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

Larissa Strub[1,*], Simone Mueller Loose[1,2]

[1]Hochschule Geisenheim University, Von Lade-Str. 1, 65366 Geisenheim, Germany
[2]Ehrenberg-Bass Institute, University of South Australia, Adelaide, SA 5000, Australia

[*]corresponding author: larissa.strub@hs-gm.de

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
2	General viticultural management	Canopy management	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
		Pest 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
					Biotechnological measures, such as the manual distribution of ampoules with insect pheromones, to prevent mating of the insects	None	1
		Soil management	1100 1200	Mineral or Organic Fertilisation	Distribution of mineral or organic fertiliser in the vineyards to improve nutrient supply-mechanically, manually only steepest sites	Full	Every few years as required
			1300	Cultivation	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
			1400	Cover crop management**	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
			1500	Under-vine cultivation	Removal of weeds between vines to decrease competition for water and improve ventilation between vines – mechanically, manually only steepest sites	Full	4–5
			1600	Chemical weed control	Chemical removal of weeds by herbicides-mechanically, manually only steepest sites	Full	2
			1700	Straw application	Manual distribution of straw on the surface to prevent erosion and evaporation – usually only in steep sites	None	1
			2100	Irrigation	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
3	Harvesting		900		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					
Slope and Access to Vineyard Sites	Orientation of Rows Towards the Slope	Pruning*	General Management	Harvesting		
No limitation	-	Manual	Unsupported	SH	1	Standard
Limited access for machines	DSS	Manual	Unsupported	SSH	2a	SSH
		Manual	Rope	SSH	2b	Rope
	TT	Manual	Unsupported	SSH	2c	TT
No access to machines	DSS/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 (Schreieck, 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_{2017}	n_{2018}	n_{2019}	n_{total}	Site Type	
No limitation	-	Unsupported	SH	3	5	6	14	1*	Standard
Limited access for machines	DSS	Unsupported	SSH	-	2	3	5	2a	SSH
	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_{total}
		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 $(i=1,\ldots, 30)$, 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).

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

t* = amortisation period in years

At NPV = 0 €, 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[F]	Estate[R]	Year[R]	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).

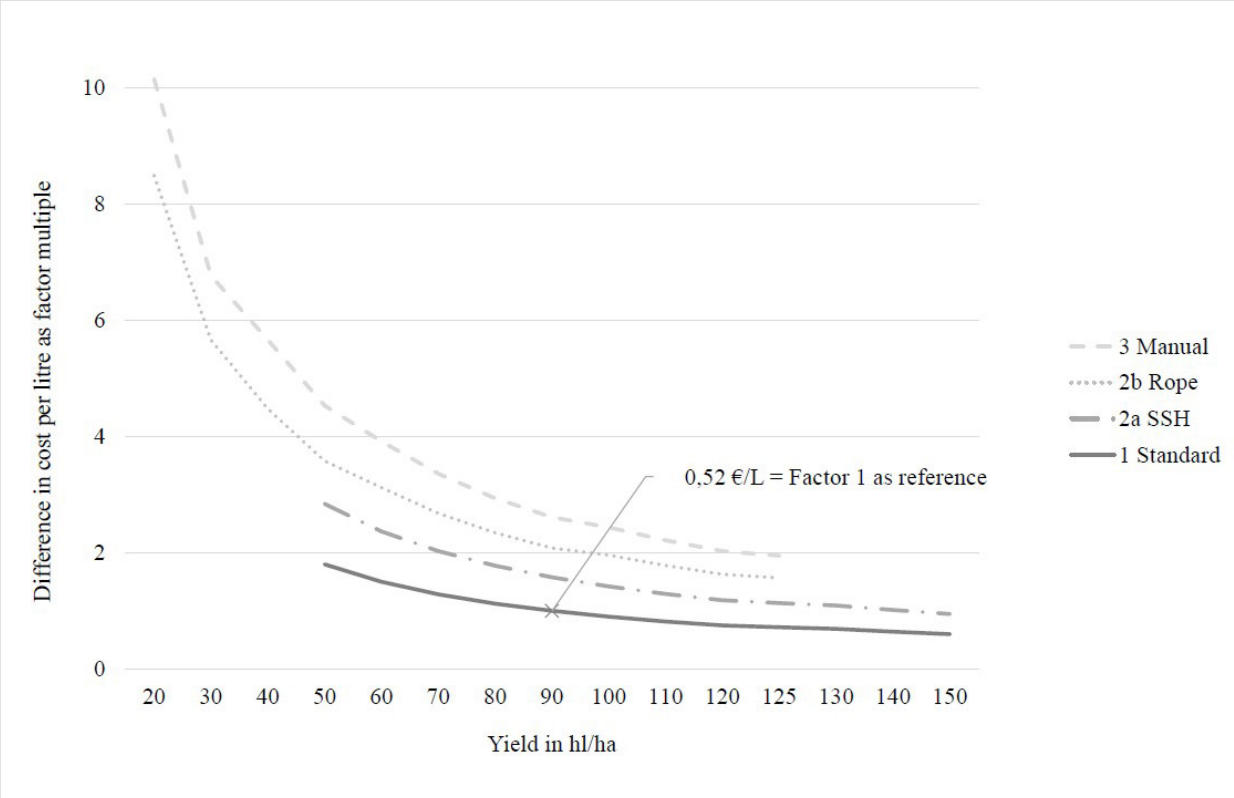

FIGURE 1. Cost per litre as a function of yield per hectare for site types 1, 2a, 2b and 3.

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. [1]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

[1]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.

		A	B	C	D	E	F	G
	Site Type	2c TT	2b Rope	2b vs. 2c		3 Manual	3 vs. 2c	
Code	Process	Cost [€/ha]	Cost [€/ha]	Absolute Δ in €/ha	Relative Δ in %	Cost [€/ha]	Absolute Δ in €/ha	Relative Δ 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, Rheinhesse) 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; Clingeleffer, 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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