKL (2020). The costs for pest control by helicopter and harvesting by SSH were based on contractors' prices and also included costs for personnel and their profit margin.

Average cost shares of the total cost for all process steps were calculated across all observations of each site type, independent of whether the viticultural process step was actually conducted or not. Thereby, the relative share was small for processes that were not compulsory and were rarely performed, and the sum of shares added up to 100 %. Total cost shares would exceed 100 % if the average was only calculated across those vineyards performing the processes.

The costs included in the analysis of variance were limited to labour and machine costs that in the following are referred to as "total cost". For the full viticultural cost, the following cost components would have to be added:

- a) Costs for viticultural materials and consumables of around 1000 €/ha (Becker and Dietrich, 2017).
- b) Depreciation costs for the vineyard plantations (around 1000 € per year and hectare for DSS, higher for TTs).
- c) Interest for tied-up capital for land and vineyard plantations, which is highly variable depending on land value.
- d) Costs related to the transit time from the machine shop to the vineyards, which are highly specific to individual wine estates.

#### 6. Analysis of variance with fixed and random effects (RQ 1-2)

The data include 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. *Site type* served as a fixed effect, and *Year* and *Estate* served as random effects. A series of univariate models of variance with fixed and random effects were estimated in SPSS to test whether the dependent variables total viticultural and process-related costs differed significantly between site types. Post-hoc differences between the site types were estimated using Tukey-B. Because of the limited number of observations ( $n = 3$ ), site type 2c TT could not be included in the analysis of variance.

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

Out of the processes analysed, only (900) *Manual harvesting* (positive correlation) and (800) *Yield reduction* (negative correlation) depend on yield. The costs of all other process steps can be assumed to be independent of yield. To account for the yield effect on costs, based on practitioners' experience, the cost for manual harvesting was reduced by 20 % for yields below 50 hl/ha and increased by 20 % for yield levels above 100 hl/ha. Also, the cost for yield regulation was set to zero for yields below 30 hl/ha. Total machine and labour costs were divided by different yield levels to obtain the cost per litre. Material cost, cost of depreciation and interest, as well as the cost of transit time were not included.

The average German yield of 90 hl/ha (2014 to 2018, Federal Statistical Office Germany, 2015–2019) for the standard site type 1 was used as the reference value for the analysis. For ease of interpretation, the costs of the other types dependent on yield were expressed as relative factors, where a factor of 2 represented 100 % higher cost.

For the different site types, the yield levels analysed were chosen to represent ranges from 20 hl/ha to 150 hl/ha observed in German vineyards. There are no official data available for yields at different site types. Practitioners estimated 75 hl/ha as the average German yield level for site types 2b and 3, but considerably lower levels down to 20 hl/ha were observed for the driest sites without irrigation. The maximum yield level for quality wine of the German Mosel region was limited to 125 hl/ha, which was chosen as the maximum of the range analysed for site types 2b and 3. Because of higher water availability, fully mechanised sites can mostly produce larger yields, and 50 hl/ha was chosen as the minimum value for the yield range for site types 1 and 2a.

### 8. Cost comparison with transversal terraces (TTs) (RQ 4)

The mean costs for site types 2b and 3 were descriptively compared to the mean cost for site type 2c TT from  $n = 3$  observations to obtain the cost differences. Because of the limited number of observations, inferential statistics could not be performed.

### 9. Profitability of conversion into transversal terraces (TTs) (RQ 5)

The advantage of the reduction of the viticultural

cost of type 2c TT sites was compared to the cost of conversion, taking into account risk and time.

The net present value (NPV) and time of amortisation were calculated with formulas (1) and (2) to assess the profitability of the conversion of type 2b and 3 sites into type 2c TT sites:

$$NPV = -C_0 + \sum_{i=1}^T \frac{C_i}{(1+r)^i} \quad (1)$$

$NPV$  = net present value,  $-C_0$  = initial investment,  $C_i$  = cash flow at year  $i$  ( $i=1, \dots, 30$ ),  $r$  = discount rate,  $T$  = useful life of 30 years for the vines. The useful life of the terraces exceeds that of the vines. The initial investment  $-C_0$  corresponds to the installation costs, which is a summary of different cost positions for the installation of terraced sites, detailed in Table 5. The amount of 74,228 € includes vineyard management for the young vines for the first two years (Table 5). The cash flow  $C_i$  is derived from the annual saving of vineyard management costs by improved mechanisation that is discounted at an interest rate.

Scenarios with two different interest rates were analysed. First, the standard cost of capital in the wine sector of  $r_1 = 4\%$  was applied, reflecting the higher risk of private equity compared to debt capital. As a second scenario, a higher discount rate of  $r_2 = 8\%$  was applied to reflect the high risk from climate change and limited experience with the transformation of DSS sites to TTs in Germany.

The amortisation period in years  $t^*$  reflects the time at which the cost savings will balance or exceed the investment (the NPV is zero).

$$t^* := \text{if } NPV \geq 0 \text{ €} \quad (2)$$

$t^*$  = amortisation period in years

At  $NPV = 0 \text{ €}$ , the economic situation equals the (unprofitable) reference situation. The cost of the transformation is covered. Benefits will only arise after the time of amortisation.

#### 9.1. Reference condition A: transforming unprofitable steep slopes

The reference condition is unprofitable for type 2b or 3 sites, where full cost, including depreciation, interest and material costs, exceeds revenues. It is assumed that these sites are fully depreciated; i.e. they reached or exceeded the end of their useful life of 30 years. Because of its unprofitability, replanting steep slopes in DSS is economically irrational, and these sites risk falling fallow. The full cost of installation must be taken into account

**TABLE 5.** Installation cost and cost-saving potential in vineyard management of vineyards on transversal terraces (TTs).

		Cost and Cash Flow in €/ha	
		Transformation of Type 2b	Transformation of Type 3
$-C_0$	Cost of installation and plantation of terraced vineyards *	-74,228 €	-74,228 €
$C_i$	Cash flow as annual cost saving from vineyard management	3595 €	6093 €

\* adapted based on Federal Ministry of Food and Agriculture Germany (2018).

in the analysis of this condition. Profit losses for the first five years, when the vines do not produce any yield, are not to be included here, because these unprofitable sites did not produce any profit.

### 9.2. Reference situation B: transforming profitable steep slopes

The reference situation is different when a steep slope vineyard (such as a famous single vineyard site) is profitable and there are viable plans to replant it with, for instance, grape varieties that are more suitable from a climate and/or market perspective. Because it would be replanted in any case, the cost of the plantation of 30,000 €/ha cannot be counted towards the cost of transformation to TTs. Hence, the required investments are lower. Similar, if a vineyard is transformed into TTs but is not yet fully depreciated, the residual value must be added to the installation cost. Profit losses for the initial five years without yield would also occur when replanting in DSS and are therefore not to be included.

### 9.3. Subsidies for conversion

The effect of subsidies on the profitability of conversions was analysed. The Common Agricultural Policy of the EU supports restructuring and conversion plans for vineyards. For Germany, subsidies for the installation of TTs, including the plantation of new vines, are between 16,000 €/ha and 24,000 €/ha, up to 50 % of the total investment (Federal Ministry of Food and Agriculture Germany, 2018). When replanting DSS steep slope sites subsidies of up to 18,000 €/ha are granted for the adaptation of the vineyard to current viticultural techniques and climate conditions (Hessian Ministry for the environment, Climate protection, Agriculture and Consumer protection, 2017). Therefore, only the

marginal higher subsidy of 6000 €/ha applies in this condition.

### 9.4. Factors not included in the analysis

Two factors, the yield and water availability of TT sites were not included in the analysis. The relative advantage of the availability of water at TT sites over DSS sites has not yet been sufficiently examined and quantified. Similarly, it is still unknown to what degree the lower planting density of up to 50 % (Huber, 2015) caused by embankments taking up space affects yield.

## RESULTS

### 1. Total cost differences between viticultural systems (RQ1)

The results of the statistical analysis are detailed in Table 6. There was a substantial and highly significant difference in total cost between site types (Column C,  $F = 26.6, p < 0.001$  fixed effect). At a smaller effect size, total cost also differed significantly between wine estates (Column D,  $F = 4.7, p < 0.01$  random effect), suggesting a smaller influence of managerial decisions of winegrowers on the total cost. The random factor *Year* did not affect total cost. The post-hoc test confirmed highly significant differences in total cost between vineyard sites that increased the more mechanisation was limited. The total cost of manual type 3 sites was on average 2.6 times as high as the total cost of type 1 standard flat terrain types (12,320 €/ha compared to 4,720 €/ha). With a cost factor of 1.6 and 2.1, respectively, site types 2a SSH and 2b rope were positioned in between both extremes. To answer RQ1: Steep slope sites cause significantly higher total labour and machine costs than flat terrain sites, and the costs increase the more mechanisation is inhibited by slope and access.

**TABLE 6.** Univariate model of variance of total cost and cost per process step with fixed and random effects, post-hoc tests, as well as absolute and relative cost difference of manual steep slope type 3 versus standard type 1.

Code	Process	Site type <sup>F</sup>	Estate <sup>R</sup>	Year <sup>R</sup>	1b Standard [€/ha]	2c SSH [€/ha]	2b Rope [€/ha]	3 Manual [€/ha]	Absolute Δ in €/ha	Relative Δ in %
100	Winter pruning	5.6 **	5.4 ***	0.5	1520 a	1585 a,b	1975 a,b	2222 b	702	46%
200	Tying	1.0	1.2	1.1	271	289	342	411	140	52%
300	Shoot thinning	0.4	10.2 ***	1.4	465	326	379	498	33	7%
400	Lowering the wires	1.9	2.8	1.3	168	168	233	258	90	54%
500	Shoot positioning	0.9	19.4 ***	3.0	622	389	696	648	26	4%
600	Trimming	14.3 ***	1.7	1.2	130 a	258 a	547 b	627 b	497	382%
700	Defoliation	5.6 **	2.8 *	0.0	121 a	343 a	532 a,b	825 b	704	582%
800	Yield regulation	28.6 **	9.2	9.6 *	501 a	454 a	486 a	1 235 b	734	147%
900	Harvesting	23.2 ***	1.8	1.2	608 a	2250 b	2194 b	2227 b	1619	266%
1000	Pest control	13.6 ***	6.5 ***	0.6	338 a	1069 a,b	1584 b	3399 c	3061	906%
1300	Cultivation	5.3 **	1.3	1.3	159 a	152 a	566 a,b	719 b	560	352%
1400	Cover crop management	14.1 ***	4.1 **	0.5	163 a	161 a	602 b	1 212 c	1049	644%
1500+	Weed removal	5.4 **	0.7	0.4	264 a,b	203 a,b	617 b	156 a	108	-41%
	Total cost	26.6 ***	4.7 **	1.6	4720 a	7446 b	9822 c	12,320 d	7600	161%
Relative cost difference compared to standard type 1										
						58%	108%	161%		

Notes: Columns C–E: Univariate model of variance with fixed effect (Site type) and random effects (Estate, Year). F-fixed effects; R-random effects. Columns F–I: Post-hoc test Tukey-B for dependent variable “total cost per process step” and fixed effect “Site type” as an independent variable. Different superscripts indicate significantly different values at  $p = 0.05$ .  
 Columns J–K: Difference of mean value of manual type 3 (Column I) and standard type 1 (Column F) absolute in € and relative in %  
 \*\*\*  $p \leq 0.001$ ; \*\*  $p \leq 0.01$ ; \*  $p \leq 0.05$ .

## 2. Cost differences for viticultural process steps between site types (RQ 2)

For 9 out of 13 viticultural processes, the costs differed significantly between the site types (*F*-statistics in Column C of Table 6). The factor *Site type* had the most substantial effect on the costs of the processes *Yield regulation*, *Harvesting*, *Trimming*, *Cover crop management* and *Pest control*. Of these five processes, *Pest control* showed the highest increase in the relative share of costs across all site types. Because of its high frequency, *Pest control* represents the relatively most costly process step for site 3 (28 % cost share) and the third most costly process step for types 2a and 2b (14 % and 16 %, respectively). The *Trimming* and *Cover crop management* processes also had a higher frequency (Table 1), but their relative share of costs only doubled for the least mechanisable sites.

Differences in the mechanisability of single processes (Table 1 and Table 2) were reflected in significant cost differences between the individual site types compared to the standard type 1 and in relative cost-shares (Table 7). Type 2a only

differed from the standard type 1 by using an SSH for the harvest, which resulted in a significantly higher cost (3.7 times higher) for *Harvesting* and a significantly higher total cost (60 % higher). For type 2a, *Harvesting* represented 30 % of the total cost compared to 13 % for type 1 (Table 7).

Type 2b was further limited by the rope system requirement for general viticulture (Table 2). Compared to the standard, this requirement resulted in significant cost increases for 5 of 13 processes: *Trimming*, *Harvesting*, *Pest control*, *Cover crop management* and *Weed removal*. Because of less time-efficient processes resulting from the double passing of rows and the higher machine cost for rope systems, the cost of these five processes was on average 3.9 times as high as that of standard type 1. Since the total cost more than doubled, with an increase of 110 %, the relative cost share of these five processes was about twice as high relative to type 1 (Table 7).

As expected, manual type 3 showed the largest number of processes for which costs were significantly higher than for standard type 1 (8 out of 13 processes analysed). Detailed absolute

**TABLE 7.** Share of process costs of the total cost per site type.

Code	Process	Cost-Share per Type in %				
		1 Standard	2a SSH	2b Rope	2c TT	3 Manual
100	Winter pruning	32	25	20	15	16
200	Tying	6	4	3	4	3
300	Shoot thinning	9	4	4	4	4
400	Lowering the wires	1	0	0	1	1
500	Shoot positioning	13	5	7	11	5
600	Trimming	3	3	6	1	5
700	Defoliation	2	4	4	2	7
800	Yield regulation	2	2	1	0	3
900	Harvesting	13	30	22	20	18
1000	Pest control	7	14	16	21	28
1300	Cultivation	3	2	5	2	3
1400	Cover crop management	3	2	6	15	5
1500+	Weed removal	6	3	6	3	1
	Sum of %	100	100	100	100	100
	Total cost in €/ha	4720	7446	9822	6227	12,320

Note: Percentage share values are based on the mean cost across all observations per site. Observations in which process steps were not performed were entered with zero cost.

and relative differences are provided in Columns J and K of Table 6. The *Pest control* cost increased the strongest, by a factor of 10, due to expensive external helicopter service providers or extensive manual work. Costs for *Cover crop management*, *Defoliation* and *Yield regulation* increased by factors of 7.4, 6.8 and 2.5, respectively, and significantly differed from all other site types.

The cost for *Harvesting*, representing between 13 % and 30 % of the total cost, did not differ between the three steep slope site types but was about 3.6 times as high compared to type 1. Although SSHs enabled mechanical harvesting for types 2a and 2b, the higher machine cost currently still compensates for the saved labour cost compared to type 3 manual steep slopes. As expected from Table 1, the costs of generally manual processes, such as *Tying*, *Lowering the wires* and *Shoot positioning*, did not differ significantly across site types.

Besides the three factors (1) higher investment cost for specialised machines, (2) less time-efficient processes and (3) the frequency of processes, the degree of necessity of viticultural processes is the fourth factor that explains cost differences. This factor expresses how imperative a process is for vineyard management. The frequency of process observations in Table 4 indicates that viticultural management does not necessarily have to include processes such as *Yield regulation*, *Cover crop management*, *Lowering the wires* and, partially, *Defoliation*. These processes show very high absolute cost differences in Table 6, but their relative share across all vineyards in Table 7 only increases marginally because many wine estates refrain from conducting these processes at all on steep slopes. For instance, *Cover crop management* is required for flat terrain sites to permit the trafficability of machines, but it is not often performed at type 3 sites where machines cannot be used in any case.

To summarise the results for RQ2, the factors mechanisability, frequency of repetition and necessity of the processes determined relative cost disadvantages. The *Winter pruning*, *Harvesting*, *Pest control* and *Cover crop management* processes showed the highest absolute differences and were thus the most potent cost drivers for site types 2b and 3. All these processes are mandatory except for *Cover crop management*, which can be omitted from very steep sites. *Pest control* and *Cover crop management* require several repetitions throughout the vegetation cycle, and potentially small cost differences add

up across repetitions. For the *Winter pruning* and *Harvesting* processes, type 2b and type 3 sites were disadvantaged through time-inefficient and expensive mechanisation or manual labour.

### 3. The influence of random factors *Estate* and *Year* on variance

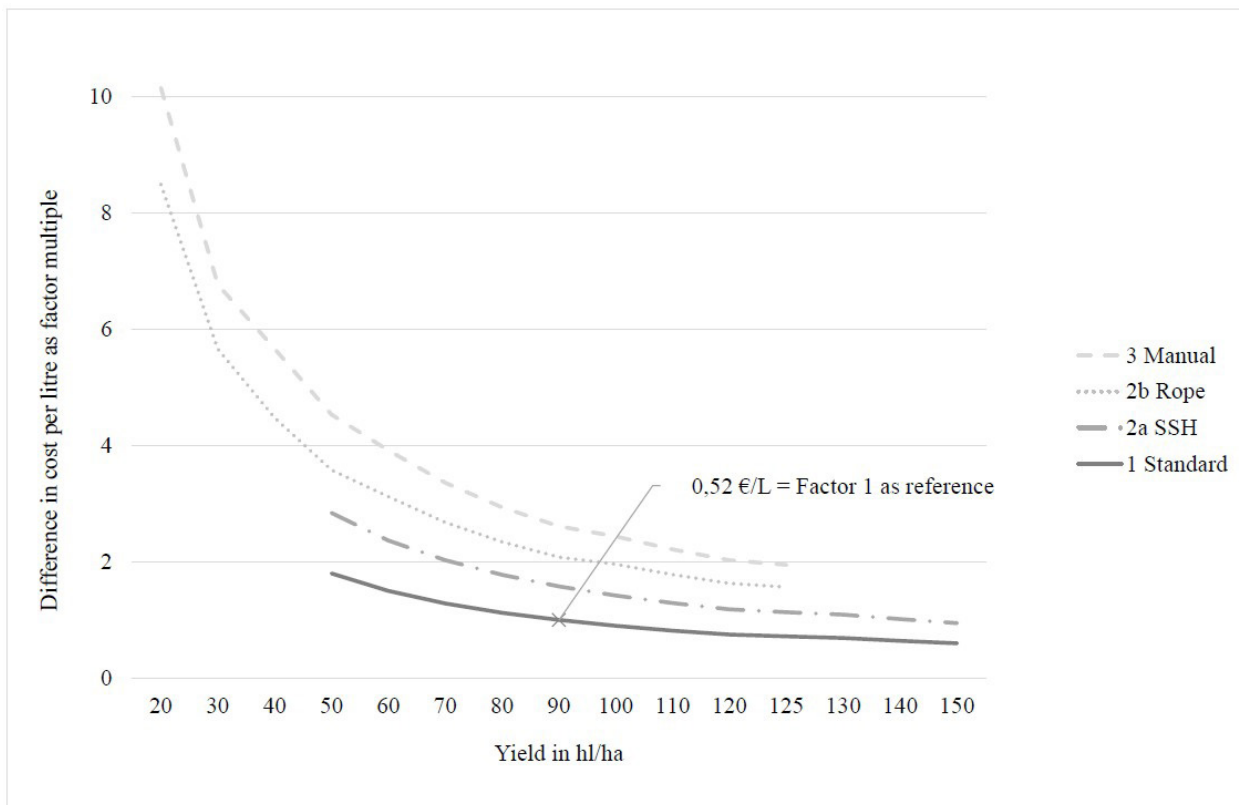
The random factor *Estate* had a significant effect on 6 out of 13 process steps. The effect was most substantial for *Shoot positioning*, *Shoot thinning* and *Pest control*. For both shoot-related processes of canopy management, the variance explained by the *Estate* factor was higher than that of *Site type*, suggesting that wine estates differ in their canopy management and can thereby influence and reduce the costs of processes that jointly represent between 9 % and 21 % of the total viticultural cost. The random factor *Year* only affected the *Yield regulation* process that was related to the plentiful 2018 harvest, when most wine estates reduced their yield significantly more than in other years. For all other processes, the random factor *Year* did not significantly explain the variance, suggesting generalizable results.

### 4. The influence of yield on cost per litre (RQ 3)

The per litre cost for different yield levels was calculated from labour and machine costs (total cost), not including the costs for materials, depreciation, interest and transport time. The results are presented in Figure 1 as factors relative to the cost of 0.52 €/litre for the average yield of 90 hl/ha for standard type 1. In Figure 1, there is a distinct convex shape, and cost per litre decreases less than proportional with rising yields. For type 1, cost per litre decreases to 0.31 €/litre when the yield rises to 150 hl/ha. On the contrary, cost per litre increases more than proportional when yields decline. For type 3, manual cost per litre increases from 1.37 €/litre for a yield of 90 hl/ha to 5.32 €/litre when yields decline to 20 hl/ha, resulting in a cost 10 times higher than the reference.

At a given yield on the x-axis, the vertical cost differences between the vineyard types represent the cost disadvantages from limited mechanisation. The horizontal effect on costs from lower yields represents the uncontrollable effect of climate change and lower availability of water as well as the controllable effect of yield reductions. Considering the substantial increase of costs with lower yields, their leverage on per litre price is considerably stronger than the effect of mechanisability (vertical differences between the curves).





**FIGURE 1.** Cost per litre as a function of yield per hectare for site types 1, 2a, 2b and 3.

To answer RQ3: Yield levels play a more critical role in the profitability of steep slope sites than mechanisability.

### 5. Cost reduction from reshaping steep slopes into horizontal terraces

For type 2c TT, the average total cost and process costs are provided in Column A of Table 8. Compared to the standard type 1, the total cost is 34 % higher. Of all steep slope sites, the TT type has the lowest cost disadvantage.

Reshaping type 2b rope and 3 manual steep slopes into TTs can strongly reduce annual labour and machine costs by 3600 €/ha and 6100 €/ha, or 37 % and 49 %, respectively. <sup>1</sup>The highest absolute cost-saving potential comes from *Harvesting* and *Winter pruning* for both types and *Pest control* and *Yield regulation* for type 3. The relative cost can be reduced the greatest for *Yield regulation*, *Defoliation* and *Trimming*.

### 6. Profitability of conversion to transversal terraces (TTs)

At the time of amortisation, the cost of conversion equals its benefit. Further benefits result in a profit that can be discounted to its NPV. For unprofitable vineyards that would fall fallow (reference

condition 1), the transformation of type 3 starts to pay off after 17 years, accruing an NPV of about 31,132 €/ha during its useful life of 30 years (under standard discount rate  $r_1 = 4\%$ , first line in Table 9). The transformation of type 2b only pays off after 45 years, and its NPV after 30 years is negative. The NPV increases to 11,937 € (55,130 €) for site type 2b (3 manual) when maximum subsidies of 24,000 € are included in the analysis. Then, the investment starts to pay off after 21 and 10 years, respectively.

If the high risk of climate change and its impact on water availability and temperature are considered through a risk premium in the higher discount rate of  $r_2 = 8\%$ , the transformation is only economically viable for subsidised type 3 sites.

For profitable vineyards, the replanting cost does not count towards the transformation into TTs (reference condition 2), and the investment is hence reduced by the average planting cost of 30,000 €/ha to 44,228 €/ha. The transformation is paid off sooner at 9 years for type 3 and 17 years for type 2b (Table 10). Subsidies are not required to motivate a transformation at the standard discount rate. Taking into account future risks by the higher discount rate, the investment will reach the break-even point with cost savings after 54 years

<sup>1</sup>The cost savings only relate to the main processes outlined in Materials and Methods and therefore differ marginally from the values in Strub *et al.* (2021a), where all processes were included in the analysis.

**TABLE 8.** Annual cost saving from the transformation of DSS to TT sites. Comparison of type 2c with types 2b and 3 for mean cost values.

Code	Site Type	Process	A		B		C		D		E		F		G	
			2c TT	Cost [€/ha]	2b Rope	Cost [€/ha]	Absolute $\Delta$ in €/ha	Relative $\Delta$ in %	3 Manual	Cost [€/ha]	Absolute $\Delta$ in €/ha	Relative $\Delta$ in %	3 vs. 2c	Absolute $\Delta$ in €/ha	Relative $\Delta$ in %	
100	Winter pruning		938	1975	-1037	-53%	2222	-1284	-58%							
200	Tying		245	342	-97	-28%	411	-166	-40%							
300	Shoot thinning		271	379	-108	-28%	498	-227	-46%							
400	Lowering the wires		126	233	-107	-46%	258	-132	-51%							
500	Shoot positioning		715	696	19	3%	648	67	10%							
600	Trimming		84	547	-463	-85%	627	-543	-87%							
700	Defoliation		109	532	-423	-80%	825	-716	-87%							
800	Yield regulation		31	486	-455	-94%	1235	-1204	-97%							
900	Harvesting		1275	2194	-919	-42%	2227	-952	-43%							
1000	Pest control		1331	1584	-253	-16%	3399	-2068	-61%							
1300	Cultivation		196	566	-370	-65%	719	-523	-73%							
1400	Cover crop management		907	602	305	51%	1212	-305	-25%							
1500+	Weed removal		167	617	-450	-73%	156	11	7%							
	Total cost		6227	9822	-3595	-37%	12,320	-6093	-49%							

Notes: DSS-Direction of steepest slope; TT-transversal terraces.

**TABLE 9.** NPV and time of amortisation of transformation of DSS into TTs (reference condition 1- unprofitable steep slopes).

	Cost in €/ha	
	Transformation of Type 2b	Transformation of Type 3
Without subsidies		
NPV ( $r_1 = 4\%$ )	-12,063 €	31,132 €
$t^*$	45	17
NPV ( $r_2 = 8\%$ )	-33,756 €	-5634 €
$t^*$	-	48
With subsidies of 24,000 €/ha		
NPV ( $r_1 = 4\%$ )	11,937 €	55,132 €
$t^*$	21	10
NPV ( $r_2 = 8\%$ )	-9756 €	18,366 €
$t^*$	-	©

NPV = Net present value at 30 years of useful life in €/ha;  $r$  = discount rate;  $t^*$  = amortisation period in years; DSS = direction of steepest slope; TTs = transversal terraces.

**TABLE 10.** NPV and time of amortisation of transformation of DSS into TTs (reference condition 2 – profitable steep slopes).

	Cost in €/ha	
	Transformation of Type 2b	Transformation of Type 3
Without Subsidies		
NPV ( $r_1 = 4\%$ )	17,936 €	61,132 €
$t^*$	17	9
NPV ( $r_2 = 8\%$ )	-3756 €	24,365 €
$t^*$	54	11
With marginal subsidies of 6000 €/ha		
NPV ( $r_1 = 4\%$ )	23,936 €	67,132 €
$t^*$	14	7
NPV ( $r_2 = 8\%$ )	2244 €	30,366 €
$t^*$	25	9

NPV = Net present value at 30 years of useful life in €/ha;  $r$  = discount rate;  $t^*$  = amortisation period in years; DSS = direction of steepest slope; TTs = transversal terraces.

(11 years) for type 2b (type 3) sites. Subsidies reduce the amortisation period to 7 to 25 years, depending on site type and discount rate.

## DISCUSSION

### 1. Economic sustainability of steep slope viticulture

Steep slope viticulture in Germany suffers from 1.6 to 2.6 times higher labour and machine costs. In a highly competitive market environment, wine estates have few options to compensate for this substantial disadvantage. Wine from steep slopes generally does not benefit from a higher reputation or price mark-ups (Loose *et al.*, 2017; Strub and Loose, 2016). A few famous single vineyard sites, such as Bernkasteler Doctor (Mosel), Roter Hang (Nierstein, Rheinhessen) or Würzburger Stein (Franconia), profit from high reputation and price mark-ups. Generally, wine estates with steep slopes have to focus on profitable market channels, such as direct cellar door sales with its high margins or premium wine retailers with high average prices. However, both market channels are limited in size and have been declining in Germany (Loose and Pabst, 2018).

Over the short term, wine estates can cross-subsidise their steep slope vineyards by returns from cost-efficient flat sites. Cross-subsidisation poses difficulties in wine-growing areas such as the Mosel valley or the Middle Rhine valley, where flat sites rarely exist. Many family estate owners perceive their steep slopes as a personally imposed obligation and are willing to sacrifice part of their income to preserve the heritage of their families (Loose and Strub, 2017). While this might work in the short term, the insufficient economic sustainability of small steep slope wine estates poses a significant risk for their long-term survival (Loose *et al.*, 2021). Required investments in equipment and marketing cannot be undertaken, further deteriorating long-term perspectives and opportunities to find successors for their businesses.

### 2. Strategies for cost reductions

Generally, mechanisability reduces manual labour and decreases cost disadvantages. Besides this overall relationship, the analysis identified four particular factors as cost drivers: (1) time-inefficiency of mechanisation solutions (double-passing of rows with rope) that require more labour and machine time, (2) higher costs from investment in specialised machinery (SSH, rope systems), (3) the number of repetitions of

processes required, and (4) the degree of necessity of processes. Of these factors, the first two are related to the cost of mechanisation and the last two are associated with viticultural processes. Three particular strategies for cost reduction can be derived from these factors and can be applied on their own or in combination.

#### 2.1. Cost-efficient mechanisation of costly processes

The mechanisation of steep slope viticulture should focus on the costliest compulsory processes of *Harvesting*, *Pest control* and *Winter pruning* and provide time-efficient solutions that do not require major investments which increase machine costs. For instance, Strub *et al.* (2021a) showed that the total time and machine costs of the SSH harvester are currently still on par with manual harvesting costs. Economies of scale and cooperation in the ownership and usage of machines are viable options for decreasing costs in the future. This also applies to the current development of spraying solutions with drones as an alternative to helicopters, which also permit a significant reduction of energy intake as well as treatment doses.

#### 2.2. Change in viticultural management

Viticulture on steep slopes must take advantage of developments that make costly processes unnecessary or reduce their required frequency. Fungus-resistant grape varieties only require one or two spraying applications per year. So far, however, these varieties still suffer from limited market acceptance. Similarly, growing vines in low input training systems i.e. minimal pruning (MP; Clingeffer, 1983) or semi-minimal pruned hedge (SMPF; Molitor *et al.*, 2019) and to some degree in cordon training systems replaces manual pruning and tying in mechanised sites (Strub *et al.*, 2021b). Some of these changes only apply to newly planted vineyards, and this strategy cannot be implemented in the short term.

#### 2.3. Weighing costs and benefits of optional processes

The analysis provided wine estates with cost benchmarks for processes that are not mandatory but very costly to conduct on steep slopes, such as *Yield regulation*, *Cover crop management*, *Lowering the wires* and *Defoliation*. Individual estates must weigh the costs of these optional processes against their benefits, which are mainly related to the quality of the grapes and potential price mark-ups. Producers must critically evaluate

their product portfolios (quality differentiation), volumes and pricing strategies. They must assess for which products marginal turnover exceeds the extra cost for these processes to pay off. Similarly, relative cost and quality potential must be taken into account for product allocation. High-quality wines that require particular processes should be produced at mechanisable sites if their quality potential suffices. If they do not benefit from a famous reputation or superior quality, type 3 steep slopes should be left to qualities that require minimal processes.

### **3. Stabilisation of yields to improve profit situation**

The current observable reduction in the availability of water on steep slopes will further increase with climate change (Hannah *et al.*, 2013). The resulting yield losses will have an immense impact on cost per litre. Already today, yields on steep slopes as low as 20–30 hl/ha are increasing the cost per litre by a factor of 7 to 10 compared to flat terrain (see Figure 1). Water availability is crucial for the survival of viticulture at these sites, and future research must therefore extend the analysis of this study to the installation and operation costs of irrigation.

Irrigation can be a mid-term solution in areas where water is available at a low cost. Contrary to Australia, Germany and many other European wine-growing countries still lack a systematic water allocation system for agriculture. The principle “first-come, first-serve” will soon break down the more agricultural businesses wish to access declining water resources. Dams to store water from winter precipitation are costly to build in densely settled European areas. Like in Australia, German society has begun discussing the social license of crop production (Dumbrell *et al.*, 2020), whether scarce water should be used for the production of alcoholic beverages or instead for essential grains and vegetables (Motoshita *et al.*, 2020). Drought-resistant rootstocks could be a long-term option by which experts can hope for successful breeds and selection in 30 years or more. However, these developments might come too late for German steep slope viticulture.

### **4. Assessment of vineyard transformation into terraces**

The transformation of unprofitable manual type 3 sites can be an economically viable option, even when positive external benefits to tourism, biodiversity, etc. are not accounted for.

Quantifying these positive externalities will help to provide an economic rationale for subsidising the transformation that shortens the time of amortisation and provides an incentive for wine producers to continue steep slope viticulture even under the high risk of climate change.

The transformation into TTs is an investment in a future dominated by the accelerating impact of climate change. Temperatures and extreme rain events will increase; the availability of water will further decline. Any new planting today must therefore anticipate these imminent changes (Santos *et al.*, 2020; van Leeuwen *et al.*, 2019). Such planting must include preventive measures, such as the use of heat-tolerant, fungus-resistant grape varieties or water stress-resistant rootstocks planted for low-input training systems, thereby securing available water resources. That said, it remains uncertain whether such measures will suffice considering the 34 % cost disadvantage TTs have against standard flat sites. Considering this climate risk economically through a higher-risk premium strongly reduces the profitability of the transformation into TTs.

### **5. Consequences for agricultural policy**

The rationale for subsidies for steep slope viticulture should be based on their positive benefits for biodiversity, touristic attractiveness of viticultural regions and wine producer business clusters as well as the public value of historic landscapes (Cox and Underwood, 2011; Job and Murphy, 2006; Tafel and Szolnoki, 2020). Unfortunately, those positive external effects are as of yet unassessed and therefore unavailable. From a pure cost perspective, subsidies should be aligned to differences in variable costs (here labour and machine costs) between steep slope and flat terrain sites. Current subsidy allocation that is based on slope alone must be revised. Instead, mechanisability and related cost disadvantages serve as a better basis for a fair and economical allocation of subsidies.

The results of this study indicate that steep slope viticulture with VSP systems suffers from a variable cost disadvantage of 1507 € (type 2c), 2726 € (type 2a), 5102 € (type 2b) and 7600 € (type 3) per hectare. The current German scheme of direct payments of up to 3000 €/ha only depends on the slope gradient and does not take mechanisability into account (Strub and Loose, 2016). It does not suffice to cover the cost disadvantages of types 2b (rope) and 3 (manual). If the full cost disadvantage was to be covered, this would require additional

subsidies of 30.4 Mio. € annually, assuming 4 % of German vineyard acreage to be type 3 and type 2b each. In the long term, required payments could be reduced for all mechanisable type 2 sites by low-input training systems and fungus-resistant grape varieties.

Finally, society must make a political decision on how it will allocate the available public funds (taxpayers' money). Besides the public benefits provided, the next best use of funds and land should be evaluated open-mindedly. Considering all these aspects, steep slope sites outside of tourist areas might possibly provide a higher overall benefit to society by being planted with trees instead of vines, thereby serving as a carbon sink (Pugh *et al.*, 2019).

## 6. Limitations and future research

Data were limited to Germany and thus require replication in other wine-growing areas and climates. The number of observations of the different site types were limited, particularly for vineyards planted on TTs. Digital viticultural management applications, such as Vineyard Cloud®, will in the future provide larger data sets that allow more robust estimates. The economic analysis of steep slope viticulture will benefit from future research on the effect of planting density and water availability on the yield of type 2c TT sites compared to other sites. Research utilising the principles of true cost accounting will be crucial in the future, which considers positive external effects from biodiversity and attractiveness to tourism as well as the true costs of irrigation and water allocation systems. Future research into viticultural mechanisation solutions must consider their impact on viticultural costs. The economically sustainable transformation of steep slopes into TT sites depends on successful research into drought-resistant rootstocks and market-accepted, fungus-resistant grape varieties.

## CONCLUSION

Through significantly higher labour and machine costs, steep slope viticulture poses a threat to the economic sustainability of viticulture that can only be partially reduced through mechanisation. The mechanisation of steep slopes comes at a cost that must be taken into account for the development of new technical solutions. The conversion of steep slopes into TTs only pays off in the future when the climate change risk for steep slope viticulture will have been further aggravated. The time of amortisation can be

shortened by subsidies. Already, the lower yields from limited water availability on steep slopes are significantly increasing costs and risk profitability. The viability of steep slope viticulture in middle Europe risks being degraded further in the future. Decisions about its preservation through public subsidies depend on the implementation of true cost accounting and the valuation of public benefits provided by steep slope viticulture.

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**Appendix I. Process steps of vineyard management for working time recordings.**

<b>Code</b>	<b>Process Steps</b>
100	Winter pruning
101	Mechanical pruning
102	Manual main pruning without frost shoots
103	Manual main pruning with frost shoots
104	Pneumatic/electric main pruning without frost shoots
105	Pneumatic/electric main pruning with frost shoots
106	Manual removal of old canes without frost shoots
107	Manual removal of old canes with frost shoots
108	Mechanical removal of old canes
109	Fastening and shortening of frost shoots
110	Chopping of old canes
111	Removal of old canes from the vineyard
200	Tying
201	Tying—one cane/ half arch
202	Tying—one cane/ flat arch
203	Tying—two canes/ half arch
204	Tying—two canes/ flat arch
300	Shoot thinning—removal of excessive shoots
301	Shoot thinning on the trunk manually
302	Shoot thinning on the trunk mechanically
303	Shoot thinning chemically
304	Shoot thinning near the head and along the canes - manually
400	Lowering the wires
401	Lowering the wires manually
402	Lowering the wires mechanically
500	Shoot positioning
501	Shoot position manually
502	Shoot positioning manually with wire spreaders
503	Shoot positioning mechanically
504	Removal of strings with reel on tractor
600	Trimming
601	Trimming mechanically
602	Trimming manually using hedge trimmers
700	Defoliation
701	Manual defoliation one-sided
702	Manual defoliation two-sided
703	Removal of first three leaves by hand
704	Defoliation with plucking machinery one-sided
705	Defoliation with plucking machinery two-sided
706	Defoliation with blowing machinery one-sided
707	Defoliation with blowing machinery two-sided
800	Yield regulation
801	Halving of compact clusters
802	Halving of all clusters
803	Removal of all grape clusters but one
804	Loosening up of clenched clusters
805	Removal of avarice grapes
806	Yield regulation applying phytohormones
807	Darwin brush
808	Selective removal of whole grapes

<b>Code</b>	<b>Process Steps</b>
900	Harvesting
901	Negative selection by hand (e.g., before harvester)
902	Pre-harvesting by hand
903	Main harvesting by hand
904	Main harvesting by standard harvester
905	Main harvesting by steep slope harvester
1000	Pest control
1001	Standard narrow track tractor
1002	Crawler tractor without winch
1003	Crawler tractor with winch/Steep slope mechanisation system with winch
1004	Helicopter
1005	Hose
1006	Ampoules with pheromones
1100	Fertilisation with mineral fertilisers
1101	Fertilisation mineral—0.1–0.2 t/ha
1102	Fertilisation mineral—0.3–0.5 t/ha
1103	Fertilisation mineral—1.0 t/ha
1200	Fertilisation with organic material
1201	Fertilisation organic—20 m <sup>3</sup> /ha
1202	Fertilisation organic—40 m <sup>3</sup> /ha
1203	Fertilisation organic—60 m <sup>3</sup> /ha
1300	Cultivation
1301	Ripper/disc harrow
1302	Rotary hoe/rotary harrow
1303	Deep plough
1400	Cover crop management
1401	Sowing of cover crops
1402	Mulching or milling of cover crops
1403	Mowing of edges by mulcher
1404	Mowing of edges by motor scythe
1405	Mowing of trenches by mulcher
1406	Mowing of trenches by motor scythe
1407	Mowing of embankments by mulcher
1408	Mowing of embankments by motor scythe
1500	Under-vine cultivation
1501	Plough blade
1502	Intermediate axle disc plough
1503	Intermediate axis rolling hoe
1504	Hoe (manually)
1505	Motor scythe
1600	Chemical weed control
1601	Manually by hump sprayer
1602	Mechanically
1700	Straw application
1800	Planting of missing vines
1801	Planting of the vines in existing plantation
1802	Hoeing
1803	Shoot thinning
1804	Tying
1900	New planting
1901	Removal of old plantation

Code	Process Steps
1902	Preparation of the soil
1903	Planting preparation and planting
1904	Construction of supporting system
1905	Vine care first year
1906	Vine care second year
1907	Soil cultivation
1908	Weed control
1909	Pest control
1910	Fertilisation
2000	Maintenance training system
2100	Irrigation
2101	Installation of irrigation system
2102	Irrigation
2103	Maintenance of irrigation system

## Appendix II. Detailed information on the sampled sites.

Site Type		Variety	Row Distance in m	Plant Distance in m	Planting Year*
1 Standard	1	Riesling	2.0	1.2	2007
	2	Riesling	2.0	1.2	2009
	3	Riesling	2.0	1.2	1988
	4	Silvaner	2.0	1.2	2008
	5	Müller-Thurgau	2.0	1.2	1989
	6	Pinot Gris	2.0	1.1	2003/2013
2a SSH	1	Riesling	2.0	1.2	2009
	2	Riesling	1.7	1.2	1992
	3	Pinot Noir	2.0	1.0	2012
	4	Riesling	2.0	1.2	2005
2b Rope	1	Riesling	2.0	1.2	2004/2005
	2	Riesling	2.0	1.1	2010
	3	Riesling	2.0	1.2	1998/2005
	4	Riesling	2.0	1.3	2004/1990
	5	Riesling	2.0	1.2	2002
	6	Riesling	2.5	1.2	1996
	7	Riesling	2.0	1.2	1995
	8	Pinot Blanc	2.0	1.2	1993
	9	Silvaner	1.6	1.4	1992/1994
	10	Riesling	1.6	1.0	1993
2c TT	1	Pinot Noir	2.1	1.1	2012
	2	Pinot Noir	3.5	0.8	1998
	3	Riesling	1.6	1.0	2014
3 Manual	1	Riesling	2.0	1.4	1998/2005
	2	Pinot Noir	1.4	1.0	1992
	3	Riesling	1.8	1.0	1987
	4	Pinot Noir	1.5	1.2	1979
	5	Riesling	2.5	0.8	2009

\* in some cases, one site consists of two parts, which were planted in different years

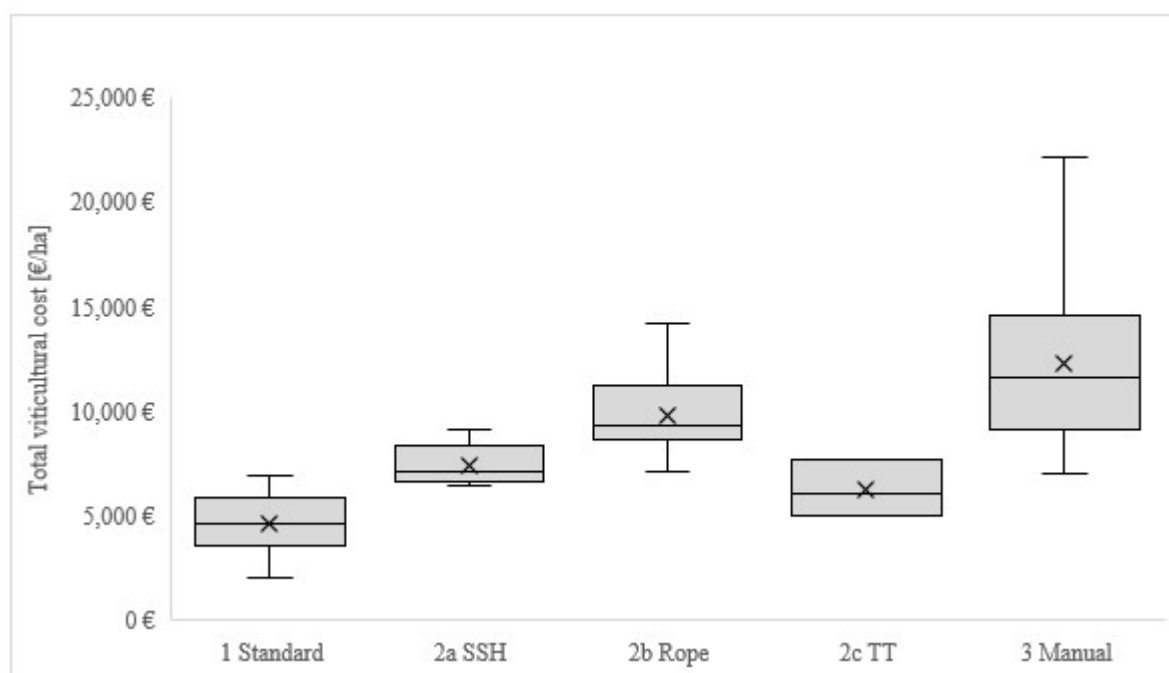
### 2.2.1 Additional information

In addition to the data provided in Table 6 and Table 8 of Paper II, Table 1 and Figure 3 below present information on the distribution of the mean values for the total viticultural cost of the different site types included in the study.

Table 1: Total viticultural cost (€/ha) – Confidence intervals for arithmetic means ( $\alpha = 0.05$ )

	Arithmetic mean	<i>e</i>	Lower margin	Upper margin
1 Standard	4,663	729	3,934	5,393
2a SSH	7,446	906	6,540	8,352
2b Rope	9,822	729	9,093	10,551
2c TT	6,227	1,533	4,694	7,760
3 Manual	12,320	2,934	9,386	15,253

Note: SSH – steep slope harvester; TT – Transversal terrace; *e* – standard error.  
Source: own calculation.



Note: SSH – steep slope harvester; TT – Transversal terrace; *x* – arithmetic mean

Figure 3: Total viticultural cost (€/ha) – boxplots.  
Source: own illustration.

### 2.3 Paper III: The effect of low-input training systems on viticultural costs in flat terrain and steep slope sites

This chapter is based on an article published by the author of the present work, with Manfred Stoll and Simone Mueller Loose as co-authors. Any reference to the chapter should be cited as follows:

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**Declaration of co-authorship  
for doctoral theses based on published or submitted co-authored articles**

This declaration form has to be submitted together with the thesis.  
Please use one form for each publication.

Name of the candidate:  Larissa Strub
Title of the article: The effect of low-input training systems on viticultural costs in flat terrain and steep slope sites
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Authors contributed to the work according to the following categories  
(max. 100 % per column):

A - more than 75 % B- 51 to 75 % C - 26 to 50 % D- up to 25 % 0 - no contribution

*Please insert the appropriate letter/zero for each contributing author in the resp. column*

Name	Literature review	Development of theoretical model/frame work	Concept and design of the study/ analysis	Execution, choice and development of methods	Evaluation and interpretation of results	Concept and writing of the article	Signature of the author
Strub, Larissa	A	A	A	A	A	A	<i>L. Strub</i>
Stoll, Manfred	0	0	0	0	0	D	<i>Manfred Stoll</i>
Loose, Simone	D	D	D	D	D	D	<i>Simone Loose</i>

Please use an additional sheet if more authors contributed.

# The effect of low-input training systems on viticultural costs in 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 through fewer viticultural process steps and permit a higher degree of mechanisation. However, their effect on viticultural costs and per litre costs in both flat terrain and steep slopes has not yet been analysed. This study quantifies the viticultural costs for vertical shoot positioning (VSP) and low-input training systems for the standard processes in different types of flat terrain and steep slope vineyards. Costs were derived from a dataset of 1,519 working time records for labour and machine hours of 20 vineyard sites from 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 by univariate analysis of variance with fixed and random effects and by descriptive analysis of mean values.

In flat terrain, SMPH significantly decreased the costs for the viticultural steps of winter pruning, tying, shoot positioning and defoliation but increased the cost for pest control. Hence, the total cost in flat terrain decreased marginally, but still significantly, by 46 %. The cost effects in 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 compared to VSP the production costs per litre further declined.

The study confirmed the strong cost-saving potential for wine growers through 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 within mechanisable steep slope vineyards can be reduced to amounts approximating VSP in 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 steep slope growers' cost-based pricing policy. 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

## 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 bulk wine producers' profitability (Couderc and Marchini, 2011).

Since the 1950s, viticultural costs have been significantly reduced through mechanisation (Schreieck, 2016). However, in 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), the processes of 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 for mechanisable VSP steep slope sites remains 60 % to 110 % higher compared to standard VSP in 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 represent a viable option to further reduce the cost of manual labour in the viticultural processes of 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 for a single or total viticultural process, for 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 can 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 in a trellis with VSP is the most common training system in German viticulture (Müller *et al.*, 2000). In this training system, 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, which requires manual pruning of vines, the manual removal of canes from the wireframe and manual tying of the remaining canes. Such intensive labour (total labour demand of app. 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 increasingly unavailable (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 canes on the very top and to shred the removed canes. Recently caneprunner® or vinestripper® are used to remove canes from their wireframe. However, because these machines are



very expensive and prone to malfunctions (Walg, 2016a, 2016b), they are not widely used. For cordon systems, as a special kind of VSP pruning system, specific mechanisation options are available for winter pruning and cane removal. Yet these systems are primarily employed in countries bordering the Mediterranean Sea as well as countries in the Southern and Western Hemispheres, and are rarely used in Germany.

After winter pruning, most VSP systems require the manual tying of canes. In the summer, all VSP systems demand 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 in flat terrain sites (Strub and Loose, 2021). This cost does not differ significantly in 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 in a trellis, but they are grown in 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 the minimal pruning (MP) system. In MP vineyards, the hedges are only trimmed on the bottom to hinder the canes from touching the ground, but other than that are left unpruned resulting in very wide canopies which become bare inwardly. MP requires vineyards with wide row distances of approximately 3 metres to allow a wide canopy to develop and the tractor passing through. Currently, 65 % of all viticultural sites in Australia are managed via MP systems, particularly in warm and well-irrigated regions conducive to vigorous vine growth (Clingeffer *et al.*, 2005).

Since the beginning of the 21<sup>st</sup> century, low-input systems have been increasingly employed in European viticulture as well, partly suitable 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 standard 2 metre row distance. Such SMPH systems combine features of traditional VSP-type trellising systems with the concept of minimal pruning (Intrieri *et al.*, 2011). To do so, canes from the past vegetation period are not pruned in the winter; instead, they are tied to the wireframe and mechanically pruned in winter to a hedge shape using normal grapevine hedging machines. Consequently, in spring, a high number of buds burst all over the canopy, creating a green hedge. During the vegetation period mechanical leaf trimming will be required two to three times per season. Because of their identical row distance and heavily trimmed canopy, SMPH vineyards look similar to VSP vineyards, once the canopy will be 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 for MP a decrease in labour hours by 100 % for pruning and 85 % for canopy management. Likewise, Bates and Morris (2009) reported for MP 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 the total viticultural cost.

The cost advantages of low-input systems cannot be assessed without considering their potential drawbacks, including the prospect of lower wine quality resulting from higher yields (Deloire *et al.*, 2016), the 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, resulting in generally higher yields. This effect is strongest in the first years after conversion if no counter measures, such as thinning, are taken. Concerning 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 mainly grape harvesters 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). From 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, mainly the suitability of the variety. In Germany, for example, SMPH is recommended mostly for white varieties (DLR Rheinpfalz, Research Institute Geisenheim, 2011). Under such climatic conditions MP for red varieties often results in unsatisfying ripening and higher incidences of bunch rot. However, in SMPH due to a lower leaf area to fruit weight ratio a delay of phenological stages and thus ripening occurs, and the looser bunch architecture shows a lower susceptibility to bunch rot (Molitor *et al.*, 2019).

Because of their larger canopy, particularly MP systems also entail increased water demand (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 the 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 in 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 considered 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. Particularly for MP training systems every second row has to be removed, because the space between rows usually is too narrow (Molitor, 2010). To convert VSP into SMPH systems, the labour demand is therefore lower, because the 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 involved in the management processes of vineyards with VSP and low-input training (MP and SMPH) to identify the cost-saving potential of the systems. Thereby, focus was placed on how low-input training affects the costs of particular viticultural processes as well as the total annual viticultural cost per year for either standard flat terrain sites or two different types of steep slope sites. Because low-input systems may 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 in flat terrain sites?
- RQ2: What is the cost advantage of low-input training compared to VSP training in steep slope sites?
- RQ3: How do differences in yield impact cost differences between low-input and VSP systems?

## **Materials and methods**

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

### **1. Site types**

The six site types analysed in this paper represent a sub-selection from a complete vineyard typology derived from Strub *et al.* (2021). The site types were characterised by external factors (Columns 1 to 3 in Table 1) and, consequently, 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 the 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 remains relatively uncommon, the number of sampled low-input trained sites was smaller than the number of sampled VSP sites. Likewise, because progress in steep slope mechanisation has occurred only recently (Strub and Loose, 2021), low-input trained sites on steep slopes remain exceedingly rare, and as such 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 data available.

**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			
<i>Determined by nature</i>	<i>Determined by winegrower</i>	Training system	Pruning	General management	Harvesting		n	n	n	n
Slope and access to vineyard sites	Orientation of rows towards the slope					2017	2018	2019	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 unupp SSH	—	2	3	5
		LI (SMPH)	Mechanical	Unsupp.	SSH	2b LI (SMPH) unupp 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
<b>Sum</b>							<b>6</b>	<b>15</b>	<b>15</b>	<b>36</b>

Notes: 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 pruning 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.

Pair 1 – site type 1a versus site type 1b – vineyards in flat terrain, which are managed with 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, which allow management by standard narrow-track tractors for mechanical pruning and general management, but due to the slope demanding an SSH, consisting of a crawler tractor equipped with a harvesting head, for harvesting (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; 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 were planted with white grape varieties, which have been determined to be more suitable for low-input systems in cool to moderate climate. All sites were converted from VSP to SMPH or MP respectively 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 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.

**Table 2. Information on 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

*Notes: 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)*

## 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 introduced in Table 1. The labour and machine times were collected in daily diaries throughout the years 2017, 2018 and 2019 in five management-led wine estates sized between 50 and over 200 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 (1500) *Under-vine cultivation* and (1600) *Chemical weed control* separately, they were combined into one process: *Weed removal* (code 1500+). This was a sensible step because these two initial processes are complementary methods 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 with the corresponding sample sizes per site type.

**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-pruned hedge; MP – minimal pruning; SSH – steep slope harvester. (Site types modified based on Strub et al., 2021)*

#### 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, following Walg (2016a), Becker and Dietrich (2017) and ÖKL (2020), was calculated 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 as such the cost for these machines was determined based on contractors' prices, which include the cost for personnel and the expected profit margin.

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

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

The dataset included 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 as such only 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 were 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 between the site types. Here, a factor of 2 represented a 100 % higher cost per litre. The analysis did not take into account the planting density, which are lower for MP sites with wider row spacing.

## **Results**

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

The results of the statistical analysis for the comparison of type 1a and 1b flat terrain sites are detailed 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.

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 for the *Tying*, *Winter pruning*, *Shoot positioning* and *Defoliation* processes by on average -80 % to -100 %. The high cost reductions of -100 % for *Shoot thinning* and *Lowering the wires* (rarely performed in the sampled VSP sites) were not significant. Similarly, the cost reduction of -82 % for *Yield regulation* was not significant, likely because few cases were conducted in VSP sites. The cost for *Pest control* increased significantly by on average 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 at VSP sites) could be substantially reduced at low-input (SMPH) trained sites by 80 %. The cost savings of 2,860 € for these six processes were more than compensated for the higher costs for *Pest control* and *Trimming* (700 €) at low-input (SMPH) trained sites. Further information on the data distribution of the total viticultural cost were provided in Appendix I and Appendix II.

**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
Process steps		Univariate model of variance			Means			
		Site type (F)	Estate (R)	Year (R)	1a VSP SH in €/ha	1b LI (SMPH) SH in €/ha	Δ absolute 1a vs 1b in €/ha	Δ relative 1a vs 1b in %
		F <sup>+</sup>	F	F				
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%
<b>Total cost</b>		<b>4.7 *</b>	<b>4.8 **</b>	<b>0.7</b>	<b>4,720</b>	<b>2,559</b>	<b>-2,161</b>	<b>-46%</b>

Notes: F – fixed effects; R – random effects; LI – low-input system; SMPH – semi-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)



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, i.e. precipitation (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.

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

Because of the limited number of observations, only descriptive average cost values could be analysed for steep slope sites. Differences via the impact of *Estate* and *Year* could not be separated, and as such the analysis could provide only explorative results. The results for the site type 2d 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 (in 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 strongest 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 less strongly. 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 metres in site type 2d versus 2 metres in site type 2c, which leads to a significantly lower number of vines per hectare and hence reduces the processing metres within the vineyard's 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 an annual effect of low precipitation, while cost reductions 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 compared 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 for limited mechanisation at steep slope sites to an amount similar to the absolute cost at flat terrain VSP sites (4,720 €/ha in Table 4). In Appendix I and Appendix II, additional information on the data distribution of the total viticultural cost for the four site types are shown.

**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
		<b>Mean values</b>				<b>Mean values</b>			
		<b>2a</b>	<b>2b</b>			<b>2c</b>	<b>2d</b>		
		<b>LI</b>				<b>LI</b>			
		<b>VSP</b>	<b>(SMPH)</b>	<b>Δ</b>	<b>Δ %</b>			<b>Δ</b>	<b>Δ %</b>
		<b>unsupp</b>	<b>unsupp</b>	<b>absolute</b>	<b>2c vs</b>	<b>VSP</b>	<b>(MP)</b>	<b>absolute</b>	<b>2d vs</b>
		<b>SSH</b>	<b>SSH</b>	<b>2a vs 2b</b>	<b>2a</b>	<b>Rope</b>	<b>Rope</b>	<b>2c vs 2d</b>	<b>2b</b>
<b>Code</b>	<b>Process step</b>	<b>cost/ha in €</b>		<b>in €</b>		<b>cost/ha in €</b>		<b>in €</b>	
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%
	<b>Total cost [€/ha]</b>	<b>7,446</b>	<b>4,944</b>	<b>-2,502</b>	<b>-34%</b>	<b>9,519</b>	<b>5,137</b>	<b>-4,382</b>	<b>-46%</b>

Notes: VSP – vertical shoot positioning; unsupp – unsupported; SSH – steep slope harvester; LI – low-input system; SMPH – semi-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)

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

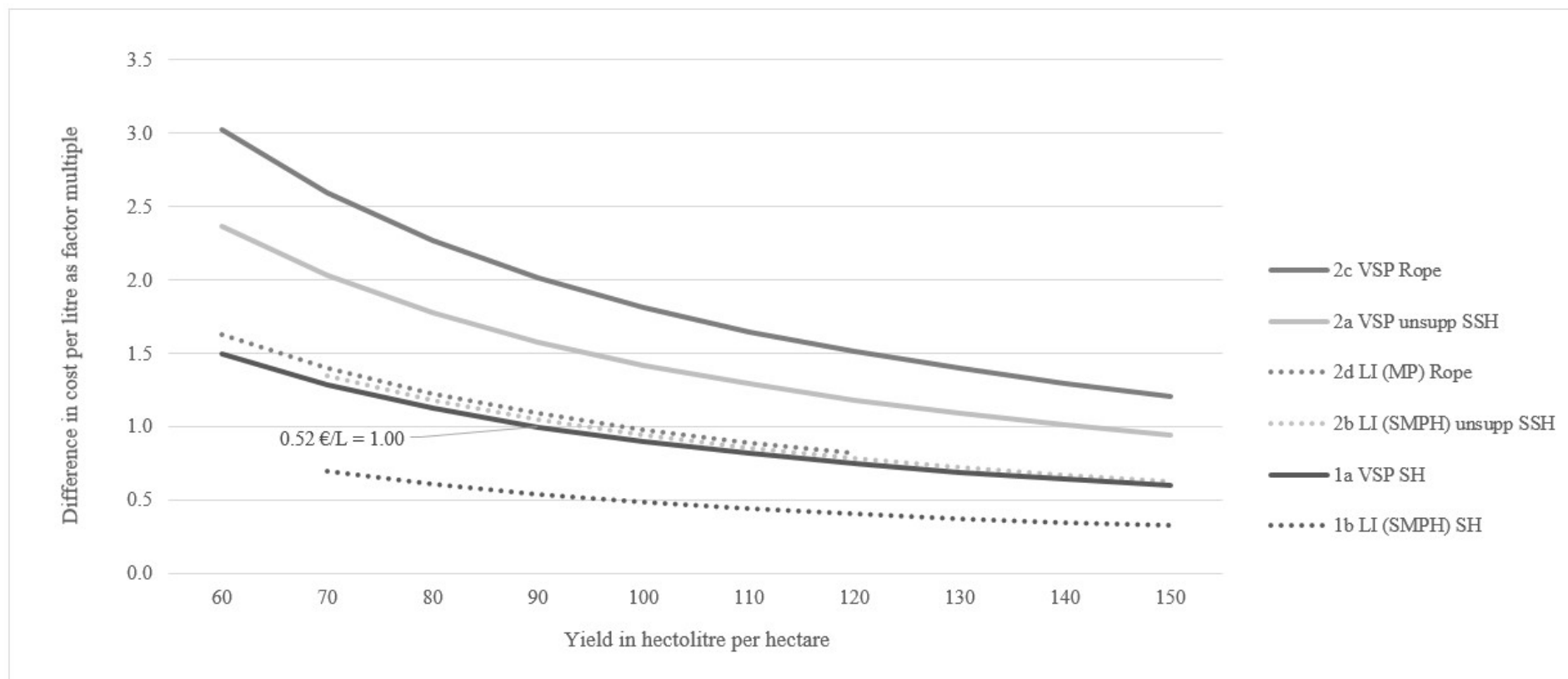
The analysis of the effect of yield on cost per litre took into account the generally higher yield of low-input trained sites compared to VSP sites which was mainly due to the higher number of buds. Table 6 provides cost per litre for the six site types analysed for a yield range between 50 hl/ha and 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. Per litre costs in €/Litre for the different site types at yield levels between 50 hl/ha and 150 hl/ha.**

	<b>1a</b>	<b>1b</b>	<b>2a</b>	<b>2b</b>	<b>2c</b>	<b>2d</b>
	<b>VSP</b>	<b>LI (SMPH)</b>	<b>VSP</b>	<b>LI (SMPH)</b>	<b>VSP</b>	<b>LI (MP)</b>
	<b>SH</b>	<b>SH</b>	<b>unsupp SSH</b>	<b>unsupp SSH</b>	<b>Rope</b>	<b>Rope</b>
<b>Total cost per ha</b>	<b>4,720 €</b>	<b>2,559 €</b>	<b>7,446 €</b>	<b>4,944 €</b>	<b>9,519 €</b>	<b>5,137 €</b>
<b>Yield</b>						
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

*Notes: VSP – vertical shoot positioning; SH – standard harvester; LI – low-input system; SMPH – semi-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)*

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). In Table 6, this value was shaded in grey as a basis for reference for the comparison with the other types. 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 could be increased slightly to 100 hl/ha this will represent cost per litre similar to that of the flat terrain VSP. Further increasing the yield reduces the cost per litre accordingly. For VSP at steep slope sites, a similar cost reduction can only be achieved by very strong yield increases to 140 hl/ha (type 2a) and 190 hl/ha (type 2c), which however will almost certainly negatively affect quality.



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

Notes: VSP – Vertical shoot positioning; un\_supp – 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)

Figure 1 visualises the effect of low-input training on cost per litre. The y-axis indicates the factor multiple, by which cost increase compared to the reference value of 0.52 €/L. For instance, with a factor of 2.02 at the reference yield the VSP rope-supported steep slope site results in about double cost. Two effects become obvious. First, introducing low-input training in 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) lie 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 in steep slopes lie clearly above and only cut the horizontal 1.0-cost factor-line at very high yields.

## Discussion

This study provided the first results gained under field conditions on the effect of low-input training systems on viticultural costs for individual processes and the total viticultural cost for 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 in flat terrain sites

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

The labour and machine costs for 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. Within this study, differences in material costs, such as cost for pesticides, were not taken into account. Due to the larger canopy, it is likely that a higher amount of pesticides for MP training will be required, which might further increase costs for pest control. The sample was dominated by older, less vigorous vineyards, which might explain why only one-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 the 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 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

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<sup>1</sup> 50 h/ha \* 12.54 €/ha German minimum wage (Federal Ministry of Labour and Social Affairs Germany (2019))

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 on processing or directing metres during the 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), leadership of personnel, risk aversion and an estate's philosophy of product quality (Mota *et al.*, 2020; 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 in 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 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 can 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 producers of market entry to medium-level 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 will be sufficient. The analysis did not include the effect of different planting densities, which differ between low input systems SMPH and MP.

## **4. Outlook**

The findings of this study concern current wine market conditions *ceteris paribus* that are unaffected by individual wine growers' decisions. That said, it must be considered 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 in 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 such as low-input training systems, as such an advantage is eventually offset by 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 biodiversity and tourism from steep slopes (Cox and Underwood, 2011; Job and Murphy, 2006; Tafel and Szolnoki, 2020) is 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 on 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. Because of the capacity of low-input training to delay maturation, it 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 are originated of five different growing regions, while the number of observations for low-input trained steep slope sites did not permit robust statistical inferential analysis. Because of data limitations the cost differences between SMPH and MP low-input training could not be separated sufficiently 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 can 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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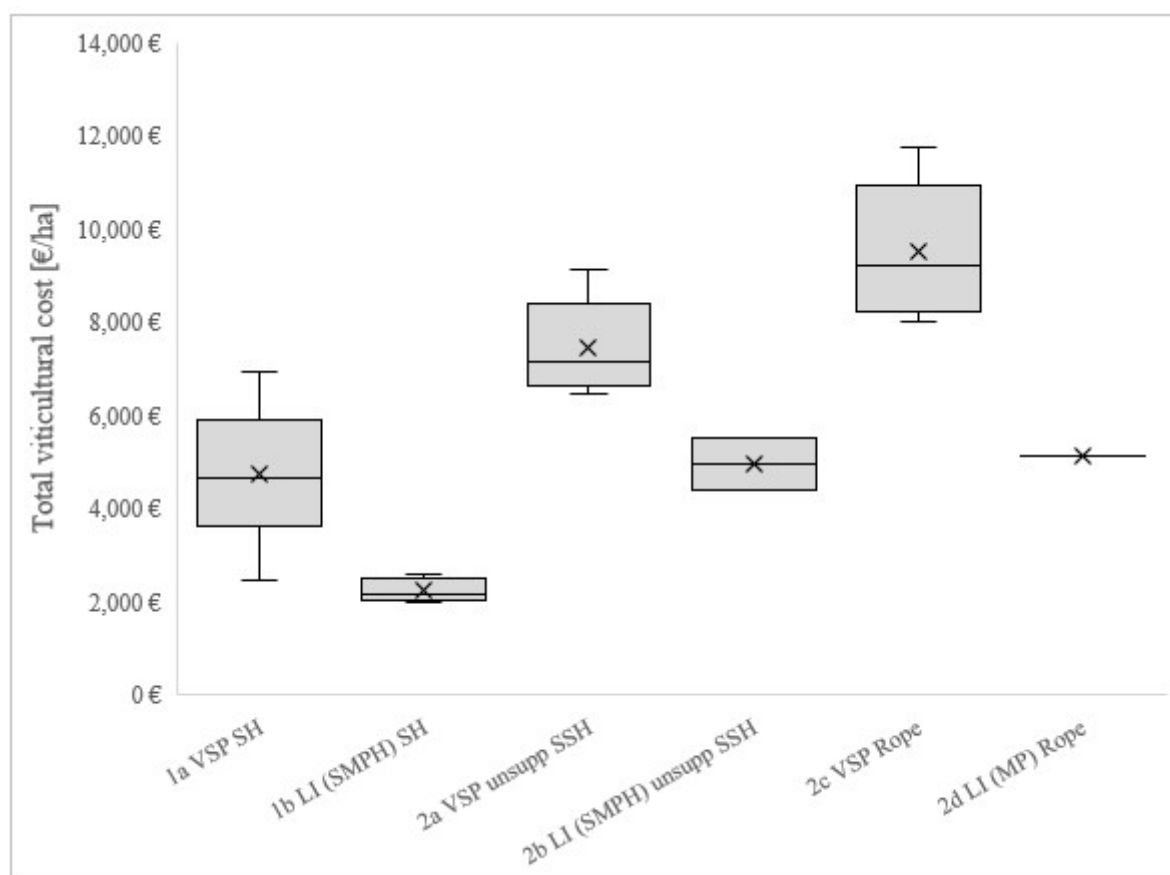
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## Appendix I. Total viticultural cost [€/ha] – Confidence intervals ( $\alpha = 0.05$ ) of the arithmetic mean

	Arithmetic mean	<i>e</i>	Lower limit	Upper limit
1a VSP SH	4,721	682	4,038	5,403
1b LI (SMPH) SH	2,232	258	1,974	2,490
2a VSP un supp SSH	7,446	906	6,540	8,352
2b LI (SMPH) un supp SSH	4,944	1,082	3,861	6,026
2c VSP Rope	9,519	970	8,549	10,489
2d LI (MP) Rope	5,137	-	-	-

Note: VSP – vertical shoot positioning; SH – standard harvester; LI – low-input system; SMPH – semi minimal-pruned hedge; un supp – unsupported; SSH – steep slope harvester; MP – minimal pruning; *e* – standard error

## Appendix II. Total viticultural cost [€/ha] - boxplots



Note: VSP – vertical shoot positioning; SH – standard harvester; LI – low-input system; SMPH – semi minimal-pruned hedge; un supp – unsupported; SSH – steep slope harvester; MP – minimal pruning; x – arithmetic mean

### **3 General Discussion**

The aim of this thesis was to identify which factors account for the cost disadvantages of steep slope viticulture as well as to quantify the cost differences in vineyard management with regard to the typology described earlier. In addition, recommendations for improving the cost efficiency of steep slope viticulture are provided in the hope that they will positively affect the profitability of the practice and help to preserve these sites not just for future viticulture but also for ES, which could benefit from various aspects of steep slope viticulture.

The following discussion delivers the answers to the research questions posed in the introduction and presents their implications for the viticultural sector, policy makers and society at large.

#### **3.1 Factors determining the structure of labour and machine costs (RQ1)**

The slope gradient of viticultural sites is not the only factor influencing the cost structure for the viticultural management of steep slope vineyards. In the extant literature, for example, the cost disadvantage of steep slope viticulture is often attributed to the lack of mechanisation. In Paper I, the authors determined that in addition to the gradient, mechanisation intensity at viticultural sites is influenced by (a) access to vineyard sites based on infrastructure and terrain, (b) the orientation of rows towards the slope, and (c) the training system in place. These three factors in turn affect (a) the relative level of mechanisation of general viticultural management, including soil and canopy management as well as pest control, (b) harvesting, and (c) pruning. The mechanisation of each of these three process groups, however, must follow a logical trajectory. That is, the first group to be mechanised would have to be the processes of general viticultural management. Only when these processes are mechanised can the mechanisation of harvesting proceed. Once this has occurred, the mechanisation of pruning and pruning-related processes can commence, as low-input systems require machine harvesting due to the growth patterns of grapes. Conversely, then, if mechanical harvesting is inhibited, training in low-input systems cannot occur.

The ANOVA evidenced a statistically significant influence of mechanisation – i.e. mechanisation of general viticultural management, harvesting and pruning – on the total viticultural cost, with mechanised viticultural management exhibiting the strongest effect. The accessibility of vineyard sites to machinery may vary from year to year depending on weather and soil conditions. This will in turn determine the relative demand for machinery or manual labour from one year to the next. If it is too wet during the

harvesting period, for example, then SSHs cannot operate, and manual harvesting of grapes will be relied upon instead; whereas in drier periods, SSHs will be the preferred harvesting method.

The combination of factors and the process groups they influence culminate in the characterisation of vineyard types, which are defined by different degrees of mechanisation. Wherever mechanisation is limited by weather conditions or other variables, demand for manual labour will correspondingly increase. The ways in which different viticultural processes can be completed are intrinsically linked with fixed combinations of requisite equipment and staff skills.

The typology of vineyards ranges from flat terrain sites that are amenable to any kind of mechanisation and which incorporate low-input training systems to steep slope sites that are far too remote to be accessed by any kind of machinery. Accordingly, labour demand and machine hours vary at a commensurate range, beginning at below 50 hours per hectare annually for fully mechanised sites with low-input training systems in place, resulting in a total viticultural cost of around 2,500 €/ha. At the other end of the continuum, 735 hours of manual labour and 80 hours of machine labour are required per hectare on average. In this case, the total viticultural cost increases dramatically, to approximately 12,400 €/ha.

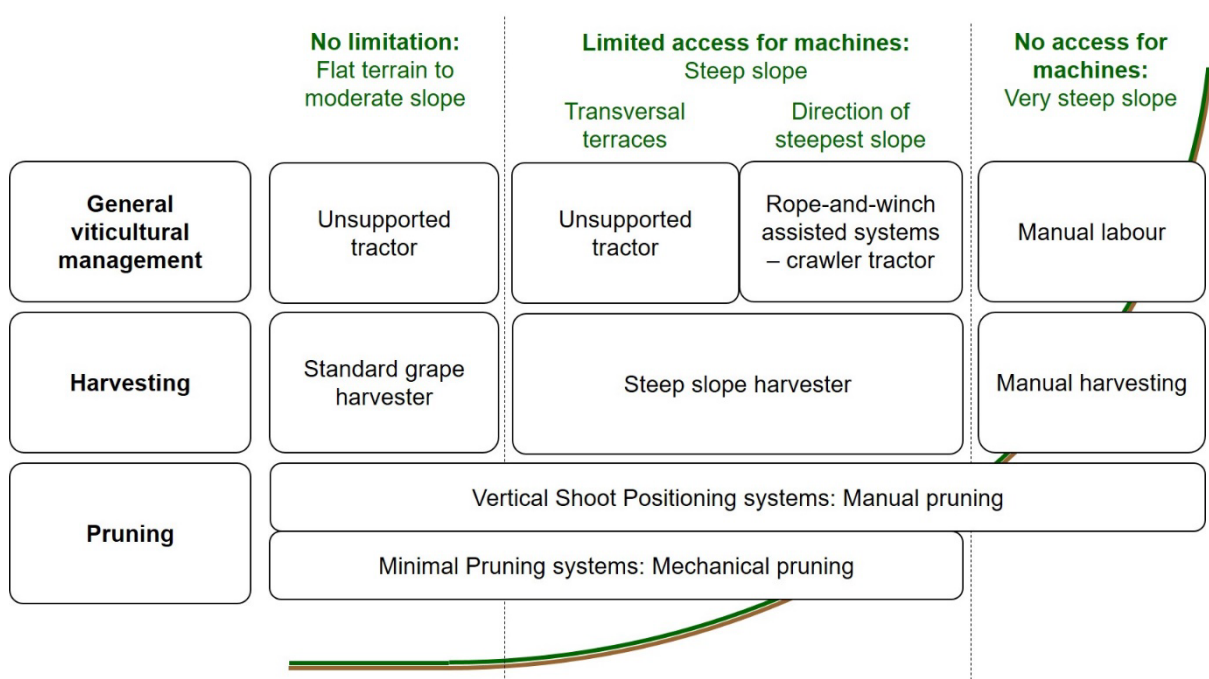


Figure 4: Combination of influential factors and viticultural processes used to define vineyard types based on mechanisation intensity.

Source: own illustration.

The other site types are situated between these two extremes, as follows: sites that combine standard narrow-track tractors without support, sites that rely on crawler tractors with or without rope-securing

methods, sites that use SHs or SSHs, sites that depend primarily on manual harvesting as well as different training systems, and sites whose harvesting techniques differ as a consequence of vineyard rows facing different directions, as illustrated in Figure 4.

The analysis covered in Paper I demonstrated that gradient alone is not sufficient to differentiate flat terrain from steep slope sites. Therefore, other factors were considered: mechanisation intensity based on terrain, level of infrastructure, soil structure, type of training system, and the presence of terraces to permit the unsupported use of tractors on steep terrain. These factors were found to be useful for the evaluation of the conditions of viticultural management and potential disruptions. The typology developed from these factors and conditions constituted the initial step towards a transparent characterisation of vineyard types and enabled sound cost comparisons of vineyard sites.

### 3.2 The cost disadvantages of steep slope vineyard sites (RQ2)

Applying the typology of vineyard sites developed in Paper I and presented in Section 3.1 above produced five different site types, all trained in a VSP trellis system. These site types were subsequently compared in Paper II. Sites with full mechanisation – i.e. sites deploying standard narrow-track tractors and SHs, but without the mechanisation of pruning-related processes due to VSP training – served as the standard for comparison to VSP sites with limited or no mechanisation, in which planting occurs in the direction of the steepest slopes or on transversal terraces. In Paper III, the influence of low-input systems on viticultural costs was analysed.

#### *Cost differences between VSP sites with different levels of mechanisation*

The total viticultural cost for sites in which planting occurs in the direction of the steepest slopes, as compared to the total viticultural cost for standard sites, ranges from 2,700 €/ha for those sites that have requested an SSH (instead of an SH) to 7,600 €/ha for those sites that require manual labour for all processes. These differences in total viticultural cost were statistically significant at  $p \leq 0.001$ .

Due to the high degree of manual labour at sites with limited mechanisation, the cost difference is bound to intensify in the future. The general wage level consistently increased year after year (Strijker, 2005; Heinrich-Böll Stiftung *et al.*, 2020; Destatis, 2021) with the exception of 2020, which is attributable to the COVID-19 pandemic. Thus, manual labour can be expected to become increasingly expensive in the mid- to long-term. In Germany, manual labour is all but guaranteed to become more costly in the short term due to the planned increase in the general minimum wage, from 9.60 €/per hour in 2021 to 10.45 €in 2022 (Bundesregierung Deutschland, 2021). This is directly relevant to the viticultural sector, as the minimum wage is applicable to seasonal agricultural workers, who constitute 58 % of the total

workforce in this sector (BMEL, 2021). In addition, the number of available seasonal workers is declining, further destabilising the viticultural sector, especially for growers relying on manual labour due to the structure of their vineyard sites.

Although steep slope viticulture with rows planted in vertical direction is relatively common in Germany, the cultivation of grapes via transversal terraces could also be implemented. Transversal terraces have the advantage of providing a flat surface for the unsupported operation of standard narrow-track tractors and SSHs, thereby superseding winch-and-rope systems. Although this type of vineyard architecture is rare in Germany, it is quite common in the Mediterranean, especially due to the wave of new plantations created in the 1990s, which were strongly supported by the EU Common Agricultural Policy (CAP), Commission Regulation (EC) No. 1227/2000 specifying Council Regulation (EC) No. 1493/1999 (European Commission, 1999, 2000) in Spain (Pla and Nacci, 2002; Ramos *et al.*, 2007; Stanchi *et al.*, 2012). The total viticultural cost of these sites is 6,200 €/ha, resulting in a disadvantage of around 1,500 €/ha compared to the standard, but generating an advantage of around 3,600 €/ha compared to winch-and-rope sites and nearly 6,100 €/ha compared to manual sites.

#### *Influence of viticultural processes on total cost differences*

The total differences in viticultural costs are primarily attributable to single viticultural processes. Changing from a narrow-track tractor to a winch-and-rope system, for instance, results in significantly different costs for mechanised general viticultural management processes in both systems, such as trimming, cover crop management and weed removal. This is caused by the need to pass every row twice, as changing from one row to the next is not possible when vehicles are tied to a rope. In all systems, however, manually completed processes demonstrated either no significant or marginally significant differences in costs in the comparison of all site types.

The largest absolute cost differences were attributable to harvest and pest control processes. Apart from winter pruning, harvesting is the most expensive process within the whole viticultural management scheme. Until 2015/2016, picking grapes was performed by hand at steep slope sites. Since then, however, SSHs have entered into commercial use, mechanically resolving the otherwise strenuous, labour-intensive harvesting process for the first time. Savings in terms of labour hours were dramatic, plummeting from 150 hours per hectare to under 10 hours per hectare in the sample. From a cost perspective, however, SSHs provided no significant cost savings compared to manual harvesting. This is because SSHs are predominantly owned by contractors, not wine growers. Unsurprisingly, contractors affix an additional cost to the price of leasing their SSHs in order to ensure that they turn a profit, thereby rendering the use of SSHs more expensive. In addition, serial sizes are still relatively small, resulting in high purchase costs for the machinery. This has ultimately created a situation in which harvesting is



significantly more expensive regardless of whether SSHs or manual harvesting are employed. That said, even though existing conditions preclude cost savings from the use of SSHs, these conditions are not immutable and there is therefore potential for such savings in the future. Presently, however, the decreasing number of available seasonal workers and increasing cost of manual labour drive manual harvest more challenging. Accordingly, a smaller manual labour force coupled with increasingly unstable weather conditions during the harvest may ask for strengthening the labour force by employing SSHs. On the downside it is to be noted, that SSHs can also not be relied upon to operate in a suitable fashion when soils are wet. Cost reductions for the employment of SSHs are to be expected once larger wine estates and machine cooperatives purchase their own machinery themselves, hence saving the contractors' margin. Likewise, rising serial sizes will lower purchase prices as well.

The third large cost factor in viticulture is pest control, mainly because it must be repeated multiple times over the course of a year, typically between 7 to 14 times depending on the type of growing system. Predictably, the cost for pest control significantly varies based on the level of mechanisation of the site. Steep slope sites have the disadvantage of making pest control more complicated simply due to the difficult inclination of the terrain. This predicament is exacerbated further during years when soil conditions are decidedly poor. And yet, pest control must still be completed within a certain time frame. In addition, as crawler tractors often are not equipped with a protective cabin, their operators must wear protective gear, including a facial mask, to prevent contact with and inhalation of pesticides.

Pest control at manual sites can also be problematic. Here, pesticides are usually sprayed by hand using a hose. As such, workers must wear protective gear, which imposes even greater physical challenges, especially during the summer. Helicopter spraying is thus common in the steepest terrain, although doing so requires an exception permit in Germany due to concerns about pesticide drift (Viret *et al.*, 2003). The drift problem has been relativized in the meantime under the assumption of good practice (Schwappach, 2006; Bäcker *et al.*, 2007). The outcome of helicopter spraying, however, is not as optimal as that generated by ground-based tractors (Viret *et al.*, 2003). Summarily, then, current pest control options at sites inhibiting the use of standard tractors leave substantial room for improvement not just from a cost standpoint but also in terms of work safety, viticultural practice and environmental protection.

*Low-input systems to improve the cost situation at sites with limited mechanisation*

The analysis of the relationship between low-input training and cost structures showed that the total viticultural cost of sites with limited mechanisation could be reduced to that of fully mechanised sites by replacing Germany's standard VSP system with low-input systems, such as minimal pruning (MP) or semi-minimal pruned hedge (SMPH) systems. As sites with limited mechanisation are used to produce both top-quality wines, which might justify a certain price premium, and basic-quality wines that in part are even sold on the bulk wine market, where growers are price takers, low-input systems might constitute a good strategy for producing satisfactory wines at a reasonable cost.

*Individual managerial decisions influencing cost structures*

Across all comparisons in the study, it became evident that the managerial decisions of each wine estate had a significant influence on cost structures, as demonstrated by the strong statistical effect of the random factor *Estate*. Variations in the data between the different estates were particularly connected with quality-related processes like shoot thinning, yield reduction or voluntary manual harvesting at sites where mechanical harvesting would also have been feasible. Since the participating wine estates were located in five different wine-growing regions, each with distinct soil and microclimatic conditions and different weather patterns, one can assume these factors to influence the cost structures of the estates. Ultimately, then, aside from external factors that allow or impede mechanisation to variable degrees, the quality requirements and production philosophies of each estate in addition to specific attributes of their locations are likely to play an important role in viticultural costs.

### 3.3 The effect of yield on viticultural costs (RQ3)

Viticultural management is characterised by multifarious processes that are independent of the yield level. Therefore, a large percentage of the resulting costs can be regarded as fixed. It is in the nature of fixed costs to be digressive in relation to unit costs such that unit costs decrease as the yield level increases. Thus, the yield level is a critical factor for the efficiency of viticultural costs.

Aside from decisions made by vineyard managers that influence the yield level, such as the number of shoots per metre, the intensity of shoot reduction activity or the removal of clusters, water supply is the most critical factor for the yield level (van Leeuwen *et al.*, 2019). Research has shown that the water supply at steep slope sites is diminished compared to flat terrain sites due to the reduced water retention capacity of vineyards planted in the direction of the steepest slopes and increased evaporation at terraced sites (Hofmann and Schultz, 2015), resulting in lower yields compared to those generated by flat terrain sites (Cichelli *et al.*, 2016). In combination with elevated temperatures and increased solar radiation in

the wake of climate change (van Leeuwen *et al.*, 2019), drought conditions have become a more daunting issue for steep slope sites than for flat terrain sites.

Assuming that the relative water scarcity of steep slope sites causes lower yield levels, cost differences measured in €/ha between sites with full mechanisation versus limited mechanisation are amplified at a per litre cost level. While in this study the costs of manual VSP sites in €/ha, for example, were 2.6 times as high as those of standard VSP sites with full mechanisation, assuming identical yield levels of 90 hl/ha, the cost differences increased to 5 times the cost of the standard sites at the per unit level, if the yield levels of the manual sites were decreased to 45 hl/ha. At an assumed yield level of 30 hl/ha, which is not uncommon at very steep sites with skeletal soils, the cost per litre would be 6.8 times as high. Thus, the difference between the standard VSP sites at 90 hl/ha and the manual sites at 30 hl/ha amounted to an absolute sum of 3.53 €/L. These differences are impossible to implement as price premiums to enable a cost-efficient marketing of these mechanisation-impeded, yield-reduced sites.

Low-input systems usually result in elevated yield levels compared to VSP systems, if a sufficient water supply can be provided (Deloire *et al.*, 2016; Molitor *et al.*, 2019). Therefore, in addition to the lowered viticultural costs per hectare, the higher yield levels make low-input training even more advantageous on a per litre scale.

### 3.4 Implications for viticulture

The results of the analysis have shown that viticulture at steep slope sites must address two main difficulties: the high costs of viticultural management, and the impacts of climate change. The following sections should provide some insights into how growers can improve production conditions.

#### 3.4.1 Measures to improve the cost efficiency of viticulture on steep terrain (RQ4)

Different options are available to reduce the cost disadvantages of viticulture on steep slopes and thereby increase the cost efficiency of these sites.

##### *Transversal terraces to allow unsupported use of standard tractors and SSHs*

The results presented in this doctoral thesis have shown that the cost disadvantages of viticultural management of transversal terraces are smaller than at most site types planted in the direction of the steepest slopes. The management of terraced vineyards is still more costly than standard flat terrain vineyards, but these costs could be halved by the transition to terracing. Adversely, the construction of terraces is generally linked to severe landscape interference (Cots-Folch *et al.*, 2006), which additionally incurs high initial costs. Thus, the potential decrease in management costs depending on the original

vineyard setup must be contrasted with the construction costs of transitioning to terraces to evaluate the true economic scope of the advantages of this investment. Moreover, the future of viticulture on sloping terrain in light of climate change is uncertain. Practitioners are already reporting difficulties with newly planted vineyards, such as problems developing roots – especially on terraces in dry microclimates – due to higher evaporation rates, resulting in prolonged periods devoid of yields. Adding the corresponding costs of delayed or lost yields to the equation degrades the value of converting to terraced vineyards. Also, the construction of terraces requires proper planning and constant maintenance, such as the sowing and management of cover crops on embankments to prevent the degradation of soil properties (Tarolli *et al.*, 2014), which can lead to landslides in the worst case scenario. This was a frequent occurrence during the Spanish conversion to terraced vineyards (Pla and Nacci, 2002; Ramos *et al.*, 2007). Thus, investment in the construction of terraces requires careful consideration, including a meticulous assessment of the costs and benefits of such a conversion.

#### *SSHs to mechanise harvesting on steep slopes*

The development of SSHs is the most recent technological innovation in the management of steep slope vineyards (Porten and Regnery, 2015). Albeit not yet conveying significant cost savings, SSHs nonetheless harvest at a much faster rate than manual harvesting. Although it is unlikely that manual harvesting will be replaced by SSHs in the near future due to their limited operating speed compared to SHs (Porten and Regnery, 2016), SSHs could complement manual harvesting especially in difficult years as well as compensate for the increasingly unavailable and more expensive seasonal workers required for manual harvesting. On the aforementioned terraces the efficiency of SSHs could be significantly improved. The crawler tractors carrying the harvesting head do not need to be secured by a rope-and-winch system here thereby increasing the work speed compared to vineyards planted in vertical direction.

#### *Low-input training systems to reduce costs for pruning and canopy management*

The development of SSHs has enabled the implementation of low-input training systems on terrains with limited mechanisation, thereby strongly reducing the demand for manual labour and the corresponding costs, as presented in Paper III. However, certain prerequisites need to be ensured. Depending on the form of the low-input system, MP or SMPH, the availability of water must be secured, if necessary by additional irrigation. Quality improvement measures requiring manual labour are not possible. However, for the production of basic-quality wines, such as wines destined for sale in bulk wine markets, low-input training systems seem to provide the potential for enhanced cost efficiency.

Based on the results of the analysis of the cost structures of terraced vineyards and of low-input training systems, a combination of low-input systems in the form of SMPH and transversal terraces would be the optimal solution from an economic perspective. The structure of the viticultural costs for this combination, as well as the suitability of the combination, could not be analysed within this thesis due to the unavailability of suitable vineyard sites within the participating wine estates.

Apart from the viticultural setups and the findings in the papers presented within this thesis, additional measures are either currently available or under development with the goal of improving the production efficiency of sites with limited mechanisation. An overview of some options in this regard is presented below.

*Use of unmanned aerial vehicles (UAVS) and unmanned ground vehicles (UGVS) to implement precision viticulture*

One major field of technical innovation, long established in agriculture, is the integration of methods of precision farming into viticultural management, thereby enabling the improvement of production efficiency. In this context, the use of UAVs for plant surveillance (Pisirofonia *et al.*, 2017) and the application of plant protection products (Xiongkui *et al.*, 2017) have shown promising results.

Pest control, once the use of standard tractors is inhibited, is a major source of the cost disadvantages of steep slope viticulture, but it is also a critical point in light of work safety and application quality. Under these circumstances, UAVs have been developed for the autonomous spraying of pesticides (Friedel, 2020). These UAVs are capable of applying the pesticides at lower costs with a better application quality compared to helicopters. In addition, the operators remain out of the direct influence of the plant protection products, sparing workers from adverse impacts as well. UAVs are already employed in other countries for this purpose. In Europe, to date, legal issues still need to be resolved (Friedel, 2020). First economic analyses have revealed the economic competitiveness of spraying drones compared to pest control by crawler tractors or helicopters, even though the annual performance of helicopters is only achieved with a certain number of drones employed simultaneously (Porten and Stephan, 2020).

In addition to the employment of UAVs for spraying, UAVs equipped with sensors that are able to monitor the status of vineyards in the context of supply status with water and nutrients, infestation with pathogens, or the ripeness and health status of the grapes represent a promising approach to demand-driven, cost-efficient management of vineyards (Sassu *et al.*, 2021). These surveillance tasks can also be completed by UGVs (Mammarella *et al.*, 2020).

### *Use of fungus-resistant vines to reduce pest control costs*

Aside from the use of UAVs for pest control, the planting of fungus-resistant vines on terrain with limited mechanisation could also support the reduction of pest control costs (Pomarici and Vecchio, 2019). Fungus-resistant vines are most commonly cultivated in organic viticulture, where the use of synthetic chemical pesticides is prohibited. The use of these vines provides benefits for viticultural management by reducing the need for pest management, thus decreasing the viticultural costs (Pedneault and Provost, 2016). The use of fungus-resistant grape varieties in combination with low-input systems is another option to further reduce viticultural costs, and is already under research (Friedel and Schäfer, 2020). Field trials have delivered promising results thus far, as long as water availability remains sufficient. However, the unfamiliarity of consumers with these fungus-resistant varieties is an obstacle for the marketing of the wines (Nesselhauf *et al.*, 2019). Therefore, acceptance amongst growers who farm their vineyards with conventional methods has thus far been limited (Pedneault and Provost, 2016). The growing demand for sustainable, good-quality food will possibly have a positive impact on consumers' acceptance (Pomarici and Vecchio, 2019), thus promoting the planting of such varieties.

### 3.4.2 Cultivation measures to manage challenges induced by climate change

In Section 3.3, the importance of a certain yield level apart from the management costs per hectare for the unit costs was presented. A strong influencing factor for the yield level is the availability of water for the vines. The increase in temperature and the variability of precipitation induced by climate change lead to regular problems with drought (van Leeuwen *et al.*, 2019), which are bound to intensify especially in steep slopes with reduced water retention capacity, elevated evaporation and intensified solar radiation (Hannah *et al.*, 2013; Hofmann and Schultz, 2015). The intensified solar radiation and higher temperatures due to climate change result in increased sugar content and earlier dates of full ripeness of grapes, possibly having a negative impact on aroma composition and quality, especially for white varieties (van Leeuwen *et al.*, 2019). Thus, adaptation strategies for viticulture, especially on the strongly affected steep slopes, must be implemented to handle the challenges of climate change and to secure wine quality and yield levels. In this context, it needs to be considered that the effects of climate change on viticulture may differ widely at different locations (Santos *et al.*, 2020). Therefore, site-specific strategies need to be established (Santos *et al.*, 2020) rather than attempting to enforce a one-size-fits-all solution. A combination of different measures should be carefully monitored, as they may be mutually reinforcing (van Leeuwen *et al.*, 2019; Gutiérrez-Gamboa *et al.*, 2021).

*Measures to handle drought issues*

To tackle drought issues and the resulting negative effects on yields and grape quality, especially for white varieties, different short- to long-term options are available.

In the short term, the reduction of the leaf area to lower transpiration may help to improve water use efficiency (WUE) (Medrano *et al.*, 2012; van Leeuwen *et al.*, 2019; Santos *et al.*, 2020). This measure is also beneficial from a cost perspective, as it does not require any changes to the vineyard setup but instead a mere adaptation to vineyard management.

A short- to mid-term solution, depending on immediate water availability, to handle the issue of water scarcity is the installation of irrigation systems. The existing sensor technology for assessing vine water status (van Leeuwen *et al.*, 2016) has enabled the determination of a demand-driven irrigation regime. Deficit irrigation (DI) has proven to be an appropriate method to balance vine water status and water saving at a constant level of yield and quality (Chaves *et al.*, 2007; Santos *et al.*, 2020). However, the water supply needed to feed the irrigation systems and the accompanying distribution problems remain unsolved in many places (Dumbrell *et al.*, 2020; Santos *et al.*, 2020). Water extraction from rivers is usually not allowed. In recent years, rivers, especially in Southern Europe (Estrela *et al.*, 2012), have carried so little water during the summer that extraction is likely impossible anyway. A trend towards more days with low water levels in German rivers during the summer months is emerging as well (UBA, 2019). The extraction of water from groundwater reserves can have an equally detrimental effect on the water availability of whole regions (van Leeuwen *et al.*, 2019). The most environmentally friendly and socially fair method would be the collection of rainwater and the extraction of water from rivers during the winter to feed the irrigation systems in the summer (Kraus, 2019; Walter, 2019). On the downside, the planning and installation of the needed water retention basins and distribution systems is very costly, thus further driving the viticultural costs on the already disadvantaged steep slope vineyards. In light of the calculatory social costs linked to irrigation, this option needs to be assessed carefully. Additionally, different, less costly, and more socially and environmentally friendly options exist, as presented below.

A mid- to long-term strategy to handle drought issues may be the adaptation of the planting strategies of new vineyards. A change in altitude, latitude or the direction of rows for new vineyards could contribute to the reduction of transpiration due to lower temperatures and reduced intensity of solar radiation (Hunter *et al.*, 2016; van Leeuwen *et al.*, 2019), thus improving the WUE (Medrano *et al.*, 2012). The use of more drought-resistant plant material, i.e. varieties with improved WUE and low-vigour rootstocks, as well as planting on soils with improved water holding capacity could counteract drought issues as well (Tortosa *et al.*, 2016; van Leeuwen *et al.*, 2019) and be simultaneously environmentally friendly and cost-efficient (van Leeuwen *et al.*, 2019).

### *Options to delay maturation to move full ripeness to a later date*

As the progress of phenology is strongly influenced by temperature, the increased temperatures induced by climate change have brought the harvest date forward in recent years, negatively affecting the quality of the grapes due to high temperatures during the post-véraison time (van Leeuwen *et al.*, 2019). Options to moderate phenology in order to move the harvest back to a later date with cooler temperatures target either a temperature reduction or a decrease of photosynthesis performance. In the short term, the reduction of the leaf area to fruit ratio could restrain photosynthesis performance (van Leeuwen *et al.*, 2019; Santos *et al.*, 2020). In the mid- to long-term, training in low-input systems could slow down the maturation process (Zheng *et al.*, 2017; Molitor *et al.*, 2019). A general change of location concerning altitude, latitude and possibly the row direction for new plantations could further help to reduce the interception of solar radiation and decrease temperatures (van Leeuwen *et al.*, 2019; Gutiérrez-Gamboa *et al.*, 2021). The choice of later ripening varieties, clones or rootstocks is another option (van Leeuwen *et al.*, 2019).

In the long term, the breeding of more heat- and drought-resistant varieties and rootstocks would provide plant material well adapted to the changing microclimatic conditions.

The presented measures are only a selection of options available to show that climate change, although a significant challenge, especially for viticulture in steep slopes, is not insurmountable. Also, the options presented here demonstrate that even though some may take more time to implement, not every measure is linked to enormous costs.

### 3.5 Social implications of steep slope viticulture

In Chapter 1.2.2, steep slope viticulture with respect to ES was presented to show that such sites provide benefits beyond those specifically associated with agricultural acreage for the production of grapes. These benefits are often referenced by the public to justify the preservation of these sites and the payment of subsidies. However, viticulture on steep slope vineyards not only provides social benefits but also incurs social costs, and these must also be considered in the overall evaluation of the environmental and social value of the sites, as presented in the following paragraph.

#### *Social costs of steep slope viticulture*

Social costs often mentioned in the literature linked to viticulture in general and steep slope viticulture in particular are soil degradation due to unsuitable soil management (Guidoni *et al.*, 2012; Pijl *et al.*, 2020) and the carbon footprint (Cichelli *et al.*, 2016). The increased demand for irrigation will further



bring the issue of the sourcing and distribution of water to public attention, as well as raising the question of a blue water footprint (van Leeuwen *et al.*, 2019).

Soils in viticulture, if not protected properly, will lose organic matter, negatively affecting soil microorganisms, fertility and soil structure (Guidoni *et al.*, 2012) due to tillage, use of herbicides and the passing of heavy machinery (Rodrigo-Comino *et al.*, 2018). Apart from reduced productivity due to decreased fertility, such as damaged soils, sloping terrain is also very vulnerable to erosion caused by heavy rainfall, which is likely to become more frequent with climate change. The worst erosion, especially in the case of inadequate soil cultivation and insufficient soil cover by cover crops, has been observed in sites with vertical cultivation (Pijl *et al.*, 2020). The improper construction and maintenance of terraced vineyards with embankments pose a substantial threat of soil degradation as well. Degraded soils together with heavy rainfall can produce landslides in the worst case scenario (Pla and Nacci, 2002; Cots-Folch *et al.*, 2006; Ramos *et al.*, 2007; Guidoni *et al.*, 2012; Tarolli *et al.*, 2014), as can the abandonment of terraced vineyards (Stanchi *et al.*, 2012). Where growers are facing low levels of profitability cover crops to ensure adequate soil protection are less planted due to already prevailing economic constraints (Schütte *et al.*, 2020). Skilled cultivation, which involves taking measures to preserve soil fertility and soil structure and to inhibit erosion, thereby providing the best conditions for sustained cultivation, is in the best interest of both growers and the natural and social environment.

The increasing severity of drought conditions caused by climate change inevitably entails questions related to the distribution of scarce water resources and the consequent accrual of actual and social costs. Tardieu and Préfol (2002) discussed a full cost approach to determine the price of the water supply, enabling a fair distribution amongst all actors while stressing the importance of keeping prices at a level that does not hinder economic development. They also pointed out that once charges are imposed to cover the costs of water provision and delivery, an increased tendency to dig individual wells typically occurs, negatively affecting the groundwater supply of the region as a whole (Tardieu and Préfol, 2002). In any case, measures to enable dry land farming should be favoured over irrigation because the blue water footprint of irrigated vineyards is 100 times greater compared to dry-farmed vineyards (van Leeuwen *et al.*, 2019).

The carbon footprint caused by wine production is another factor to be considered when assessing social costs. Cichelli *et al.* (2016) have found that grape production greatly contributes to total CO<sub>2</sub> emissions of wine production. Among the strongest drivers for this effect were the number of passages by tractors, especially as a result of pest management and the amount of fertilisers distributed. Good soil conditions that reduce the demand for fertilisers and climatic conditions requiring a smaller number of pesticide applications can thus reduce CO<sub>2</sub> emissions (Cichelli *et al.*, 2016).

*Acknowledgement of the actual value of steep slope sites by society*

Based on the multifaceted services provided by viticultural landscapes, including steep slopes, but also taking into account the social costs connected to the cultivation of these landscapes for the production of grapes, the question is raised of who is paying and who is benefitting from the value of steep slope viticulture. Torquati *et al.* (2015) presented results from Italy, where wine estates have made concerted efforts to preserve traditional cultural viticultural landscapes for differentiation, thus achieving a comparative advantage and improving economic performance even without additional financial support from public authorities. However, in Germany, usually no mark-ups are paid for wines from steep slope sites, and thus no rewards are offered for any positive side effects, as substantiated by findings from surveys, confirming no increased willingness to pay by consumers for standard steep slope wines to compensate for growers' efforts linked to grape production in these sites (Strub and Loose, 2016; Loose *et al.*, 2017). The exception may be wines from a few famous vineyard sites, such as Bernkasteler Doctor (Mosel), Niersteiner Pettenthal (Rheinhessen) or Würzburger Stein (Franconia), that convey the added value of a good reputation.

### 3.6 Implications for policy makers

The literature shows that properly managed steep slope sites provide an invaluable contribution to landscape preservation, thus fostering the touristic appeal and environmental value of these regions. However, under the current conditions, the study has demonstrated that sites that are impeded in mechanisation suffer from significant cost disadvantages. The examples from Germany and Italy demonstrate that whether or not viticulture on steep slopes is profitable depends on the willingness of consumers to pay a price premium. In Germany, many consumers appear to be unwilling to pay a price premium for wines produced from steep slopes to reward the multifunctionality of steep slope vineyards, consequently creating a gap between increased costs and stable prices. It can thus be deduced that growers are typically left to bear the costs. Currently, in response to this gap, growers – if the economic pressure is sufficiently severe – are abandoning unprofitable steep slope sites, resulting in the observed decrease in the acreage of steep slope vineyards.

The public, which is in large part opposed to the abandonment of these sites, has expressed a marked interest in sustaining steep slope viticulture due to its myriad positive impacts (MLR BW, 2016; MWVLW RLP, 2021). Therefore, the proposal to recruit the public to support steep slope viticulture is hardly surprising. The only real question is on what basis the determination of whether – and if so, how much – support should be granted should be made – for example, should it be based on the cost disadvantages incurred or on the individual total value each vineyard site provides for society? With this question in mind, current supportive practices for steep slope viticulture in Germany are reviewed below.

*Public support based on the cost disadvantage of steep slopes*

In Germany, state authorities took the initiative to allocate a certain amount of their budget from the second pillar of the CAP, i.e. rural development in the EU, in addition to a portion of national funds to support steep slope viticulture (MWVLW RLP, 2018). Apart from investments intended to improve the mechanisability of steep slope sites annual acreage-dependent subsidies are allocated for the cultivation of steep slope sites. The distribution and the amount of these subsidies are set by each federal state and are mainly based on the gradient of the slopes, i.e. 30 % or greater (HMUKLV, 2017; DLR RLP, 2020). The state of Baden-Württemberg is an exception insofar as it only supports manual sites exceeding a 45 % gradient (MLR BW, 2017). From the findings of this thesis, it can be argued that the determination and size of subsidies based on differences in gradient and irrespective of the diversity of viticultural practices and contributions is a shortsighted and arbitrary policy.

Concerning the actual size of the subsidies, amounts range from 765 €/ha (DLR RLP, 2020) per year for steep slope sites with a minimum gradient of 30 % to 3,000 €/ha (MLR BW, 2017) per year for manual sites that exceed a 45 % gradient. If these subsidies are intended to compensate growers for the cost disadvantages they accept in order to keep steep slope sites in operation, then they are insufficient to neutralise the cost disadvantages of any VSP site limited in terms of mechanisation. Using the figures from Paper I, the most limited sites, those that do not permit any form of mechanisation, suffer considerable cost disadvantages of more than 4,700 €/ha per year even when the maximum amount of financial support is offered. On the other end of the spectrum, vineyards on gradients just above 30 % that permit the use of standard tractors and SHs given favourable landscape conditions may receive financial support even in the absence of any cost disadvantage (Lauer, 2015). The discrimination of growers cultivating the steepest slopes is enforced by the method of acreage measurement. The cadastral size of the plots, that is used for the payment of subsidies, is measured using the top view. The actual acreage that is ultimately cultivated, however, is larger due to the slope gradient. A vineyard site with 60 % gradient, for example, has an actual, cultivated acreage that is nearly 17 % larger than the acreage according to the cadastre (Achilles *et al.*, 2010). This leads to lower payment rates for the actual acreage cultivated as the terrain becomes steeper (Lauer, 2015). As such, if the current payment scheme is designed to compensate for higher viticultural costs, then its goal is only partially achieved. It is therefore recommended here that available budgets for the support of steep slope viticulture be more evidence-based and precisely targeted with respect to the actual degree of mechanisation.

*True cost approach for the determination of support payments*

Apart from its multifunctional ES contributions, steep slope viticulture also incurs social costs, particularly when environmental questions like soil conservation or over-reliance on irrigation are ignored, as discussed in the extant literature. When support payments are only based on viticultural costs, both positive and negative side effects are omitted from consideration. The positive environmental effects addressed earlier in this thesis are especially reliant on appropriate management practices. If such practices are ignored, the negative side effects as presented in Section 3.6 will quickly emerge. Therefore, addressing not just viticultural costs but also additional services and the social costs of viticulture at steep slope sites within discussions of government support, as recommended in the true cost approach proposed by Falcone *et al.* (2015) is fully warranted. In light of the evidence presented here, it is advisable to reassess the basis for the allocation of subsidies for steep slope viticulture by on the one hand evaluating production conditions in a more detailed and fact-based manner and, on the other, by considering both ES and social costs in the determination of who receives these payments as well as how much they receive.

## **4 Limitations and Future Research**

The papers included in this thesis provide initial insights into the cost structures of viticultural management based on the relative intensity of vineyard mechanisation. However, some limitations of this research must be addressed.

The cost analysis was based on a relatively small number of wine estates and vineyard sites, all of which are located in Germany. Due to the small sample size, the data are affected by a strong variance. The influence of the random factor *Estate* in the analysis of variance showed that many factors associated with the individual character of single estates, such as their general strategies, quality requirements, production philosophies and managerial style, were missing from the analysis. Thus, the validity of the analysis could have been improved had a larger number of wine estates and vineyard sites – possibly from different countries – been included in the sample as well. The so-called ‘big data’ generated by emerging digital tracking programmes, such as VineyardCloud®, which automatically records labour and machine hours, may represent a suitable database from which this study could be replicated.

Special attention should be paid to the cost analysis of those vineyard site types that remain uncommon in Germany, such as low-input systems and transversal terraces, as well as their combination and comparative assessment to validate the initial findings concerning these site types as presented in this thesis.

An extension of this study should also include information on the targeted quality level of the wines produced from the grapes grown in different vineyards as well as the actual yield levels to facilitate a better understanding of the relationship between cost structures, targeted quality levels and expected versus actual yields.

Insufficient profitability and therefore degraded or nonexistent economic sustainability is a major concern of the wine-producing sector in Germany as well as abroad, as discussed in Section 1.2. Initially, the author of this thesis assumed that steep slope viticulture exerted a negative impact on the profitability of wine estates, as this assumption would have explained why steep slope vineyard sites in Germany continue to be abandoned. Although the evidence presented in this thesis laid the groundwork for structured assessments of the costs of viticulture at steep slope sites, it neither confirmed nor refuted the assumption concerning the negative profitability of steep slope viticulture or its relationship to the abandonment of such sites. Therefore, the overall impacts, positive and/or negative, of the cost disadvantages of steep slope viticulture on the relative profitability of wine estates have yet to be fully elucidated. Combining business data on the economic performance of wine estates with detailed information on the types and locations of viticultural sites could constitute a useful approach to conclusively determining the nature and quality of the impacts of steep slope viticulture on profitability, be they positive or negative – or a mixture of both.

The discussion of the nature of government support for steep slope viticulture indicated that, to date, assessments of the overall value of steep slope sites have been decidedly shortsighted and arbitrary. In addition to incorporating the findings of this thesis into a more thorough estimation of the actual production conditions at steep slope sites, determining the true costs of these sites in light of ES and social costs would culminate in a more complete and detailed picture of steep slope viticulture, which is crucial for calculating the eligibility of these sites for future public support and thereby the likelihood of their preservation.

## 5 Conclusions

Viticulture on steep slopes will always compete with flat terrain viticulture, given its greater mechanical efficiency. Different applications of such machinery generate variable viticultural costs for different types of vineyard sites. In the context of Germany, in most cases, the higher costs of sites with more limited mechanisation cannot be offset by higher-priced products. Most consumers are only willing to pay price premiums for products grown on steep slopes if their quality is superior to that of products grown on flat terrain or they are known to have been produced at famous vineyard sites. Additionally, a certain percentage of wine from steep slopes is sold in bulk wine markets, where prices are typically fixed and therefore do not permit the addition of margins to cover additional costs. The intensifying effects of climate change experienced worldwide in recent decades have contributed to an overall increase in the rate of ripeness of grapes, thereby nullifying the former phenologic advantage of steep slope viticulture. Thus, absolute efficiency in the management of steep slope vineyards is the only way to reliably reduce their cost disadvantages. Such efficiency could be achieved by further technological developments and implementations, such as introducing SSHs or precision farming methods, especially for pest control. Secondly, adaptations of increasingly widespread practices, such as the establishment of low-input systems, the construction of terraced vineyards – albeit in consideration of all known benefits and costs – or the use of fungus-resistant grape varieties could substantively contribute to improvements in cost efficiency. Again, such efforts could be impeded by the adverse consequences of climate change, such as the potential for more frequent and increasingly severe drought conditions, on viticultural yields. However, measures can be taken to mitigate such negative effects, such as changes in viticultural practices, the application of different grape varieties and rootstocks, the installation of irrigation systems, or alterations in the direction or location of the vineyards. That said, measures such as these might be insufficient or unfeasible for various reasons. In these cases, and in consideration of national and international competition in the viticultural sector, as well as misallocated financial support, the abandonment of steep slope vineyard sites may be the only remaining option from the economic perspective of wine-producing businesses. While the older generation, approaching the age of retirement, may continue the cultivation of steep slope vineyards due to the lack of alternatives, the younger generation may find well-paid alternative employment more easily, therefore deciding not to take over an unprofitable family business. Lastly, if the continued abandonment of steep slope sites were to accelerate, it could spiral out of control and eventually pose dire environmental and economic consequences for entire regions, such as elevated risks of erosion and landslides and diminished natural appeal to tourists.

## 6 References

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