

Research article

Farmer adoption and effectiveness of copper-reducing strategies in Swiss viticulture

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ABSTRACT

Copper is widely used in agriculture as an active ingredient in plant protection products. Especially viticulture accounts for the largest share of copper use, primarily to control downy mildew in grapes. Copper use has raised significant environmental concerns, and copper is now classified as a high-risk substance, with phase-out expected in European agriculture. In this study, we analyze data from a pre-registered design involving 489 grape growers in Switzerland to investigate: (i) whether and to what extent growers adopt copper-reducing measures; (ii) the individual measures or combinations of these measures employed; and (iii) which strategies have the greatest potential for copper reduction at the farm level. We find that 57% of copper-using growers adopt some copper-reducing practices. Adoption patterns are highly diverse, with 94 distinct strategies used among 203 growers using copper-reducing measures. Short- and medium-term measures, such as preventive and efficiency strategies, are most frequently implemented. In contrast, substitution and redesign measures—that are often characterized by longer time horizons—are less common. We find that the greatest copper-reduction potential is achieved through integrated strategies combining prevention, efficiency, and redesign measures. We discuss policy implications.

1. Introduction

The management of grapevine diseases is one of the major challenges in both conventional and organic crop production systems. Indeed, phytopathogens (Furiosi et al., 2022; Vallejo et al., 2019) are responsible for significant yield and quality losses worldwide (e.g. Fuller et al., 2014) and in the last decades growers have traditionally relied on repeated applications of a wide range of fungicides (Mailly et al., 2017; Pirello et al., 2023). Fungicides account for roughly a third of all pesticides used in European and Swiss agriculture (de Baan, 2020; Muthmann and Nadin, 2007). Within them, copper-based fungicides are among the oldest plant protection products still in widespread use (Furiosi et al., 2022; Gessler et al., 2011).

The fungicidal properties of copper were first discovered in 1882, when Pierre-Marie Alexis Millardet observed that grapevines sprayed with a mixture of copper sulfate and lime to deter passersby from eating grapes remained free of downy mildew (*Plasmopara viticola*). This observation led to the development of the Bordeaux mixture, which rapidly gained worldwide recognition for its efficacy and persistence as fungicide and by the early 20th century, its use had become a standard

practice in viticulture. Over time, additional copper compounds (e.g. copper hydroxide, copper oxychloride, tribasic copper sulfate and cuprous oxide) were also introduced and became the cornerstone of grapevine protection until nowadays (Furiosi et al., 2022; Gessler et al., 2011). In modern viticulture, copper continues to play a critical role in disease management, in conventional but particularly in organic viticulture, where synthetic fungicides are prohibited, mainly to control *P. viticola* and *Guignardia bidwellii* and a range of secondary pathogens (e.g. *Diaporthe ampelina*, *Allorhizobium vitis*, etc.) (Dagostin et al., 2011).

The continuous use of copper fungicides is driven by several factors (Gessler et al., 2011). First, copper has broad-spectrum activity that allows it to target multiple pathogens with a single application and a good level of efficacy. Second, it has a multi-site mode of action, as copper ions denature proteins and consequently disrupt multiple enzymatic processes in fungal, oomycetes and bacterial cells. This makes it extremely difficult for pathogens to develop resistant populations, in contrast to several modern fungicides that act on a single biochemical site only. As a result, copper plays a key role in resistance management strategies, where it is commonly applied in combination or alternation with those fungicides that are more prone to develop resistance. Third,

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Table 1
Technical measures to reduce copper use in vineyards.

Category	Approach	Measure	Description	Time dimension	Sources
Efficiency	Treatment orientation	Precision application technology (AT)	Using specific machines (e.g. drones) or equipment (e.g. low drift nozzles)	Medium	Llorens et al. (2010) (Dubuis et al., 2014, 2019; Kuflik et al., 2009) (Siegfried et al., 2007; Viret et al., 2019)
		Disease forecasting models (DF)	Using a disease forecasting model		
		Dosage or formulation (DO)	Using variable copper dosages in relation to the disease pressure or copper fungicides with improved formulations		
Substitution	Treatment orientation	Copper alternatives (CA)	Copper alternatives of natural origin (non-chemical synthetic) are used (e.g. calcium carbonate, calcium hydroxide, microbial biocontrol agents or derivatives, plant extracts)	Long	Dagostin et al. (2011) Burandt et al. (2024) Harm et al. (2011)
		Synthetic Chemical fungicides (SC)	Reduction comes from applying more synthetic chemical fungicides		
		Resistance inducers (RI)	Resistance inducers are used to substitute copper (e.g. whey, cos-oga)		
Redesign	Disease prevention	Preventive measures (PM)	Reduction comes from investing more in preventive measures (e.g. pruning to avoid leaf wetness, balance fertilization to avoid excessive growth, field hygiene, canopy management)	Short	Tamm et al. (2022)
		Fungus-resistant varieties (FR)	Copper reductions are achieved by planting fungus-resistant varieties which are more tolerant towards fungal pressure		
		Less susceptible traditional varieties (TR)	Less susceptible <i>V. vinifera</i> varieties and clones are chosen to reduce copper and produce traditional wine	Very long	(Eisenmann et al., 2023; Speiser et al., 2015) Boso et al. (2014)
		Training system (TS)	Using pathogen resilient trellis and training systems		

being a natural element, it is compatible with organic farming regulations and therefore it is indispensable in these systems where synthetic fungicides are prohibited.

However, despite these advantages, copper use is increasingly scrutinized due to its environmental persistence and ecotoxicological effects (Barmettler et al., 2026; Burandt et al., 2024; Flemming and Trevors, 1989; Mackie et al., 2013; Thiollot-Scholtus et al., 2021). Indeed, copper does not degrade in the environment; it strongly binds to soil particles such as organic matter and clay, and it has limited plant uptake (Barmettler et al., 2025). Therefore, repeated applications lead to its accumulation in vineyard soils, where it can negatively impact soil microbial communities, bacterial diversity and various organisms involved in organic matter degradation, as earthworm populations, with consequent perturbation of nutrient cycling processes (Barmettler et al., 2026; Mackie et al., 2013).

In response to these issues, regulatory bodies—most notably in the European Union (EU) and Switzerland—have progressively restricted copper use (La Torre et al., 2018; Tamm et al., 2022). Under Commission Implementing Regulation 2018/1981 (European Commission, 2018), copper compounds are approved only as “candidates for substitution”, with a maximum application limit of 4 kg of metallic copper per hectare per year averaged over seven years. Some countries, such as France, withdrew market approval for 19 copper-based fungicides effective January 15, 2026 (ANSES, 2025). These measures aim to limit environmental accumulation and adverse effects on worker health while still permitting use where alternatives are lacking. However, this regulatory pressure has intensified the search for more sustainable plant protection strategies. Similar measures have been adopted in Switzerland, where copper is listed among active ingredients with exceptional risk potential (Bundesamt für Landwirtschaft, 2024; Bundesrat, 2017). At the same time, ambitious policy targets such as of the EU of halving pesticide use and risk by 2030 (Schebesta and Candel, 2020) further increase pressure to reduce copper dependency in viticulture. Similar targets are set also Switzerland (Finger, 2021). While progress has been made on certain pesticide risk reduction goals, those targeting the reduction of persistent substances in soil (such as copper) are still unmet (Bundesrat, 2024;

European Commission, 2024).

Viticulture is one of the most pesticide-intensive agricultural sectors, accounting for around one third of all pesticides used in Europe and Switzerland (de Baan, 2020; Muthmann and Nadin, 2007) and, among them, fungicides are the largest class of substances used (Muthmann and Nadin, 2007; Pertot et al., 2017). Within fungicides, copper remains a key input (Furiosi et al., 2022; Gessler et al., 2011). For example, organic vineyards in twelve European countries apply approximately 990 tons annually (Tamm et al., 2022).

Due to the continuous and intensive use, copper contamination has been reported in vineyard soils across the EU (Ballabio et al., 2018; Knuth et al., 2024) and Switzerland (Barmettler et al., 2025), with average concentrations often exceeding critical thresholds (Komárek et al., 2010), raising concern for long-term soil health (Karimi et al., 2021). Although these levels threaten soil biodiversity and ecosystem functions, little is known about whether and how grape growers actually implement copper-reducing practices, or which combinations of measures offer the greatest potential for reduction. To our knowledge, only two studies examine factors affecting copper-based fungicide use and the use of biopesticides as alternatives (Nefti et al., 2023; Ortega et al., 2023). However, understanding if and how extensively growers adopt copper-reducing measures, which measures or combinations they use, and which offer the highest stated reduction potential is crucial for achieving ambitious pesticide reduction goals. This is particularly relevant in grapevine production, which is a major consumer of copper compounds and thus plays a critical role in shaping policy measures and achieving pesticide risk reduction goals.

Although the use of fungicides, including copper-based compounds, is the dominant strategy, growers have several tools at hand to cope with fungal diseases (see Pertot et al. (2017) for a review). These measures can be grouped within the efficiency-substitution-redesign framework (Hill and MacRae, 1996) (Table 1). In the efficiency stage, copper applications are optimized to reduce usage, for example through precision application technologies, disease forecasting to time sprays only when infection conditions are met, and improved formulations or dosages to minimize residues while maximizing efficacy. These require a moderate

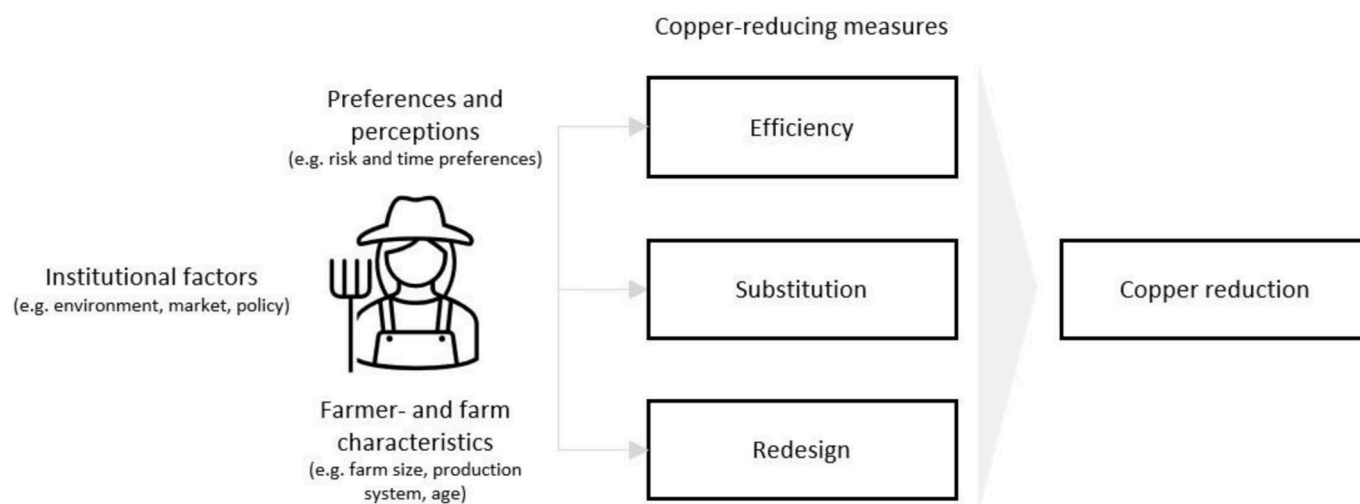


Fig. 1. Conceptual framework on the pathway of factors influencing the use of copper-reducing measures and stated on-farm copper reduction.

time horizon, as growers need time to acquire knowledge, machinery, and tools. The substitution phase involves replacing copper with chemical-synthetic alternatives, alternatives of natural origin (e.g. minerals, microbial biocontrol agents or derivatives, plant extracts) or plant resistance inducers (e.g. whey, cos-oga, laminarin).¹ The time dimension for substitution demands a longer timeframe, as it requires the development, approval, and adoption of effective alternative products, as well as adjustments in vineyard management practices and market acceptance. Both efficiency and substitution remain treatment-oriented. On the opposite, the redesign stage focuses on disease prevention. This can take two forms depending on the time dimension, i.e. including immediate preventive measures such as pruning or managing canopy to avoid leaf wetness or balance fertilization to avoid excessive growth. On the other hand, very long-term redesign measures address root causes of disease susceptibility through re-structuring the system, and as such reducing the need for plant protection overall. Measures in the redesign stage are choice of cultivars since grapes are typically replanted every 25 to 35 years (Carbone et al., 2019), i.e. less susceptible traditional varieties or disease-resistant varieties, or the use of more pathogen resilient trellis and training systems.

Factors affecting the use of these copper-reducing measures are linked to farm-level factors such as farm and farmer characteristics and preferences and perceptions as well as institutional factors such as the environmental, market and policy context (Fig. 1) (Finger et al., 2024). For, instance farms producing under organic standards use more copper-based products than conventional farms due to a lack of alternatives (Ortega et al., 2023). Moreover, the adoption of preventive strategies against copper is often costly, time-consuming, and risky for growers, thus time and production risk preferences matter (Tamm et al., 2022). Similarly, farm size and the level of specialization may influence the level of professionalism of application technologies used, such as the use of precision application technologies. Also, the educational level of the grower may be linked to knowledge regarding plant protection strategies, such as dosing and formulations (e.g. Ortega et al., 2023). Finally, the length of the supply chain matters for the uptake of fungus-resistant varieties, with farms mainly marketing their wines directly to consumers adopting these varieties more often (Finger et al., 2023).

¹ Notably, the primary chemical-synthetic fungicide used in Swiss viticulture (Folpet) raises ecotoxicological concerns, as it has been classified as posing a high risk to birds, mammals, bees, non-target arthropods (excluding bees), and earthworms (European Food Safety Authority (EFSA) et al., 2023).

Furthermore, environmental characteristics such as regional pest pressure may influence the use of copper-reduction strategies. More specifically, growers in high pest pressure regions (from e.g. downy mildew) may be using more effective measures, such as synthetic chemical fungicides.

Finally, the policy and market environments may influence the use of on farm copper-reducing measures. The production system followed (and audited) defines the degree to which copper must be reduced (e.g. Zachmann et al., 2024a). For instance, all growers not following any production systems must not apply more than 6 kg/ha/year pure copper as mandated by the Swiss environmental law (Speiser et al., 2015). Similarly, growers who comply with the proof of ecological performance record requirements, which is the minimum standard to receive direct payments according to Swiss agricultural policy may apply up to 4 kg/ha/year. Furthermore, market mechanisms through private sector initiatives limit copper use of copper-based products (Tamm et al., 2022). For instance, growers following integrated production (e.g. IP-Suisse) or organic production (e.g. Bio Suisse) may apply up to 4 kg/ha/year, and growers following certified biodynamic production (e.g. Demeter) must not apply more than 3 kg/ha/year of pure copper (see Appendix A for details). Despite maximum allowable levels of pure copper application are set, many growers apply quantities below these limits (Speiser et al., 2015).

Our study has three objectives. First, we analyze whether, and to what extent, grape growers adopt practices to reduce copper use in viticulture. Second, we investigate which individual technical measures or combinations of measures are employed to achieve copper reduction, going beyond simple binary measures (e.g. Finger et al., 2024) (see Table 1 for the measures). Third, we identify measure categories or combinations of measure categories that yield the highest (stated) copper reduction potential at the farm level. We analyze 489 farm-level observations from grape growers across Switzerland, encompassing all major wine regions and the country's three main languages spoken—German, French, and Italian (Höper et al., 2026). Following a pre-registered protocol, we examine the data both descriptively and using a multinomial treatment effects model, which accounts for non-random selection into strategy choice and controls for unobserved heterogeneity (Deb, 2009; Deb and Trivedi, 2006).

2. Methodology

2.1. Data collection

We use data from a survey of 489 grape growers in Switzerland,

conducted in German, French, and Italian, and covering all six wine regions (see Appendix B) (Höper et al., 2026). The research protocol has been pre-registered prior to data collection, following best practices in the field (Greibitus and Hu, 2025).² The survey received ethical approval from the Ethics Commission of ETH Zurich (with No. 2024-N-385).

In the online questionnaire, grape growers were asked how they control pathogen infections in their vineyard, letting them choose from 11 multiple choice answer options, including the use of copper-containing fungicides.³ If grape growers indicated that they use copper-containing fungicides, they were subsequently asked if they employ copper-reducing measures in their vineyards. If so, growers were asked which measures or measure combinations they employ to reduce copper in their vineyard, with various answer options (see Table 1). Finally, growers were asked how much pure copper they use on average per hectare and year.

2.2. Research approach

We follow a pre-registered research approach (Fig. 2). In step 1, we identify 356 growers who use copper-containing fungicides (i.e. conventional and organic producers) and only include farms that do use copper in the analysis (i.e. we drop 133 growers who stated that they do not use copper-containing substances, see Appendix C for pest management differences of these groups, and farm profiles associated with copper use).

In step 2, we identify growers who invest in copper-reducing measures. In step 3, we assess which measure categories and combinations thereof (i.e. strategies) are most frequently applied (see Table 1). Since we elicited ten binary copper reduction measures (i.e. use or not), there are $2^{10} = 1,024$ possible measure combinations, including the case where no measures are applied (the baseline in stage 3). Given the high heterogeneity in adopted measure combinations—94 distinct and unique strategies are used among the 203 copper-reducing farms (see Appendix D)—analyzing individual measures or combinations thereof is statistically infeasible due to limited power. To address this, we group measures into broader categories: prevention, efficiency, substitution, and redesign. Consequently, there are $2^4 = 16$ possible measure combinations. The seven most frequently used combinations account for approximately 90% of growers, whereas the remaining eight combinations are adopted by only a small number of growers (see Appendix D). These less frequent combinations are therefore aggregated into a single category, resulting in $J = 8$ measure category combinations.⁴ Next, we use farm- and farmer characteristics, preferences and perceptions and institutional factors to model the use of copper-reducing measure categories or combinations thereof in step 2 ('selection into copper-reducing measures').

Finally, we are interested in which measure categories and combinations thereof are associated with the highest copper reduction potential at the farm (compared to not using any copper reduction measures) in step 4. Copper reduction at the farm is the difference between the farms' maximum (i.e. specified by the production system) and stated actual copper use level per hectare and year (see Appendix E). The difference serves as a proxy for the reduction potential, indicating how much growers can reduce copper use beyond the limits specified for the

production system.

2.3. Data analysis

Empirically, we use the Multinomial Endogenous Treatment Effects model (Deb, 2009; Deb and Trivedi, 2006), which has been employed by Khonje et al. (2022) in a similar context. This model provides two significant advantages for our analytical purposes. First, the two-stage estimation approach allows for both, controlling the factors influencing the use of specific copper reduction measure categories and combinations thereof ('selection into copper-reducing measures'), such as the production system employed, and unobserved heterogeneity, thereby addressing potential endogeneity in the measure combination selection. Second, by incorporating latent factors into the measure combination selection process, the model can capture unobserved traits that influence both the choice of copper-reducing measure categories and combinations thereof ('selection into copper-reducing-measures') and the stated copper reduction potential (e.g. the growers' ambition to reduce copper introduction into the environment).

The model is thus operationalized using two stages. In the first stage, we model the use of copper reducing measures (or not; the baseline) among the copper-using farms. Thus, we assume that farm i derives indirect utility EV_{ij}^* from using copper-reducing measure category (or combinations thereof) $j \in \{1, \dots, 8\}$. This indirect utility depends on a vector of covariates (z_i') and latent factors (l_{ij}), which capture unobserved characteristics of farm i 's choice of copper-reducing measure categories or combinations thereof j and the stated copper reduction potential (e.g. the duration of employing copper-reducing measures), along with independent and identically distributed errors (θ_{ij}):

$$EV_{ij}^* = z_i' \alpha_j + \delta_j l_{ij} + \theta_{ij} \quad (1)$$

The vector z_i' includes a rich list of factors which are relevant to explain the choice of copper-reducing measure category combinations by a farm (see section 3). These factors are farmer characteristics such as the age (in years) and gender of the grower, as well as whether the grower has further education in plant protection. Additionally, we include time and production risk preferences of the grower. Furthermore, we use farm characteristics such as farm size (in hectare), whether the farm is certified organic, whether most of the income comes from agriculture (i.e. off-farm specialization), whether most of the agricultural income comes from viticulture (i.e. on-farm specialization), and whether the farm mainly markets directly to consumers. Finally, we use regional downy mildew pest pressure. We estimate the first stage using a mixed multinomial logit. The coefficients α_j show if and which grape growers invest in copper-reducing measure category combinations j .

In the second stage, we model the stated reduction potential ($Reduction\ potential_i$) as a function of copper-reducing measure category combinations ($Category\ combination_{ij}$) and latent factors (l_{ij}) with corresponding coefficients λ_j , potentially influencing the copper reduction potential:

$$E[Reduction\ potential_i] = \sum_{j=1}^J \beta_j Category\ combination_{ij} + \sum_{j=1}^J \lambda_j l_{ij} + \mu_i \quad (2)$$

We cluster the error term μ_i at the wine-region level to account for heteroskedasticity and intra-cantonal correlation which may arise due to cultural as well as climatic difference across the regions (Finger et al., 2023; Zachmann et al., 2024b). Thus, β_j measures the stated copper reduction potential at the farm of measure category combination j .

3. Results

3.1. Descriptive statistics

We find that most farms use copper-containing fungicides ($N = 356$,

² The pre-registration is available here: <https://aspredicted.org/q48h-246y.pdf>.

³ Answer options were removing infected material, using decision support tools, doing canopy management, using microorganisms, controlling fertilization, using grapevine resistance inducers, using inorganic material, using chemical-synthetic fungicides, using copper-containing fungicides, and using sulphur-containing fungicides. See Appendix C for fungal pathogen management by copper users and non-copper users.

⁴ Note that due to the heterogeneity of this latter group, we do not report coefficients for this group.

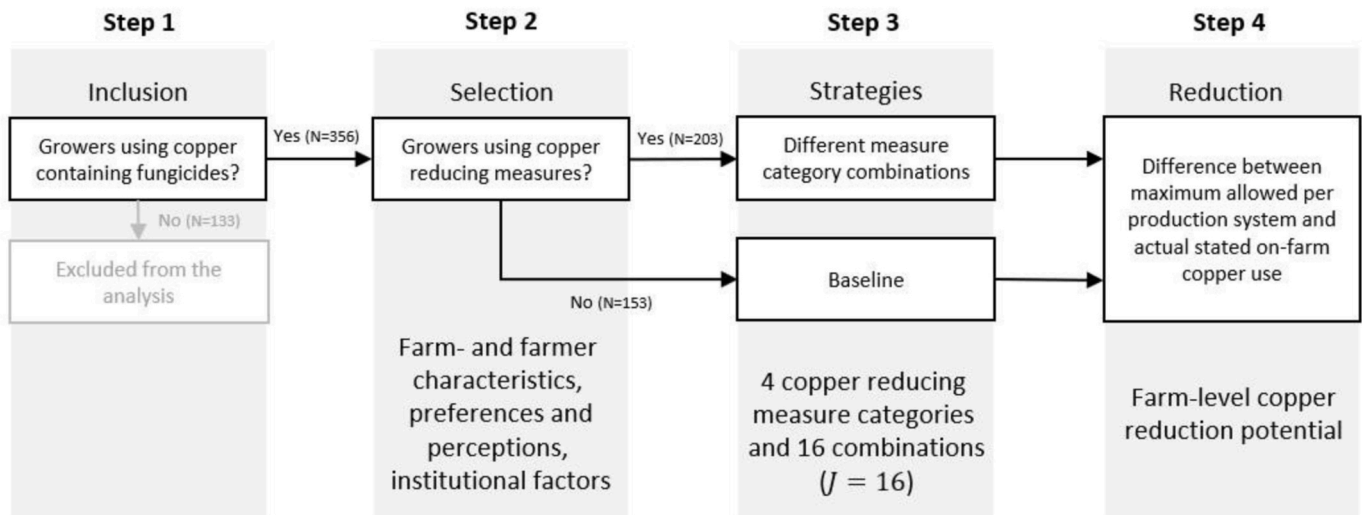


Fig. 2. Overview of the research approach. The figure shows an overview of the approach used to address the three research questions. The figure highlights the interconnections between the research questions and how insights from one inform the others.

Table 2
Descriptive statistics by production system.

	Number of observations	Uses copper-containing fungicides?		
		No	Yes	
			Uses copper-reducing measures?	
			No	Yes
Production system				
None (i.e. not following any pre-defined production system)	81	35 (43.2%)	20 (24.7%)	26 (32.1%)
Proof of ecological performance	183	40 (21.9%)	75 (41%)	68 (37.2%)
Integrated production	94	33 (35.1%)	35 (37.2%)	26 (27.7%)
Non-certified organic production	39	10 (25.6%)	8 (20.5%)	21 (53.8%)
Certified organic production	68	11 (16.2%)	14 (20.6%)	43 (63.2%)
Biodynamic production	24	4 (16.7%)	1 (4.2%)	19 (79.1%)
Copper use				
Average farm-level copper use (kg/ha/year)		NA	2.17	1.97
Total	489	133 (27.2%)	153 (31.3%)	203 (41.5%)

Note: 'None' refers to farms not following any pre-defined production system, while 'Proof of ecological performance' is the minimum requirement to receive federal direct payments. It is important to distinguish between certified organic producers and those who follow organic practices but are not certified (see Zachmann et al., 2024a).

72.8%) and among these copper users, 57% invest in copper-reducing measures (N = 203) (Table 2). While organic and biodynamic growers have a high reliance on copper, they also show the strongest commitment to copper-reducing strategies. Non-organic and biodynamic growers use copper-containing fungicides less frequently and are also less likely to implement reduction measures when they do use copper. Farms without a formal production system show limited use of copper. Furthermore, copper use intensity is lower among growers using reduction measures.

Various copper-reducing measures are employed (Fig. 3, panel A). 153 copper-using farms do not employ copper-reducing measures, while

most growers who invest in copper-reduction use three to five measures. Various individual measures or combinations of measures are employed to achieve copper reduction (Fig. 3, panel B). The measures are grouped into the four broader categories, such as investing into preventive measures, applying copper more efficiently, substituting copper fungicides with alternatives or re-designing the system. Most growers use efficiency measures (category average of 36.8%) with dosage and formulation improvements to be the most frequently applied measure. Preventive measures are used by 34% of the farms investing in copper-reducing measures. Substitution (14.1%) and redesign (10.9%) measures are used by fewer growers.

Copper application efficiency increasing measures are frequently combined with one another (Fig. 4), while substitution and redesign measures are rarely combined with within-category alternatives. Most growers combine dosage or formulation adjustments (efficiency) with disease forecasting models (efficiency). Similarly, dosage or formulation adjustments are frequently used in combination with copper alternatives (substitution) and fungus-resistant varieties (redesign).

3.2. Results from data analysis

The regression output from model 2 on the copper reduction potential by measure combinations is reported in Table 3. We find that farms using prevention, efficiency and redesign measures jointly report the largest stated copper reduction potential compared to the baseline group, which does not invest in copper-reducing measures but use copper. The estimated reduction potential is statistically significant and with 0.65 kg/ha/year the largest reduction potential (measured as the difference between maximum copper use in kg/ha/year given by the production system compared to stated actual copper use in kg/ha/year) compared to all measure category combinations. We further find that growers investing in efficiency measures only have a statistically significant reduction potential of 0.56 kg/ha/year compared to growers who are using copper but do not invest in copper reducing measures. We do not find statistically significant reduction potential for all other measure category groups.

Furthermore, growers using these prevention, efficiency, and redesign measure combinations are more future-oriented, as indicated by their lower discount rates (i.e., they place greater value on future outcomes), risk-averse regarding risks related to production and are male (Table 4, column 8). Finally, organic producers engage more in category combinations including copper substitutions (Table 4, columns 2, 3, 4 and 7). Farms who receive the majority of their income from agriculture

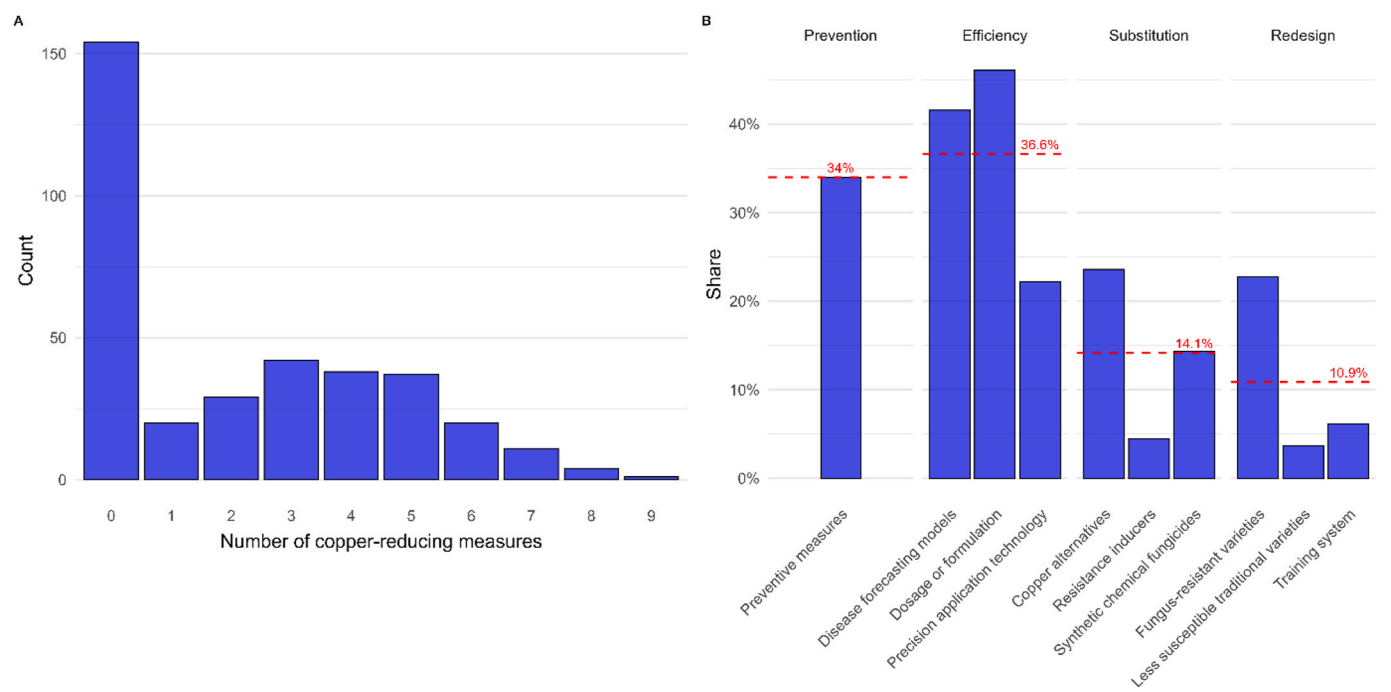


Fig. 3. Count of number of copper-reducing measures employed (A) and share of individual measures per category employed (B). The red dashed horizontal lines refer to the category mean shares.

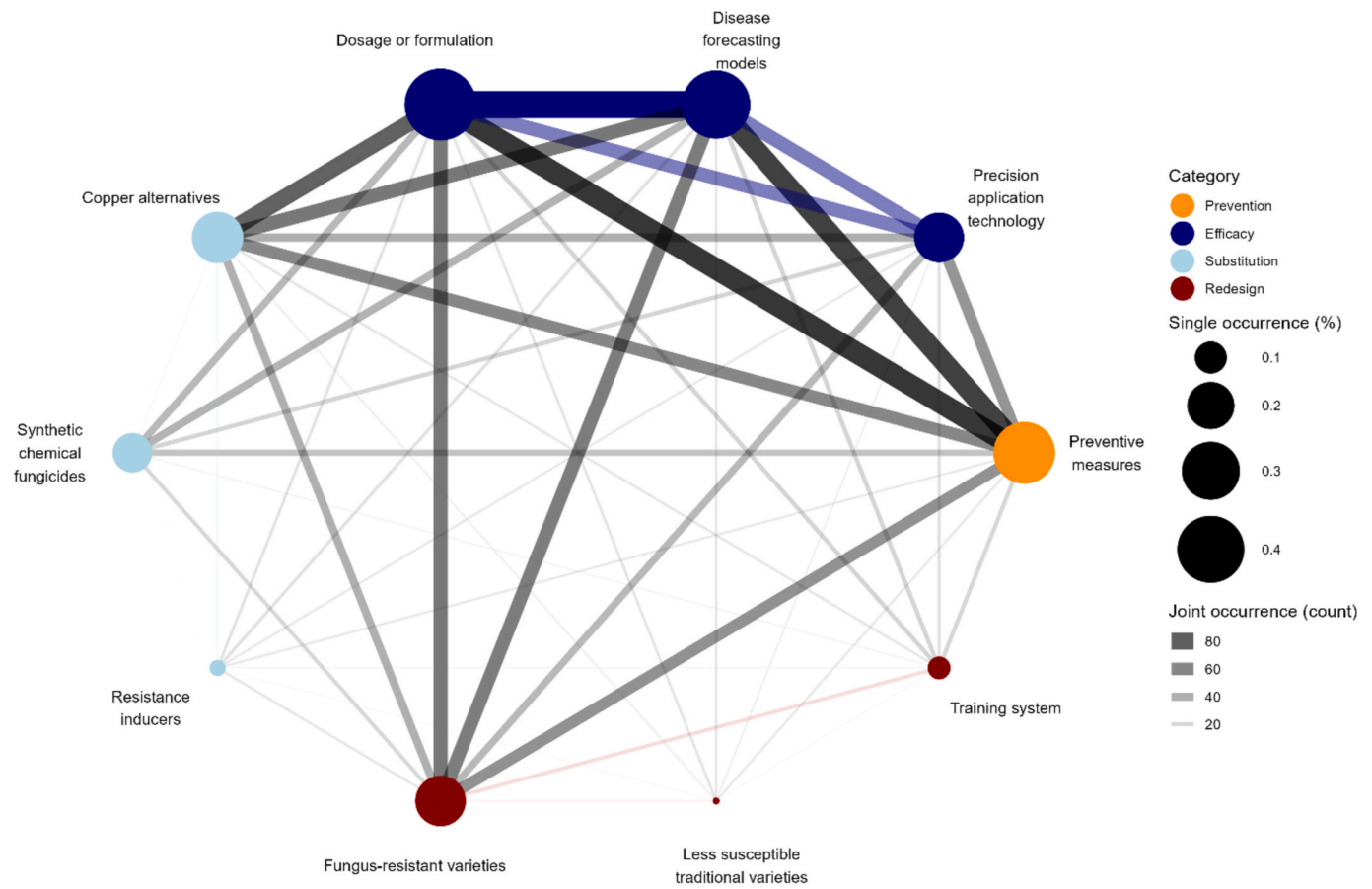


Fig. 4. Joint occurrence of copper-reducing measures by category indicating which copper-reducing measures tend to be implemented together across different categories (Appendix D reports all possible measure combinations).

Table 3

Regression output from Model 2 on the copper reduction potential by category combinations.

	Copper reduction	Lambda (λ)
	(1)	(2)
Prevention, Efficiency, Substitution, Redesign	−0.194 (0.144)	0.513** (0.161)
Prevention, Efficiency, Substitution	−0.102 (0.289)	0.653 (0.287)
Efficiency, Substitution	0.057 (0.201)	0.103 (0.152)
Efficiency only	0.564*** (0.085)	−0.668*** (0.177)
Prevention, Efficiency	0.125 (0.514)	0.163 (0.388)
Efficiency, Substitution, Redesign	−0.247 (0.932)	0.412 (0.207)
Prevention, Efficiency, Redesign	0.656*** (0.138)	0.111 (0.191)
Observations	289	289

p < 0.01, *p < 0.001. Note that category treatment 8 shown in [Appendix D](#) is included in the regressions but not shown due to lack of interpretability. Column 2 reports the lambdas (λ) from model 2 that include unobserved characteristics influencing a farm's use of copper-reducing measure combinations and the copper reduction potential.

are more likely to employ copper-reducing measures from all categories, that is prevention, efficiency, substitution and redesign (column 2), while growers which obtain most of their agricultural income from viticulture are more likely to combine various measure combinations but less likely to employ efficiency, substitution and redesign measures jointly (columns 2, 3, 4 and 7). Growers with further education in plant protection are more likely to use prevention and efficiency measure only (column 6).

Table 4

Regression output from Model 1 on the selection into copper-reducing measures and explanatory variables.

	Selection into copper-reducing measures						
	Prevention, Efficiency, Substitution, Redesign	Prevention, Efficiency, Substitution	Efficiency, Substitution	Efficiency only	Prevention, Efficiency	Efficiency, Substitution, Redesign	Prevention, Efficiency, Redesign
	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Age (in years)	0.004 (0.029)	0.011 (0.027)	−0.022 (0.011)	−0.028 (0.032)	−0.011 (0.027)	−0.018 (0.033)	−0.021 (0.024)
Female (1/0)	−0.176 (1.142)	0.049 (0.922)	−1.494 (1.402)	−0.676 (1.678)	0.422 (1.302)	−41.257*** (0.985)	−4.359** (1.431)
Farm size (ha)	−0.000 (0.000)	0.000 (0.000)	−0.000 (0.000)	−0.000 (0.000)	−0.000 (0.000)	−0.000** (0.000)	0.000 (0.000)
Organic producer (1/0)	2.859** (0.907)	2.689*** (0.638)	2.429*** (0.644)	1.277 (1.139)	0.731 (1.365)	4.068*** (1.005)	1.147 (1.735)
Time preferences	0.050 (0.076)	0.077 (0.082)	0.096 (0.065)	−0.134 (0.102)	0.082 (0.161)	0.163 (0.129)	0.268*** (0.070)
Production risk preferences	−0.029 (0.079)	0.106 (0.084)	−0.145 (0.076)	−0.069 (0.155)	0.091 (0.085)	−0.045 (0.155)	−0.235*** (0.045)
Majority of income is from agriculture (1/0)	0.825** (0.307)	0.128 (0.445)	0.182 (0.308)	0.239 (1.032)	0.013 (0.432)	1.298 (0.962)	−0.307 (0.785)
Majority of agricultural income from viticulture (1/0)	1.751*** (0.429)	1.031** (0.324)	1.139*** (0.272)	−0.401 (0.579)	0.222 (0.446)	−1.145** (0.382)	2.448 (1.254)
More than 50% sales are directly marketed (1/0)	0.139 (0.295)	−0.402 (0.260)	−0.690 (0.466)	0.620 (0.408)	−0.909 (0.778)	−0.731 (0.714)	−0.020 (0.585)
Further education in plant protection (1/0)	−0.090 (0.395)	0.723 (0.311)	1.128 (0.557)	0.570 (1.300)	1.308*** (0.387)	0.601 (0.665)	1.457 (0.846)
Pest pressure from downy mildew	2.527 (1.156)	1.517** (0.558)	2.522 (1.480)	−1.889 (1.703)	−1.887 (1.713)	0.408 (1.268)	−0.980 (2.311)
Cantonal fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Clustered standard errors	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	289	289	289	289	289	289	289

Note: **p < 0.01, ***p < 0.001. Note that category treatment 8 shown in [Appendix D](#) is included in the regressions but not shown due to lack of interpretability.

4. Discussion

Our survey among Swiss growers confirms a widely empirically-observed pattern in European viticulture, indicating that copper-containing fungicides remain the backbone of grapevine disease management. In fact, most grape growers use copper-containing fungicides (72.8%), which is also consistent with the observation that viticulture concentrates a very large share of fungicide use ([Tamm et al., 2022](#)) and that copper remains a main tool, in conventional but particularly in organic systems, because of its broad-spectrum efficacy and legal status. Although most growers still use copper, a substantial share (57% of copper users) reports active copper-reduction behaviour. The very large variety of measures (94 distinct strategies among 203 copper-reducing growers, with many unique combinations) suggests two complementary phenomena. From one side growers actively applying locally adapted solutions and from the other, there is no single, dominant pathway for copper reduction. In addition, only 20 growers (10%) rely on a single copper-reducing measure, suggesting the need of combining copper-alternative measures to reach an acceptable level of disease control. This heterogeneity in vineyards is similar to other crops, which emphasise a plurality of context-specific technical and managerial choices rather than one-size-fits-all approaches ([Tamm et al., 2022](#)).

Consistent with the efficiency-substitution-redesign conceptual framework, the most frequently adopted measures in our sample fall into the efficiency category (dosage and formulation adjustments, improved timing guided by disease-forecasting models), followed by preventive actions and substitution measures (use of alternatives) and redesign measures (use of resistant varieties). In particular, growers first optimize existing practices by optimizing the available copper and try to prevent the diseases as much as possible, then substitute it when possible with alternatives and then only gradually move toward system-level redesigns that require larger structural change, for example with replacing the vineyard with resistant cultivars or by changing the

training system. The introduction of forecasting and timing tools and copper dosage reduction in growers' strategies is expected because various studies have already demonstrated that decision-support tools can reduce the number and/or dose of fungicide applications while maintaining disease control (Kuflik et al., 2009).

Regarding substitution, namely alternatives to copper, previous studies have identified various potential alternatives, for example biopolymers as chitosan or laminarin (Garde-Cerdán et al., 2017; Romanazzi et al., 2024), plant extracts (Dagostin et al., 2011), microbials (El-Sharkawy et al., 2018; Sun et al., 2024) and some new concept formulations (Roda et al., 2024) that can contribute to disease suppression, but practical field trial observations have often shown that many of these products do not reach the same disease control efficacy as copper when used alone (Dagostin et al., 2011). Indeed, copper has several physicochemical and biological properties that hinder its substitution by natural alternatives. It remains effective under rainfall due to its rainfastness and slow release, acts on multiple sites within the pathogen, and persists on plant surfaces, ensuring prolonged protection (Gessler et al., 2011). Combining low-copper dosages with alternatives sometimes improves performance, but the evidence suggests that, at present, substitution often requires integrated use rather than one-to-one replacement (Romanazzi et al., 2016). This is consistent with our finding that growers frequently combine copper alternatives with prevention, better timing and dosage/formulation adjustments rather than relying on substitution alone. Indeed, most of Swiss growers use combinations of various measures and only a minority rely on a single copper-reduction measure (10%). In particular, efficiency measures are commonly combined, especially dosage or formulation adjustments with better timing. Dosage and formulation adjustments are also often employed jointly with copper alternatives, but also with pathogen-resistant varieties, whereas substitution and redesign measures are rarely combined within their respective categories. Our findings underline that combinations of measures are the norm, and more importantly, that the largest potential reductions are achieved when prevention, efficiency and redesign measures are implemented jointly. This synergistic effect is also supported conceptually by the agroecological approach (Wezel et al., 2014) and empirically by studies in other crops showing that management changes (for example canopy management, altered microclimate) reduce disease pressure and therefore allow lower fungicide inputs (Catalogna et al., 2022).

Our results also suggest that growers most frequently adopt short- and medium-term measures, such as preventive and efficiency strategies, while long- and very-long-term options—substitution and redesign measures—are less commonly implemented, in line with previous literature on farmer time preferences (Wüpper et al., 2023). In particular, despite the clear benefits of pathogen-resistant grapevine cultivars in reducing copper use, their uptake by Swiss growers is modest, that is only 3% of land is currently devoted to pathogen-resistant varieties (Zachmann et al., 2025b). This can be explained by several reasons such as for example cultural preferences for traditional varieties and doubts about wine quality and market acceptance, high uncertainty over long-term performance and durability of resistance traits over a vineyard's lifespan, which is commonly 25 to 35 years. In addition, the weak branding and consumer recognition of newly bred cultivars (often bearing unfamiliar names) increases the perception of marketing risk, especially in established wine regions, where tightly regulated denominations of origin appellations (e.g. PDO/PGI) sometimes restrict varietal or training system change (Finger et al., 2023; Trapp et al., 2025; Zachmann et al., 2025b).

Nevertheless, the greatest potential for reducing copper use arises from the combined implementation of prevention, efficiency, and redesign measures, highlighting the importance of promoting very-long-term strategies such as fungus-resistant varieties (Trapp et al., 2025; e.g. Zachmann et al., 2025a). Moreover, only a small minority of growers rely on a single copper-reducing measure; the majority employ three to five measures simultaneously. This suggests that studies focusing on

individual measures and their reduction potential in isolation may provide a misleading picture and overlook the synergies achieved through combined adoption (e.g. Ortega et al., 2023).

The greatest reduction of copper use is achieved when prevention, efficiency, and redesign measures are employed jointly (i.e. by 30%).⁵ Importantly, the use of preventive measures, both in the short term (e.g. pruning to avoid leaf wetness, balance fertilization to avoid excessive growth, field hygiene, canopy management) and in the long term (e.g. vineyard redesign, adoption of fungus-resistant varieties), emerges as central for reducing reliance on copper. Promoting preventive approaches therefore aligns with broader sustainability goals, as they address disease pressure before treatment is required and reduce dependence on external inputs. This is important because further analysis highlights the relevance of chemical-synthetic fungicides as a copper-reducing measure (see Appendix F). When assessed in isolation, growers who report to use chemical-synthetic fungicides as instrument to reduce copper use show large copper-reduction potential. However, the reliance on chemical-synthetic fungicides as substitutes for copper-containing products runs counter to policy objectives of reducing pesticide risks from chemical and hazardous substances (Möhring et al., 2020; see Schebesta and Candel, 2020). This substitution pathway risks creating undesirable spill-over effects, namely a shift from one high-risk plant protection substance to others (e.g. Finger, 2018). Thus, while chemical-synthetic fungicides appear effective for reducing copper use, they do not represent a sustainable or policy-aligned solution.

Our results further indicate that copper use among the sampled growers in Switzerland is with 2 kg/ha/year below regulatory thresholds. However, owing to copper's persistence in soils, past frequent and high applications may continue to cause negative effects, even when current usage levels are lower. Long persistency of pesticides in soils is an important issue, for example, residues of up to 32 pesticides remained detectable after 20 years of organic farming, with several compounds persisting far longer in soil than indicated by their reported half-lives (Barmettler et al., 2025). Therefore, copper substitution remains a central driver for policy and research.

5. Conclusion

This study provides insights into how Swiss grape growers adopt practices to reduce copper use. More specifically, we identify which measures and measure combinations are employed, and which have the greatest reduction potential. Our findings show that while most Swiss growers rely on copper-based fungicides, more than half have introduced at least one copper-reduction strategy. Adoption patterns are highly heterogeneous: 203 copper-reducing growers reported 94 distinct strategies, with most combining multiple measures rather than relying on single interventions. Efficiency-oriented measures, such as dosage and formulation adjustments and the use of disease-forecasting model, are the most common. In contrast substitution and redesign measures are less common. However, the greatest potential for copper reduction is achieved through integrated strategies that combine prevention, efficiency, and redesign measures. This also confirms that systemic and multi-level approaches are more effective than isolated technical interventions.

Our findings carry important implications for policy. Policy and extension programs should prioritize the promotion of preventive and redesign measures over purely treatment-oriented approaches focusing on efficiency and substitution, whether with natural products or synthetic chemicals. Prevention and redesign offer more robust and durable solutions, which also minimize trade-offs with environmental and health objectives. Strengthening advisory services, supporting peer learning

⁵ Note that a reduction of 0.65 kg/ha/year of copper corresponds to approximately 30% less copper use compared to the baseline group, which applies on average 2.1 kg/ha/year of copper.

and knowledge exchange, and incentivizing the adoption of preventive strategies can help growers' transition away from treatment dependence and contribute to sustainable viticulture. Policy intervention should also promote bundled strategies, rather than isolated measures. For example, coordinated strategies, as combinations of prevention, efficiency, and redesign measures yield substantially higher reduction potential than single measures applied in isolation (e.g. [Finger et al., 2024](#)).

Beyond policy, several areas warrant targeted research and innovation efforts. Future research shall investigate the impacts of different policy instruments such as regulatory limits and incentive schemes, e.g. subsidies for decision-support tools, taxes on copper ([Finger and Pedersen, 2025](#)) or payments for redesign-oriented measures. Such policy instruments could accelerate the adoption of integrated strategies, particularly if linked to soil copper monitoring programs. The greater availability of disease-forecasting models and precision-spraying technologies can markedly improve efficiency. However, more research is needed to develop user-friendly, validated tools that integrate local weather data, remote sensing, and advanced spraying equipment. Research into copper alternatives, such as biocontrol agents and natural products, should focus on their effectiveness, cost-efficiency, and compatibility with reduced copper doses. Given that many growers already combine measures, the development of optimized “low-copper plus alternatives” programs could facilitate a more rapid adoption. Disease-resistant grapevine varieties and agroecosystem redesign strategies offer the greatest long-term potential for copper reduction. However, adoption remains limited, therefore breeding programs, that integrate resistance traits with desirable oenological characteristics, combined with participatory trials involving growers and winemakers, could help overcome these barriers. New breeding techniques can also speed up the process. Controlled, multi-season field trials that explicitly test combined strategies under realistic commercial conditions are also a priority, because they can demonstrate the feasibility (e.g. efficacy and cost-efficiency) to growers. In addition, long-term monitoring of soil copper dynamics and biological indicators could help to quantify the ecological and agronomic benefits of copper-reduction strategies.

Our study demonstrates that the transition away from copper dependence in Swiss viticulture is already underway, driven by farmer

experimentation and contextual adaptation. However, achieving substantial and durable reductions will require coordinated action across technology, policy, and behavioral domains. These findings also hold relevance beyond Switzerland, offering insights for other wine-producing regions seeking to reduce copper use while maintaining sustainable and resilient viticultural systems.

CRediT authorship contribution statement

Lucca Zachmann: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Ilaria Pertot:** Writing – review & editing, Conceptualization. **Robert Finger:** Writing – review & editing, Supervision, Conceptualization.

Declaration of generative AI use

During the preparation of this work the authors used ChatGPT in order to improve the writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Maximum copper use in various production systems in Switzerland

This table summarizes the maximum amount of copper that can be used per hectare and year per production system in Swiss viticulture. It also links the production systems to the labelling standard.

Table A1
Maximum copper use in various production systems in Switzerland

Production system	Labelling standard	Maximum quantity of pure copper per year and hectare (kg)	Remarks	Sources
None (i.e. farms not following any production system)	-	6.00	Environmental law applies	Speiser et al. (2015)
Proof of ecological performance record (PER, minimum production standard to receive direct payments)	VitiSwiss	4.00		Link
Integrated production	IP-Suisse	4.00	No direct restriction on copper use, but follows the PER requirements	
Certified organic production	Bio Suisse, federal bio	4.00	Not more than 20 kg averaged over 5 consecutive years	(Steinemann et al., 2022; Tamm et al., 2022)
Biodynamic production	Demeter	3.00	3 kg on average over 5 years (max 4 kg y ⁻¹)	(Steinemann et al., 2022; Tamm et al., 2022)

Note: At the European level, copper use limits for wine grapes vary across countries, ranging from 2.6 to 4 kg/ha/y in organic production ([Tamm et al., 2022](#)).

Appendix B. Sample visualization

The figure below shows the spatial distribution of the sampled farms across the six wine regions in Switzerland.

Figure B1: Sample visualization

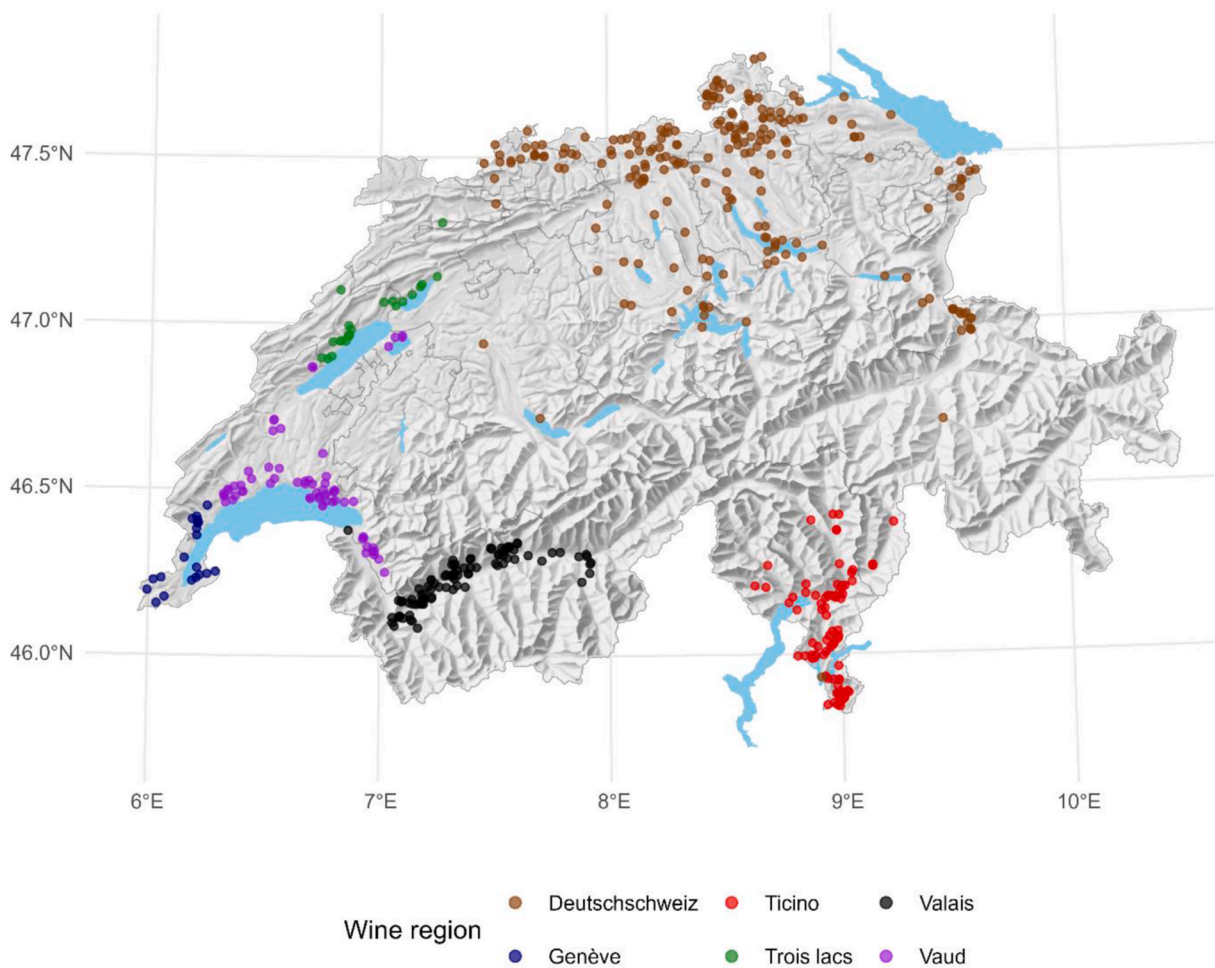
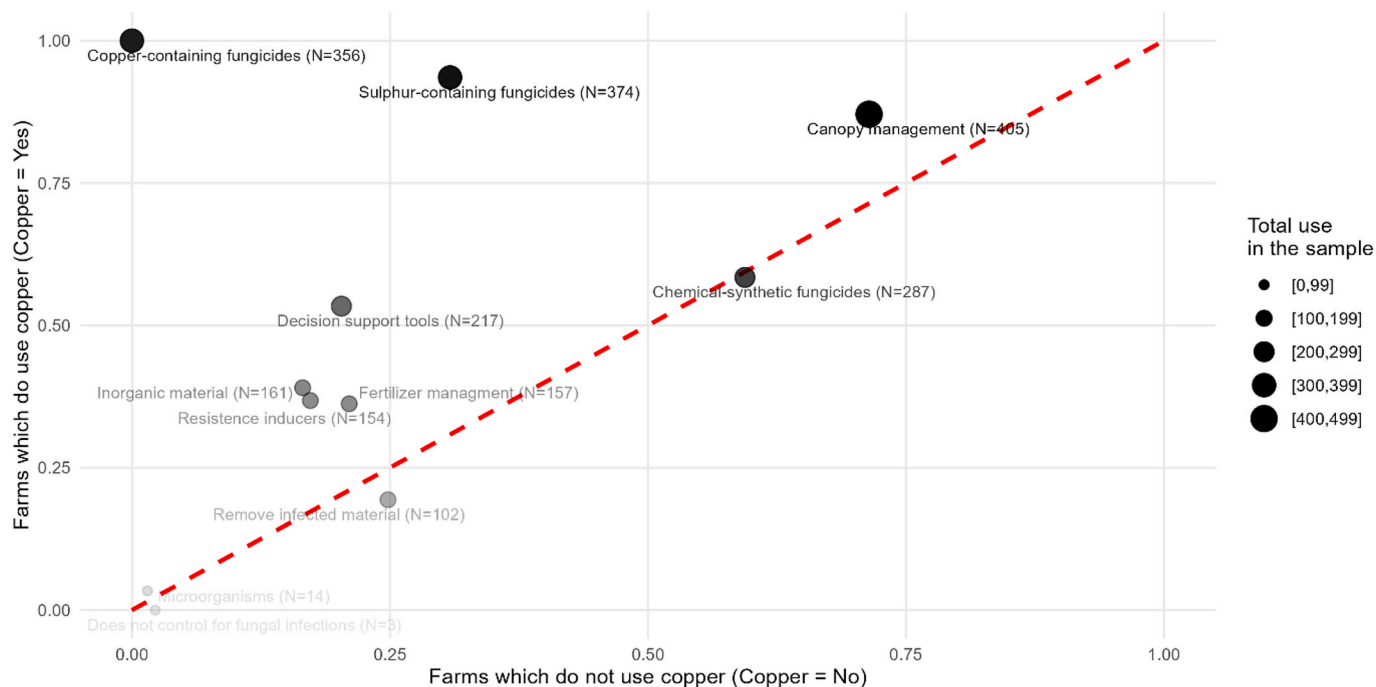


Fig. B1. Sample visualization.

Appendix C. Fungal pathogen management by copper users and non-copper users

The graph below shows the count of farms using specific measures to cope with fungal diseases, on the x-axis farms who do not use copper and farms who use copper-containing fungicides on the y-axis. The scatters refer to the share of the specific measure used from the copper-using farms (N = 356) on the y-axis and the share from non-copper using farms (N = 133) on the x-axis. The size of the scatters refer to how many farms overall in the sample indicated to use the specific measure.

Table C1
Fungal pathogen management by copper users and non-copper users



The figure shows that copper-using farms engage in relative terms much more with other management strategies against fungal diseases. This is clearly visible most scatters lie higher than the dashed red line. The only exceptions are farms which do not control for fungal diseases at all ($N = 3$), farms which remove infected material as a strategy against fungal diseases ($N = 102$), and farms which use chemical-synthetic fungicides ($N = 287$).

Appendix D. Measure combinations

The figure displays the individual measures and their combinations.

PM stands for preventive measures (prevention), DO for dosage and formulation (efficiency), AT for precise application technology (efficiency), DF for disease forecasting models (efficiency), CA for copper alternatives (substitution), SC for synthetic chemical fungicides (substitution), RI for resistance inducers (substitution), FR for fungus-resistant varieties (redesign), TS for training system (redesign), and TR for less susceptible traditional varieties.

The figure shows that combinations such as preventive measures, dosage and formulation, and disease forecasting ($N = 10$), as well as preventive measures, disease forecasting, dosage and formulation, copper alternatives, and fungus-resistant varieties ($N = 10$), are the most commonly used bundles among growers.

Among the 203 copper-reducing growers, 94 distinct and unique strategies are applied to reduce copper, with 26.7% of growers using a strategy that is not shared by any other farmer. Only 20 growers (10%) rely on a single copper-reducing measures, while the large majority uses measures combinations.

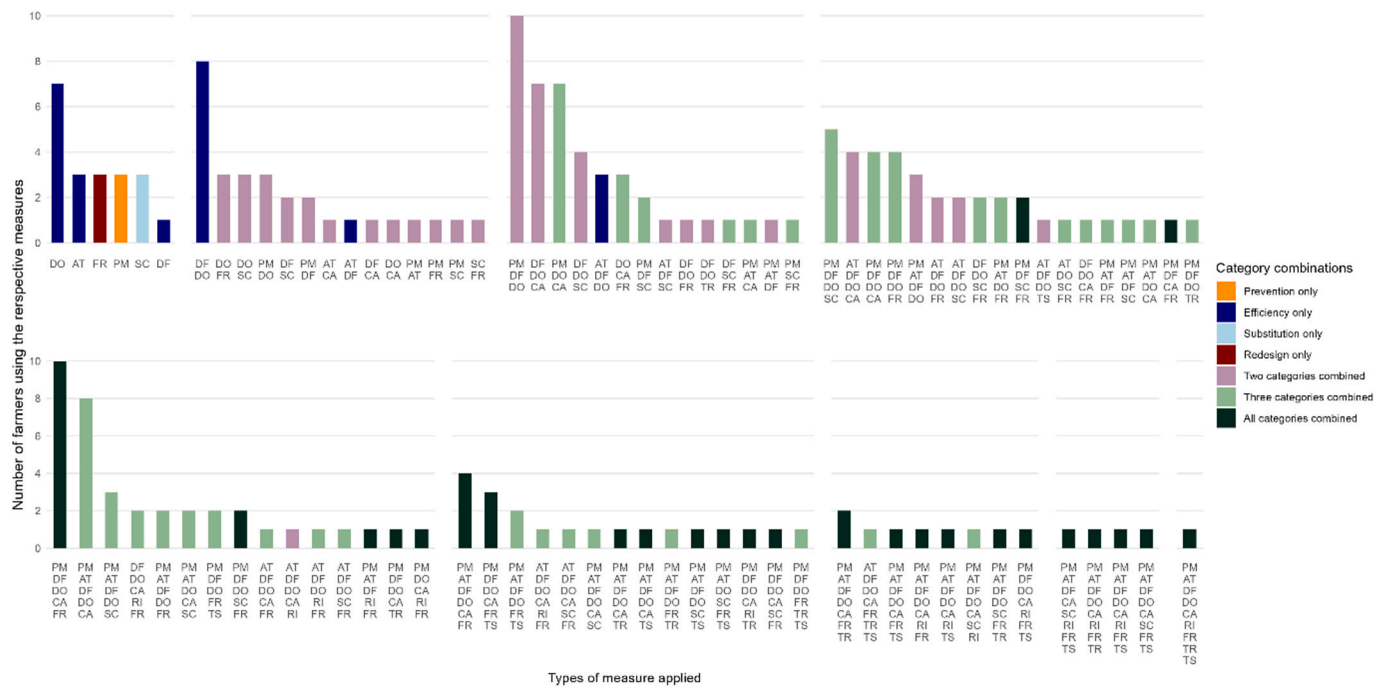


Fig. D1. Measure combinations.

Next, we provide summary statistics of the measure category combinations in the table below. We see that among the 203 copper-using and reducing farms, most use measure from all four categories (i.e. high diversification) with 21.8%. Together, the top seven combinations cover nearly 90% of all farms. The remaining combinations are less frequent, with several used by only 1–3 farms. Thus, we group the remaining farms with mixed measure category combinations into a separate group and do not report them in the regression output due to interpretation difficulty.

Table D1
Measure category combinations

Measure category combinations	Treatment group	Number of farms	Share of farms (%)	Cumulative share of farms (%)
Prevention, Efficiency, Substitution, Redesign	1	44	21.8	21.8
Prevention, Efficiency, Substitution	2	36	17.8	39.6
Efficiency, Substitution	3	27	13.4	53
Efficiency only	4	23	11.4	64.4
Prevention, Efficiency	5	19	9.4	73.8
Efficiency, Substitution, Redesign	6	16	7.9	81.7
Prevention, Efficiency, Redesign	7	16	7.9	89.6
Efficiency, Redesign	8	8	4	93.6
Prevention only	8	3	1.5	95.1
Substitution only	8	3	1.5	96.6
Redesign only	8	3	1.5	98.1
Substitution, Redesign	8	1	0.5	98.6
Prevention, Substitution	8	1	0.5	99.1
Prevention, Redesign	8	1	0.5	99.6
Prevention, Substitution, Redesign	8	1	0.5	100
Total		203		

Appendix E. Copper use and reduction

The figure is a scatter plot showing the relationship between the share of farms using copper-reducing measures (x-axis) and the share of farms using copper-containing fungicides (y-axis) for different farm management categories.

As the share of farms using copper-reducing measures increases, the share of farms using copper-containing fungicides also remains high (above 60%), particularly for organic and biodynamic categories. Conventional or no-certification farms (None, IP) report lower levels of copper-reducing measures and slightly lower copper fungicide use compared to certified organic or biodynamic farms.

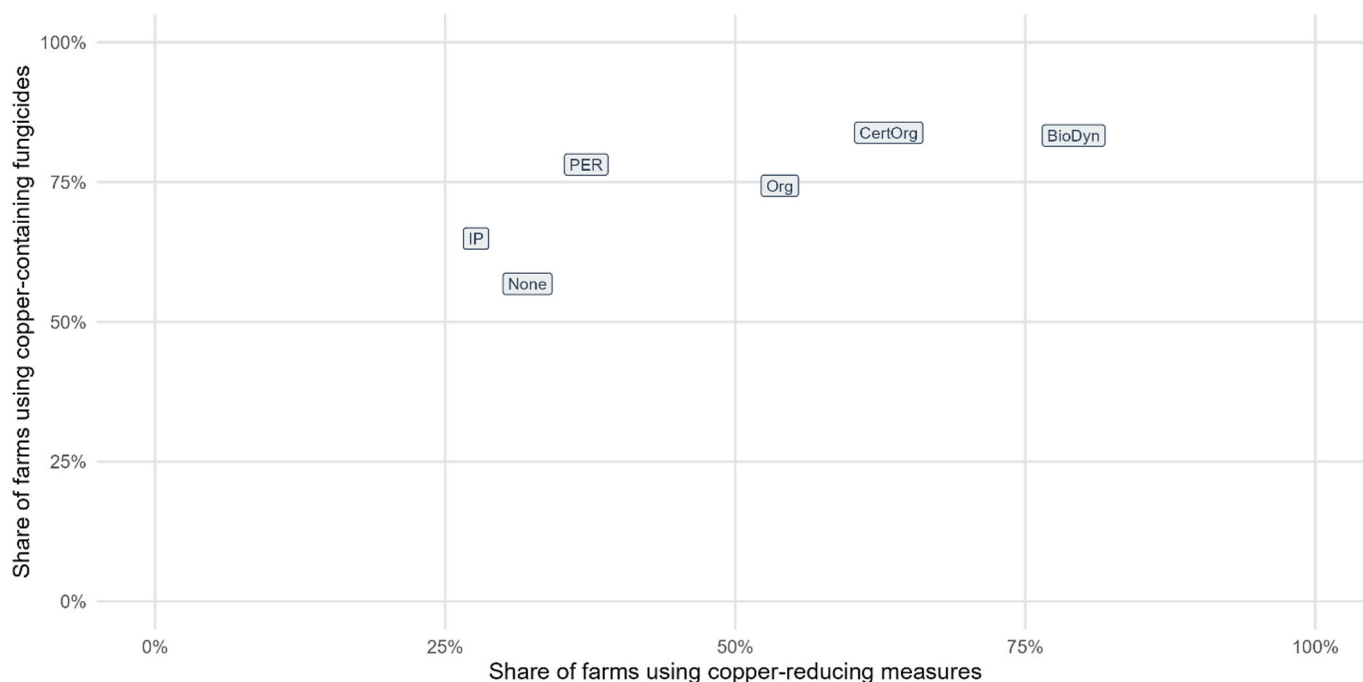


Fig. E1. Copper use and copper-reducing measures by production system.

The figure below is a grouped bar chart that compares copper use and copper reduction between two groups of growers: those who apply copper-reducing measures and those who do not. The y-axis shows the amount in kilograms per hectare per year, ranging from zero to six (i.e. the legally maximum amount), while the x-axis distinguishes between the two farmer groups. Dark blue bars represent average copper use, and light blue bars represent average copper reduction. The figure shows that growers who apply copper-reducing measures report an average copper use of 1.97 kg/ha/year and an average reduction of 2.37 kg/ha/year. Growers who do not apply copper-reducing measures report an average copper use of 2.17 kg/ha/year and an average reduction of 2.04 kg/ha/year. Overall, growers who apply copper-reducing measures have lower copper use and higher average reduction values compared to those who do not apply such measures.

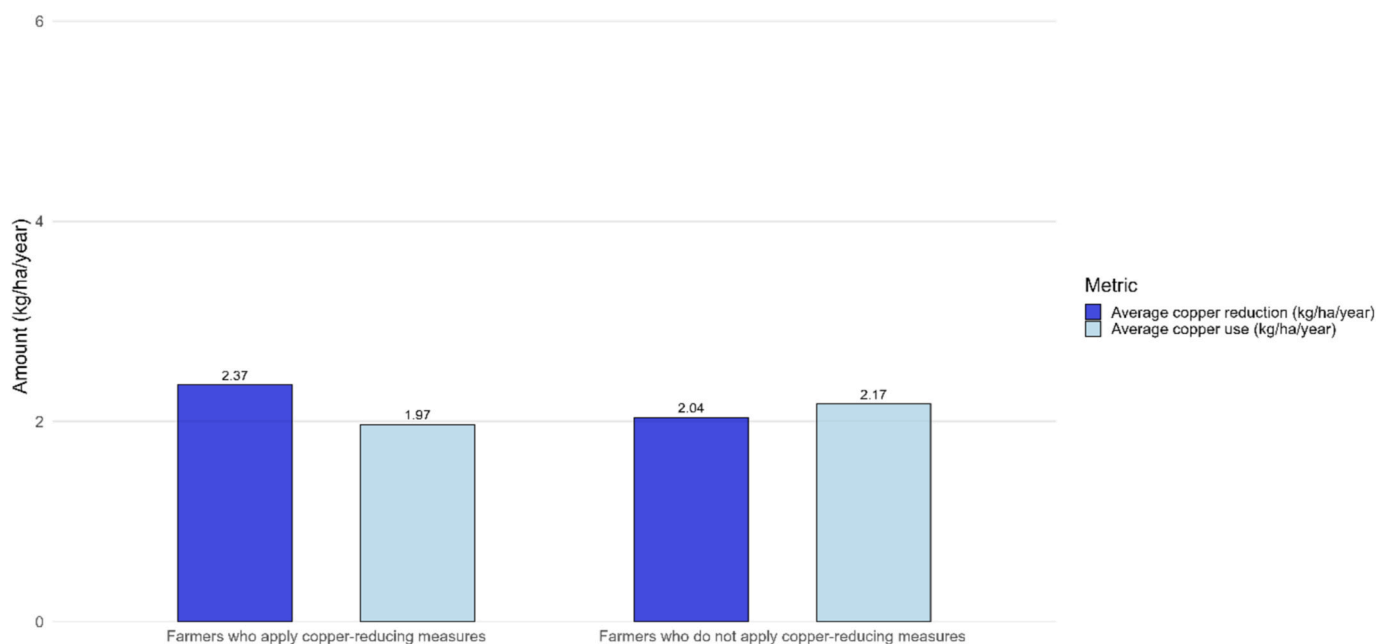


Fig. E2. Copper use and copper reduction by farms who employ copper-reducing measures and not.

Appendix F. Alternative models specifications

Here we provide alternative model specifications, namely ordinary least squares estimations without selection into treatment. We show in column (1) regression results including category treatments and in column (2) binary measures only, both including controls and clustered standard errors.

We largely find similar results as presented in Table 3 (column 1), namely that the largest reduction potential occurs with using prevention, efficiency and redesign measures jointly. However, we do not find that efficiency only measures yield statistically significant copper reduction potential, but we find that prevention, efficiency, substitution and redesign measures jointly employed yield some statistically significant reduction potential.

When assessing simple binary measures (i.e. used in isolation) (column 2), we find that growers stating to use chemical-synthetic fungicides as well as fungus-resistant varieties to reduce copper use report the largest copper-reduction potential. While the use of fungus-resistant varieties is advisable to reduce fungicide use overall, the use of chemical-synthetic fungicides as substitutes for copper-containing fungicides is not in line with policy goals (e.g. Möhring et al., 2020; Schebesta and Candel, 2020), thus indicating potential undesirable spill-over effects of efforts to reduce copper use in viticulture.

Table F1
Alternative models specifications

	Copper reduction potential (kg/ha/year)	
	(1)	(2)
Categorical treatments		
Prevention, efficiency, substitution, redesign	0.54** (0.25)	
Prevention, efficiency, substitution	0.34 (0.30)	
Efficiency, substitution	0.24 (0.32)	
Efficiency only	0.05 (0.25)	
Prevention, efficiency	0.03 (0.22)	
Efficiency, substitution, redesign	0.31 (0.47)	
Prevention, efficiency, redesign	0.85*** (0.20)	
Binary treatments		
Prevention		0.29 (0.20)
Precision application		−0.13 (0.09)
Disease forecasting models		−0.07 (0.04)
Dosage and formulation adjustments		−0.004 (0.20)
Copper alternatives		−0.09 (0.24)
Chemical-synthetic fungicides		0.39*** (0.14)
Plant resistance inducers		−0.30 (0.21)
Fungus-resistant varieties		0.39** (0.16)
Less susceptible traditional varieties		0.22 (0.26)
Training system		−0.28 (0.48)
Age (in years)	0.01 (0.01)	0.01 (0.01)
Female grower (1/0)	−0.27 (0.35)	−0.36 (0.36)
Farm size (in are)	0.0000*** (0.0000)	0.0000*** (0.0000)
Organic producer (1/0)	−0.93*** (0.31)	−0.68** (0.31)
Constant	Yes	Yes
Cluster SE at wine region	Yes	Yes
N	312	312
Adjusted R ²	0.06	0.05

Notes: ***Significant at the 1 percent level. **Significant at the 5 percent level. Note that we include category treatment 8 shown in Appendix D is included in the regressions but not shown due to lack of interpretability.

Data availability

A Data in Brief publication of the data is currently in progress. Upon completion, the full dataset and accompanying code will be made publicly available to ensure transparency and reproducibility.

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