Technical Efficiency and Water Use in Wine Grape Production in Mendoza, Argentina

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Abstract

This paper analyzes technical efficiency (TE) of wine-grape production in Mendoza, Argentina by employing a unique dataset of production and management at the plot level. The analysis employs stochastic frontier analysis (SFA) based on data for 647 grapevine plots from 177 farms. The sample is divided into two separate groups, first, wine-grape producers that sell their output (viticulturists), and second, producers that elaborate their own wine (wineries), based on substantial differences in the technology between the two groups. The average technical efficiency is estimated at 0.91 for viticulturists and 0.84 for wineries, which implies that the observed output is below its potential. On a per ha basis, viticulturists and wineries are operating at 1.0 and 1.8 tons of grapes below their frontier output level. Technical inefficiency is associated with certain management decisions that are simultaneously modelledin the estimation. Among those factors, in both subgroups an improved efficiency is associated with technical advice, increasing vine density and the adoption of drip irrigation. In contrast to the wineries, viticulturists' TE is positively associated with membership in producer associations, and their performance is affected by the distance to good quality groundwater resources. However, vineyards that rely solely on groundwater perform relatively better than other farmers with both irrigation sources.

Keywords: technical efficiency; stochastic frontier analysis; SFA; water use efficiency; benchmark

Resumen

Este artículo estima la eficiencia técnica (TE) de la producción de uvas de vinificación en Mendoza, Argentina, utilizando una base de datos única en términos de producción y manejo a nivel de parcela. El análisis realizado es mediante fronteras estocásticas (SFA) basado en datos de 647 parcelas de vid de 177 fincas. La muestra se divide en dos grupos, primero, productores de uva de vinificación que venden su producción (viticultores), y segundo, productores que elaboran su propio vino (bodegas), basándose en diferencias sustanciales en la tecnología entre los dos grupos. La eficiencia técnica media se estima en 0,91 para los viticultores y 0,84 para las bodegas, lo que implica que la producción observada está por debajo de su potencial. Por hectárea, los viticultores y las bodegas están operando a 1.0 y 1.8 toneladas de uva por debajo de su nivel de frontera. La ineficiencia técnica está asociada con ciertas decisiones de gestión que se modelan simultáneamente en la estimación. Entre esos factores, en ambos subgrupos una mayor eficiencia se asocia con el asesoramiento técnico, el aumento de la densidad de la vid y la adopción del riego por goteo. A diferencia de las bodegas, la TE de viticultores se asocia positivamente con la pertenencia a asociaciones de productores y su desempeño se ve afectado por la distancia a las fuentes subterráneas de agua de buena calidad. Sin embargo, los viñedos que dependen únicamente del agua subterránea se desempeñan relativamente mejor que otros agricultores con ambas fuentes de riego.

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Abstract

Introduction

Argentina is the 5^{th} largest wine producer worldwide. The industry gained increasing international recognition after three decades of wine quality innovations, value chain upgrades, and foreign direct investments (INV, 2019; OIV, 2019). In western Argentina the wine industry has historically played a relevant role on development, employment and value addition. However, environmental threats and economic constraints have remained a permanent challenge to further develop the industry. Many of these are visible in the province of Mendoza, the main wine-producing region with over 150,000 hectares. Mendoza accounts for 70 per cent of the national grape production and for 85 per cent of the Argentinean wine making (INV, 2019).

Despite the steady growth in production and exports from Mendoza, the grapevine sector is facing challenges arising from low prices paid to producers, agronomic risks, and climate contingencies. Small and medium producers face an uncertain business environment with a relatively large share of fixed costs in total production, combined with limited access to natural resources. Hence, their economic performance is sensitive to changes in regional markets and macroeconomic policies. While aridness and altitude are valued assets for wine quality, grapevine performance in arid environments is continuously challenged by climate variability (Ashenfelter & Storchmann, 2014). Water plays a central role in the scarcity or abundance scenario: In the former by coping with vines evapotranspiration and preparing vineyards for higher solar radiation; in the latter by administrating stress for differential phenolic composition and sensory characteristics. Balanced irrigation practices are hence an important attribute of vineyard management in semi-arid regions, with a strong effect on wine quality. Yet, there is a gap to effectively address vineyards' performance accounting for their use of water, heterogeneity in the management of plots and agroclimatic characteristics that determine their production decisions. Under a surface water scarcity scenario since 2009 (FAO & PROSAP, 2015), the existing restriction to the construction of groundwater wells further shaped the irrigation practices in the region (Foster & Garduño, 2005). As water access is accessible with land tenure, the ongoing water scarcity and pollution threats derived on the *zoning restrictions* imposed by the water administration in 1998 (Diaz Araujo & Bertranou, 2004, p. 75). Under special circumstances, this institution provided new drilling permits in the research region, which indirectly creates a semi-fixation of productive land.

In the current setting, wine-grape producers in Mendoza could be trapped in a *declining spiral* of water scarcity, declining production quality and profitability. However, emerging new marketing alternatives as wine rankings and agricultural management, that reveal enological potential excelled by *terroir* characteristics, and export orientation has led to an increasing focus on the production of quality grapes, which need to be managed in a suitable way to adapt to the frequency of water stress. The adaptation of such new vineyard management strategies, however, has remained incomplete and has led to a relative heterogeneous structure of grapevine production in the region, with the simultaneous presence of highly profitable as well as economically non-viable farms, holding them to fully exploit the production potential of their vineyards.

By employing an unique dataset of production and management at the plot level, this papers aims to identify the driving factors of vineyards' technical efficiency, accounting for market orientation and the role of water management in the performance assessment in the wine valley of Luján de Cuyo, Mendoza. Moreover, we aim to unveil the effects of heterogeneous management decisions based on grapevine plot characteristics.

Frontier function methodologies allow for an assessment of technical efficiency by determining a benchmark frontier. They a measure of technical efficiency in terms of the potential proportional reduction in input given output levels (input-oriented) or of the potential output expansion given input endowments (output-oriented) with respect to the frontier (Farrell, 1957). The literature applying these methods to wine-grape production, in particular with regard to the role of scarce water resources, is relatively scarce. Only a few studies include information of agroclimatic conditions or irrigation systems in an attempt to better understand the performance of vineyards (Andrieu et al., 2014; Coelli & Sanders, 2013; Moreira et al., 2011). One reason is presumably that measuring irrigation water is usually not easily done so that alternative measurement methods have been proposed, e.g., by using energy consumption as a proxy for groundwater irrigation (Conradie et al., 2006). More in detail, the work of Moreira et al. (2011) decoupled the performance of vineyards at the plot level but did not include the water used as a productive input. Coelli & Sanders (2013) and Andrieu et al. (2014) considered water at the vineyard level in their analysis of wine production in the Murray-Darlin Basin (Australia) and in San Juan (Argentina), respectively.

Here we analyze the economic performance of small and medium grapevine producers in the area Luján de Cuyo; a promising area for high-quality grape production and environmentally challenging due to existing conflicts over pollution potential that affect water quality. These effects have led to an intensification of agricultural management and viticultural practices in the research area, where farmers seek to maximize the production potential of quality vines and optimize the use of natural resources and intermediate inputs. Therefore, it is relevant to analyze the production efficiency to estimate general scores controlling for location, water quality and technology adoption among others.

In particular, this paper focuses on two issues: (*i*) the analysis of the determinants of technical efficiency of grapevine producers and (*ii*) the role of water management practices in improving farm productivity. In order to disentangle the implications of efficiency determinants, the Stochastic Frontier Analysis (SFA) is employed. Functional forms were tested considering the technology endowment, market orientation and irrigation practices of wine-grape plots.

This comprehensive analysis of efficiency determinants will contribute to understanding the performance of vineyards with respect to their productive potential and deriving recommendations for the design of policy tools. The following sections reviews the existing literature of TE in wine-grape production, further explain the theoretical framework and describes the employed data in the analysis. The results are presented and discussed in detail before we conclude with some major policy recommendations.

Background Literature

The literature on TE analysis is divided into two approaches: non-parametric and parametric. Widely known as Data Envelopment Analysis (DEA), the non-parametric framework allows for the analysis without specifications of the functional form with the drawback of indivisibility of the inefficiency effects from the random noise. On the other hand, the parametric or deterministic frontier analysis allows for the decomposition of the statistical noise into, random noise and inefficiency (Aigner et al., 1977; Meeusen & van Den Broeck, 1977). While, the Stochastic Frontier Analysis (SFA) gained popularity in the field of agricultural economics as a mean to assess farmers performance, behavior and technical change (Battese, 1992); there is scarce literature on the application of this approach to wine-grape production. There are a few reasons why technical efficiency in grapevine production systems are hardly documented: data availability, heterogeneous management and climate contingencies of uneven effects. Recall that wine-grape are perennial crops that provide the essential input for high-value product as wine. Desired agricultural performance and enological virtues rely on intensive craft activities that vary within the vineyard and, simultaneously, are wrongly averaged in accountancy books. Also, vineyard hectarage is commonly divided in plots or blocks according to planted variety, management characteristics, irrigation technology, among others reasons. These plots respond unevenly to rain or water stress periods, pest, diseases and even sunlight orientation.

In the seek of modeling the unobserved heterogeneity, the existing literature on benchmarking wine-grape production systems has partially overcome the mentioned data limitations. Moreira et al. (2011) represented an initial step in the direction of considering differential plot management within vineyards. They estimated the TE at the plot level of chilean vineyards considering traditional production inputs and controlled for region, training system and expected quality. Bravo-Ureta et al. (2020) propose a repeated cross-section to assess the time-variant technology use and inefficiency utilizing the same data frame but recognizing management decisions at a vineyard-level and dummy variable for cool agro-climatic conditions. Piesse et al. (2018) relied on a panel data frame to assess technological changes in new and old regions in South Africa relying on traditional production inputs while controlling for innovation on viticultural practices including irrigation.

Vineyards are thirsty in arid climates and measurement of applied water and irrigation infrastructure challenge researchers to include them in production and benchmarking analysis. Coelli & Sanders (2013) and Andrieu et al. (2014) documented the only work that explicitly includes water as a production input. The former used a panel data set for 135 farmers in the Murray-Darlin basin (Australia) and measured a mean TE of 79 per cent and a mean shadow price ratio of 1.07 for water. The latter a cross-sectional of

700 farms in a district of San Juan (Argentina) and estimated an average TE score of 0.41. Both studies lack specific agroclimatic conditions and detailed information on irrigation systems. Given the limitations of water measurement, few studies include agroclimatic conditions or irrigation systems in an attempt to better understand the vineyard performance (de Sousa Henriques et al., 2009). Energy consumption has been utilized as a proxy for groundwater irrigation (Conradie et al., 2006).

In general, wine-grape production systems are the recipients of governmental assistance through specific policy tools. The perception that small producers are missing out on technology and quality improvements is an intense discussion. Gibbons et al. (2016) and Maffioli et al. (2011) analyzed the effect of public policies on the adoption of technologies and agricultural extension services in Western Argentina. The effect of subsidies on productivity continues to divide researchers in literature (Pfeiffer & Lin, 2014). For Argentina it is relevant considering the regional effects of potential spill over of grapevine production (COVIAR & OVA, 2018). Other studies that estimated performance in vineyards have also aimed in acknowledging irrigation water consumption and differential viticultural practices from conventional. Conradie et al. (2006) modeled inefficiency by including variables of labor quality, age and education of the farmer, location and energy expenditures for irrigation in the Western Cape, South Africa. Guesmi et al. (2012) compare the performance of traditional and organic grapevine producers in Catalonia following the translog specification. In this study, the average TE score of organic vineyards was 0.80 and 0.64 for farms that followed conventional practices. Latruffe & Nauges (2014) analyzed the performance of French grapevine farmers and their possibility to convert to organic farming with parametric and non-parametric techniques. The TE scores varied between 0.33 and 0.35 using DEA and 0.69 and 0.72 employing stochastic frontier.

In summary, the literature reviewed showed progress in the assessment of heterogeneity in wine-grape production through methodological innovations and the will to evaluate agro-climatic conditions. But the main input for quality wine elaboration relies in a complex production process also shaped by enological preferences, viticultural management decisions, climate contingencies and local-specific policies. With respect to methodological approaches, there is a slight preference for parametric techniques in the assessed literature. Most functional forms for production processes selected a flexible specification as translog, followed by the Cobb-Douglas specification.

Methodology

The estimation of technical efficiency in a stochastic frontier analysis requires a parametric specification of a production function that links the output at the plot level to the input use. The output variable (*Grapevine*) represents production in tons per observation, based on information from the farm survey. We include four inputs that determine the production potential. First, the flow of services from the capital stock is measured by the services obtained from the vineyard at the plot level X_1, as explained in appendix 1. Second, the labor input is measured by the total number of working hours per year (X_2). Third, agrochemical inputs enter the production frontier in terms of their monetary expenses (X_3), and fourth, the use of irrigation water

(X_4) is measured in cubic meters of water used by the producer, including all sources of irrigation water. Additionally, our model includes six additional shifter variables S_j: binary variables for the training system (S_1), variety color (S_2), age of the vine (S_3), the total vineyard size (S_4), regional dummy variables for the district location of the vineyard (S_5 to S_9) and the categorical classification of soils (S_{10} and S_{11}). The production frontier for observation i is specified as a translog function in all four inputs, augmented by the set of six shifter variables. We allow the production frontier to differ depending on the market orientiation of the farmer by specifying different parameters for each group g.

$$\ln q_{i|g} = \beta_0 + \sum_{j=1}^{4} \beta_{j|g} \ln x_{ij|g} + \frac{1}{2} \sum_{j=1}^{4} \sum_{k=1}^{4} \beta_{jk|g} \ln x_{ij|g} \ln x_{ik|g} + \sum_{j=1}^{11} \gamma_{j|g} s_{ij|g} + v_{i|g} - u_{i|g} \quad (1)$$

$$\beta_{jk|g} = \beta_{kj|g}$$

$$u_i \sim N^{+}(0, \sigma^2_{ui}) \quad ; \quad \sigma^2_{u,i}(z, \delta) = \sigma_u \exp(z'\delta) \quad (2)$$

$$v_i \sim N(0, \sigma^2_{vi}) \quad ; \quad \sigma^2_{vi}(z, \rho) = \sigma_v \exp(z_i'\rho) \quad (3)$$

The β's and γ's are parameters to be estimated that determine the deterministic part of the production frontier, i.e., the maximum potential output for observation i given observed input uses and shifter variables. In the stochastic frontier framework, measurement error in the dependent variable is accounted for by a two-sided error term u that typically is assumed to be i.i.d. normal with mean zero and variance σ^2_v. In order to accommodate the effects of idiosyncratic production risk, we allow this two-sided error term to be heteroscedastic. The composed error term is completed by the presence of an additional non-negative error term u_i that is intended to capture output oriented technical inefficiency, i.e, the shortfall from the stochastic production potential caused by imperfect managerial decisions of the farmer. We employ the usual assumption of a half-normal distribution for u, allowing for heteroskedasticity, too. For both error components, the same vector of variables z is used to model the variance related paramters σ^2_{vi} and σ^2_{ui}, the corresponding parameter vectors to be estimated are ρ (two-sided error) and δ (one-sided error). For the one-sided error term, the z_i can also be interpreted as associated with the level of technical inefficiency. This approach fulfills the scaling property (Wang & Schmidt, 2002) because the base distribution is identical for all observations; the z_i affect only the scale of this base distribution.

This approach thus relaxes the standard i.i.d assumption on the one-sided error u_i in order to incorporate potential drivers of technical inefficiency by allowing for observation-specific effects in the variance related parameter of u_i (Kumbhakar & Knox Lovell, 2000; Parmeter, 2014). After estimating this model based on maximum likelihood, the conditional expectation of $\exp(-u_i)$ conditional on the estimated joint residual $v_i - u_i$ (Battese, 1992) allows to estimate the technical efficiency score TE_i for each observation.

Since the relationship between the $E(u)$ and z_i is non-linear, the magnitude of the estimated coefficients of δ_u cannot be interpreted as marginal effects of z_i. Following Kumbhakar & Wang (2015), it is possible to derive the marginal effects of the z_i variables; for the marginal effect of the kth variable, $z_i[k]$, on the expected value of inefficiency, we have:

$$\frac{\partial E(u_i)}{\partial z_i[k]} = \delta_k \frac{\sigma_{u,i}}{\sqrt{2/\pi}} \tag{4}$$

with δ_k equal to the kth parameter estimate in equation (2) . The marginal effects will be specific to each observation. However, since the sign on the estimated δ_k uniquely determines the sign of the marginal effect, the direction of the correlation between $z_i[k]$ and $E(u)$ will be the same for all observations. A positive sign indicates an increasing effect on inefficiency, while a negative sign indicates the opposite direction.

Data

The collected data seeks to address the prevalent heterogeneity in production of wine-grape producers in the region by capturing detailed information on the different management practices with respect to their quality or enological potential. Therefore, the reported information was validated through literature review, expert consultation, and institutional databases. Water resources for irrigation are granted through *water rights* that are entitled to the producer and attached to the land, which means that they are not tradable and can only be transferred with the land property. Water availability depends on the location within the research area and the infrastructure of the irrigation system. Surface water availability is extensive but not complete in Perdiel and Agrelo, therefore it cannot be directly associated with the districts. Whereas in Ugarteche and El Carrizal the irrigation network is more limited. Vineyards within the water network receive surface water based on a *turn scheme* designed by the authorities based on the climate estimates and infrastructure conditions. Groundwater remains the sole resource alternative for irrigation in Anchoris district. Conjoint sources of water (surface and groundwater) are quite frequent in the research sample.

Sample data and variable selection

The total area of the research project has 600 sq. km. and covers nearly 15,000 ha of grapevine area, farmed by 510 producers. Bulk production is estimated at 11,000 tons from approximately 2,500 plots. As the research area is situated along the Andes mountain range, the terrain and water resources vary substantially within this area (INV, 2018). From northwest to southeast, elevation decreases from 980 to 770 meters above sea level and the depth of groundwater raises from -120 to -20 meters below the surface (Foster & Garduño, 2006; Hernández et al., 2012).

The sample is composed by 647 randomly selected vine plots that belong to 177 vineyards, who were questioned on the production process, commercialization and water resource management practices

Figure 1: Research area

in 5 districts. The organization of the collected data followed a hierarchical logic. Starting at the vineyard-level, where general endowments were considered in order to later focus on production decisions at the plot level. On average, grapevine producers have 3.81 plots and the plot size is 4.22 hectares and nearly 30 per cent have 15 plots per farm.

In order to improve the analysis, information on energy consumption for pumping water, market orientation, and soil composition were considered. The use of energy data at the farm level is relevant mainly because it allows for the estimation of pumped groundwater but also acknowledges the contradictory effects of such policies that subsidize water pumping practices without considering the effectiveness of the irrigation systems. In terms of water policies, the number of wells has been fixed for over a decade with the objectives of ensuring the Carrizal aquifer's sustainability and improving of water quality[1]. Considering the inheritance principle from the water rights legislation, that ensures the permanent bond between land and the water right (or drilling permit), the *zoning restriction* is interpreted as a quasi-fixation of irrigated land. At the same time, many producers manage more than one vineyard and may share movable capital between them, which could imply lower management costs.

The exogenous variable (Z_j) is represents adoption of *drip irrigation system* as a dummy variable at the plot level. Also the use of technical advice provided by *agricultural extensionist* and plot density, measured as the number of *vines* inside the plot, are considered as exogenous variables. The analysis considers if the producer is a recipient of the *energy subsidy* to extract groundwater for irrigation. A dummy variable that acknowledges technology adoption in management practices like prunning and harvesting (*machinetechnology*). *Membership* is a dummy variable that acknowledges the participation of the producer in any farmer association. Lastly, *depth of the aquifer* is the distance in meters to the underground source used for irrigation and *leaf removal* is the dummy variable that acknowledges the hand-performed craft of ensuring light exposure of grapevine bundles.

Analysis and imputation techniques

Each wine-grape plot is considered as a production unit that has access to different services in terms of capital, intermediate inputs, and human resources at the management level. For capital variable: the plot

[1]This policy was a consequence of the diffuse pollution motivated by the excess overdraft of groundwater by farmers that damaged the sustainability of the Carrizal aquifer (Foster & Garduño, 2005). Only under special circumstances the water authority granted drilling permits.

size in hectares, the use of tractors, storage facilities, water reservoirs, groundwater wells, irrigation systems, and hail protection were considered. Accounting for the difficulties to value capital's contribution to the production function and the land quasi-fixation, the perpetual inventory method was used to assess the real economic value of vineyard endowments; this is a common practice in agricultural economics (Ball et al., 2004; Coelli & Sanders, 2013).

Management is different for each wine-grape plot. They are treated as a decision unit within the vineyard for that reason all variables were scaled to the plot size. On average, the annual value of the capital stock is 29,792 US dollars. However, for those farmers that do not use drip irrigation as much as the previous group, the mean value of capital is 28,697 US dollars. At the vineyard level, the use of agrochemicals is a common practice in grapevine production. More in detail, the mean values of table 1 state that 430 US dollars are spent annually on agrochemicals. The application of herbicides and fertilizers is strongly linked with the capital and technological endowment of the farmer and seems to be correlated with the water source, irrigation system, and management system of the grapevine crop.[2]

[2] Plausibility checks were employed based on assessments by experts in the region and were supplemented by secondary data.

Table 1: Vineyards descriptive values

		Complete sample		Viticulturists		Wineries	
component	unit	sample.mean	sd	mean	sd.1	mean.1	sd.2
Values per plot							
Production	tons	42.7	46.4	38.9	35.8	50.9	63.0
Capital services	USD	117104.8	108070.5	107158.6	88878.7	138859.3	139044.6
Labor	days	286.5	322.9	261.5	284.2	341.2	389.9
- Permanent	days	228.3	303.4	221.7	277.7	242.8	353.5
- Temporary	days	58.2	88.7	39.9	53.2	98.4	128.8
Agrochemicals	USD	1980.8	2685.1	1706.2	2405.3	2581.5	3137.0
Water	m^3	37655.8	42626.8	32194.1	28939.3	49601.4	61362.1
Average plot size	ha	4.2	4.1	3.7	2.9	5.3	5.9
Producer Age	years	53.1	11.8	52.5	11.2	54.3	12.9
Agricultural income	% total	73.3	35.0	67.7	36.4	85.5	28.1
Vine density	plants/plot	17062.3	17076.7	15595.7	13310.7	20270.2	22999.1
Average planted year	year	1990.0	25.3	1991.0	24.8	1987.0	26.3
Drip irrigation	% total	0.4	0.5	0.3	0.5	0.5	1.0
Machine adoption	% total	0.4	0.5	0.4	0.5	0.3	0.5
Values per hectare							
Yield	tons	10.2	4.7	10.6	4.9	9.2	4.0
Capital services	USD	29128.8	13259.6	29965.7	14352.5	27298.4	10276.4
Labor	days	92.4	146.2	91.9	143.0	93.4	153.5
Agrochemicals	USD	429.8	268.8	406.3	253.6	481.2	293.4
Water	m^3	9339.9	4905.8	9271.2	4829.9	9490.0	5076.6

Source: Own calculation.

As a significant expenditure, energy consumption is relevant for those farmers that rely on groundwater for irrigation. On average, a farm consumes 21,608 kWh annually, this item is of particular interest since the energy tariff remains subsidized and the effect of this policy tool on the vineyard performance is analyzed below. Grapevine production is a labor intensive crop due to the special maintenance tasks, *e.g.*, harvesting, preparation for irrigation. According to table 1, vineyards that elaborate wine employ more labor force with respect to viticulturists at the plot level but the labor days per hectare is relatively similar in both groups. Seasonal staff is normally employed for harvesting, pruning and leaf removal crafts, wine-makers employ a higher share of temporary labor 29% with respect to 15% of viticulturist. Although there is a high variability among farms, the mechanical harvesting expenditure is on average 4,684 US dollar per farm representing a growing trend of vineyards adapting to substitute for labor. The dummy variable *machine technology* was created to capture the effects of such practices.

Results and discussion

In this section the Maximum Likelihood (ML) estimates of the production frontier are presented and discussed. The sample was divided into grapevine producers that sell their output (*viticulturists* 444 plots) and those farmers that not only cultivate grape but also elaborate wine (*wineries* 203 plots). The sample division allows for a better focus on economic and managerial performance and, simultaneously, improves the interpretation of the efficiency determinants. A likelihood-ratio test validated the explanatory power of these subgroups.

Functional forms and efficiency determinants

In this region, the wine-grape production is better explained econometrically with a translog functional form: where capital, labor, agrochemical expenses, and water used are the main inputs. The first order coefficients of the production function are all significant and positive at the sample mean. Both subgroups showed decreasing returns to scale but wineries are closer to constant returns to scale. The contribution of production factors is similar between the complete sample and the farmers subgroups; while it is relatively different among these clusters. In principle, this can be explained by the smaller share of wineries in the sample and their quality preferences.

The average TE score is 0.913 for viticulturists and 0.839 for wineries. The histograms of the efficiency scores in figure 2 deploy the frequency for each subgroup. Moreover, the mean yield for viticulturists (10.6 tons) is significantly higher than the reported by wineries (9.19 tons), as confirmed by the t-test (p-value=0.0001); this translates into forgone production of 1 and 1.76 tons per hectare respectively.

Table 2: Estimation coefficients of production function

	Viticulturists		Wineries	
	β_{Vit}	SE_{Vit}	β_{Wine}	SE_{Wine}
intercept	6.173***	(1.951)	1.875	(1.180)
capital	0.246***	(0.058)	0.400***	(0.106)
labor	0.187***	(0.039)	0.118*	(0.065)
agrochemicals	0.154***	(0.040)	0.094*	(0.051)
water	0.294***	(0.043)	0.331***	(0.032)
$0.5 \times$ capital^2	0.344***	(0.132)	0.213	(0.148)
$0.5 \times$ labor^2	-0.145***	(0.048)	-0.240	(0.163)
$0.5 \times$ agrochemicals^2	0.186**	(0.081)	0.035	(0.056)
$0.5 \times$ water^2	0.107	(0.089)	0.034	(0.039)
capital $\times$ labor	0.036	(0.060)	0.386***	(0.144)
capital $\times$ agroch	-0.176**	(0.075)	-0.359***	(0.061)
capital $\times$ water	-0.031	(0.092)	0.071	(0.155)
labor $\times$ agroch	0.079*	(0.046)	-0.036	(0.097)
labor $\times$ water	-0.056	(0.049)	-0.408***	(0.062)
agroch $\times$ water	-0.074	(0.074)	0.317***	(0.075)
pergola training syst.	0.172***	(0.051)	0.402***	(0.070)
white variety	0.039	(0.057)	0.038	(0.038)
vine age	-0.003***	(0.001)	-0.001	(0.001)
vineyard size	0.003**	(0.002)	0.000	(0.000)
Anchoris	-0.984***	(0.197)	-0.055	(0.154)
El Carrizal	-0.082	(0.093)	-0.547***	(0.116)
Perdriel	-0.162**	(0.071)	-0.002	(0.043)
Ugarteche	-0.053	(0.074)	-0.014	(0.040)
stony soil	0.278***	(0.090)	-	-
excessively drained soil	0.025	(0.080)	-	-

Source: Own estimation.

Significance level: 10%(*); 5%(**); 1%(***).

The first order coefficients affirms that wineries are relatively more intensive in capital (0.4) than viticulturists (0.25). Accounting for the composition of the capital services variable and considering that wineries have greater focus on output quality, the vineyard location is relevant for the economic services of land; as well as, their machinery and infrastructure to perform special managerial practices. A possible explanation lies in the difficulties to access credit by viticulturists that may limit investments on irrigated land and, therefore, increase their capital services with other assets, which still contribute to production but the variable may be beyond their optimum. In concordance, the first order coefficient of agrochemicals is relatively more important for viticulturists (0.15) than wineries (0.09), who would rely on professional advice and finance tools to comply with crop requirements and a pest management plan, as assumed by following descriptive information and expert consultations. The coefficients of labor hours at the plot level are relatively higher for viticulturists (0.19) than wineries (0.12), as the subgroup with greater machinery adoption. This is not surprising considering that grapevine production is the main input for a high-value product such as wine, whose quality is also subject to labor quality crafts and management practices.

Unarguably, the access to quality water is determinant in the semi-arid conditions of the analyzed wine valley, the water input coefficient is the greatest among the other production factors for the viticulturists subgroup (0.29); whereas for wineries, the coefficient represents the second greatest value among the production factors (0.33). The effects of irrigation practices and technologies are visible in the interaction terms as drip irrigation entails farmers with a mechanized system that ease fertilizer application. Wineries have a positive relation between water and agrochemicals (0.32) and negative coefficient for water and labor hours (-0.41).

The selected shifter variables also have the expected sign. Pergola is the roof-topped training system for vineyards that is expected to be more productive: for wineries (0.4) and viticulturists (0.17) the variable has significant values. Also the variety color dummy variable, where the estimation confirms that white varieties are more productive than red grapevines (0.04). In both subsamples, the effect of total vineyard area is positive but only significant for viticulturists. Older wine-grapes are less productive for viticulturists (-0.003) as their mean plantation year is 1991 after the *Productive Reconversion Plan* was launched in 1990 (Maffioli et al., 2011). Accounting for the soil characteristics, those plots with relatively higher stony content become more productive for grape production but this is only significant for viticulturists (0.28)

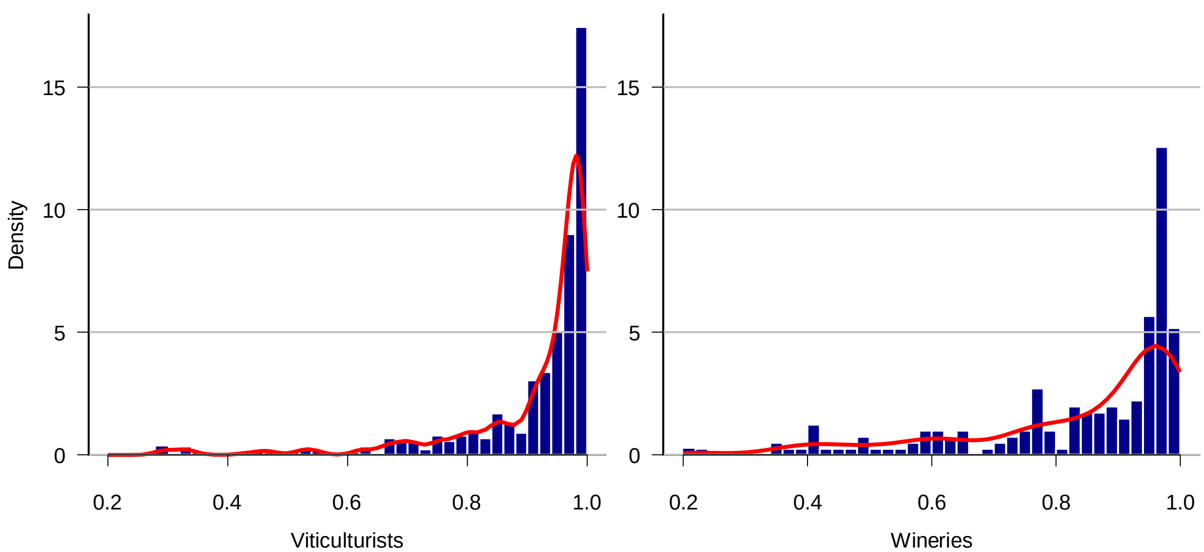

Figure 2: Histograms of TE scores

Table 3: Estimation coefficients for external variables

	Viticulturists		Wineries	
	Estimate	Std. Dev.	Estimate	Std. Dev.
Technical inefficiency				
δ intercept	-4.214***	(1.023)	-0.466	(1.433)
δ drip irrigation	-0.044	(1.053)	-2.325*	(1.237)
δ extensionist	-4.258***	(1.382)	-3.222*	(1.829)
δ vine density	-1.405***	(0.379)	-1.194***	(0.462)
δ energy subsidy	-0.264	(0.566)	0.219	(0.487)
δ machine technology	-0.005	(0.983)	1.710**	(0.830)
δ membership	-2.034*	(1.152)	0.224	(2.763)
δ depth aquifer	0.033**	(0.013)	-0.005	(0.013)
δ leaf removal	-0.962	(0.931)	-2.168	(2.316)
Statistical noise				
ρ intercept	-1.900***	(0.251)	-1.430**	(0.722)
ρ drip irrigation	-0.307	(0.214)	-0.054	(0.392)
ρ extensionist	0.127	(0.234)	-4.724***	(0.998)
ρ vine density	-0.336***	(0.121)	-1.278***	(0.304)
ρ energy subsidy	-0.252	(0.231)	0.081	(0.536)
ρ machine technology	-0.329*	(0.197)	3.081***	(0.390)
ρ membership	0.116	(0.345)	-3.437***	(1.144)
ρ depth aquifer	-0.017***	(0.005)	-0.050***	(0.009)
ρ leaf removal	1.143***	(0.231)	3.196***	(1.029)

Source: Own estimation.

Significance level: 10%(*); 5%(**); 1%(***).

In the context of competitive markets there is a higher probability for farmers to remain efficient. In accordance with this, firms are expected to show less variability in their economic performance since non-competitive vineyards will be forced out of the market in the long-run (Kumbhakar et al., 2015, p. ch.5). Higher values of the variance parameter are interpreted as more diverse performance of wineries within the region. For the inefficiency models a half-normal distribution was selected. Regarding the exogenous variables, the resulting coefficients for the inefficiency variance (σ^2_u) are generally similar but with notable exceptions between the subgroups. Adopting drip irrigation systems have the effect of decreasing inefficiency for both clusters but this is only significant for wineries (-2.33), which could be interpreted as efficiency gains from improvements in the irrigation systems. Furthermore, the technical assistance given by extensionists and vine density increases efficiency for both subsamples.

Some external variables have disparate effects between the subgroups. In the case of machine technology for wineries (1.71) and viticulturists (-0.005); while some wineries could seek to minimize labor costs through adopting these technologies, they could also apply machinery for regular management and have specialized labor to focus on quality optimization crafts. Membership to any kind of producer association, as technical clusters, producers organizations or cooperatives would represent an efficiency gain for viticulturists (-2.03). In this wine valley, water quality for irrigation improves substantially if it is withdrawn from the second confined aquifer. The distance to higher quality groundwater it is translated in greater production costs increasing inefficiency for viticulturists (0.03). Additionally, many wineries are able to irrigate vines with surface and groundwater. The effect of energy subsidies on the variance of TE is also different between the subgroups but insignificant.

The statistical noise estimation (σ^2_v) was also modeled for both groups including the same exogenous variables and distributional assumptions as the inefficiency model. Some variables have similar direction of the effects for viticulturists and wineries; as the intercept, vine density, depth of groundwater and leaf removal. Other variables would show different outcome between the subgroups. While extensionist (-4.72) and membership (-3.44) would decrease uncertainty for wineries, machine technology diminishes uncertainty for viticulturists (-0.33).

Estimations of the mean TE scores were performed at the district level and are displayed in table 4 jointly with the districts estimates of the production function.[3] Districts are organized following the surface water scheduling from north to south in the research area, groundwater dependency increases from Perdriel to Anchoris. Our econometric estimation points at a lower production potential for those districts with greater dependency of groundwater. However, some vineyards are able to achieve greater performance as depicted in the TE estimates. In general viticulturists outperforms wineries in every district. Within the viticulturists subsample, farmers in *Anchoris* and *El Carrizal* lead optimization; while the plots in *El Carrizal* and *Agrelo* have relatively better efficiency accomplishments for wineries. Interpretation would not be complete without acknowledging that the analysis is output-oriented and some plots may seek lower yield per ha to concentrate the tanins and sugar content per grape bundle.

Table 4: Mean efficiency scores and production shifter per district

	$\overline{TE}_{vit}$	X_{vit}	$\overline{TE}_{win}$	X_{win}
Perdriel	0.877	-0.162	0.821	-0.002
Agrelo	0.890	0.000	0.836	0.000
Ugarteche	0.877	-0.053	0.811	-0.014
El Carrizal	0.964	-0.082	0.931	-0.547
Anchoris	0.920	-0.984	0.804	-0.055

Source: Own estimation.

These results contradict expectations that grapevine plots located in the southern area of the research (districts of Ugarteche, El Carrizal and Anchoris) would score lower TE estimates, considering the higher production costs derived from pumping water. Instead, the results show that producers located in these districts have gained certain wisdom with respect to production inputs and groundwater management that excels their performance. In the case of wineries of these districts, they seem to manage their resources more wisely as opposed to the farmers in *Perdriel*, the first recipient of surface water in the distributional scheme.

[3] Agrelo district is the reference categorical variable which took the value zero in the econometric estimation.

Marginal effects of the external variables

The calculation of the marginal effects provides a clearer perspective of the direction of the external variables on the variance of the inefficiency, which is determined by the sign of δ_i. This statistic measures the sensitiveness of the inefficiency variance with respect to changes in the external variables (Z_i). Results are shown in table 5.

Table 5: Marginal effects of external variables

	ME_{vit}	ME_{win}
Drip irrigation	-0.002	-0.274
Extensionist	-0.236	-0.380
Vine density	-0.078	-0.141
Energy subsidy	-0.015	0.026
Machine technology	0.000	0.202
Membership	-0.113	0.026
Depth aquifer	0.002	-0.001
Leaf removal	-0.053	-0.256

Source: Own estimation.

Irrespective to their market orientation some management decisions have similar effects in the plot production but the size of the effect is different for viticulturists and wineries. These include professional advice by extensionists, adoption of drip irrigation systems, vine density and the leaf removal craft. Technical advise by extensionist is the variable with higher marginal effect for both subgroups. Vineyards that employ extensionists for agronomic or enological advice would decrease their inefficiency.

Wine-grape plots with drip irrigation systems can achieve greater efficiency performance but the size of the effect is larger for wineries than viticulturists at the sample mean. In addition, higher vine density and leaf removal craft to ensure sunlight to their grapes would perform relatively better. The size of the effects of the membership and the energy subsidy imply that the parcels managed by winegrowers who are members of associations and / or recipients of the subsidy will outnumber the wineries. Those plots that make use of machinery to replace hand-crafts or quality reasons may save in labor hours at the expense of efficiency for wineries.

Conclusions

Agricultural systems in western Argentina are characterized by heterogeneous agro-ecological conditions, e.g., strong variations in micro-climates, different soil conditions, and variable water supply. In response to these conditions, farmers in Mendoza have developed agricultural systems with a focus on high-value crops such as grapevines for wine production. Despite the economic and enological potential of the wine industry, the region is threatened by water management problems, e.g., uneven access to irrigation water, and pollution issues. Which, in combination with business uncertainties that emanate from a volatile macroeconomic environment, climate change and a relatively high share of quasi-fixed costs pose major challenges for the long-term viability of grapevine production in the region. In light of such pressures on profitability, technical inefficiency, and its relation to water use, becomes a pressing question for both farmers and policy makers alike.

This study assesses the technical efficiency of grapevine producers based on a representative sample from Mendoza, and looks into the determinants of inefficiency for these producers. Based on differences in technology and market orientation, the sample was split into two subgroups: *viticulturists* and *wineries*. The former focus solely on the production of grapevine, and sell their produce to wineries, while the latter pursue an integrated business model that includes the wine elaboration. The average technical efficiency of *viticulturists* (0.91) is higher than the average technical efficiency of *wineries* (0.84). However, substantial variation between districts is present. Looking at the output weighted technical efficiency, we find a small increase in the weighted average for both the *viticulturists* and the *wineries*, 0.94 and 0.89 respectively, which indicates that those farms with above-average output are slightly more technically efficient than those farms with relatively small output.

In general, wine-grape production is strongly focused on quality as it will facilitate the subsequent processing steps in winemaking. Hence, it seems plausible that vineyards that produce their own wine will allocate more resources into quality improvements. This is visible in our findings: The partial production elasticity for capital show larger values for the *wineries* than for the *viticulturists*.

Among the determinants of technical inefficiency, we found that areas that solely rely on groundwater for irrigation have relatively good performance compared to those that use surface water for irrigation. For both subsamples, higher efficiency scores are associated with a higher share of precision systems for irrigation, agronomic extension services, membership and vine density. In contrast to the *wineries*, the energy subsidy for irrigation is associated with higher technical efficiency for the *viticulturists* only. This finding reflects that the focus on productiveness is more marked for this group so that cheap irrigation water allows for higher output levels, while for *wineries* this subsidy is less important for their managerial decisions. Our results suggest that an increased adoption of modern irrigation systems, possibly supported by technical advice from professional extension services, would substantially contribute to narrow the inefficiency gap.

We conclude that the grapevine industry shows relatively high levels of technical efficiency. The analysis of the variables that are associated with differences in inefficiency, however, points to some shortcomings related to the use of irrigation technology and extension services – in both areas, there is a potential for more effective government interventions. The performance of farmers is good with respect to the regional documented literature but still needs improvement to put farmers in a position to cope with macro-economic instability and climate contingencies in the near future. Policy interventions that take account of these results could contribute to improving the performance of small and medium producers. However, these effects are likely to be visible only over a longer period of time. Hence, to overcome this limitation of the present cross-sectional study, future research based on panel data would allow for understanding the dynamic linkages between on-farm water use, technical inefficiency, and the institutional framework for water policy in Mendoza.

Appendix

Valuation of capital services

Vineyards are usually productive for several decades. Thus, the flow of services from a given vineyard is based on the area planted and on the capital embedded in the vines. We calculate this flow of services via the perpetual inventory approach, whis is frequently employed in agricultural economics (Coelli & Sanders, 2013). As market prices do not always reflect the economic value of capital employed on the farm, this methodology assesses the annual services provided by the stock which is priced according to their own characteristics (Ball et al., 2004). Taking into account the capital stock at the end of each period, K_t, as the sum of all previous investments weighted by the relative efficiency that decreases over time given by the hyperbolic function of d_τ:

$$K_t = \sum_{\tau=0}^{\infty} d_\tau I_{t-\tau} \tag{5}$$

$$d_\tau = \frac{L-\tau}{L-\beta_\tau} \tag{6}$$

where L is the life expectancy of the capital good, β_τ represents the curvature of the decay parameter, and d_τ is the decay in efficiency at the age τ. The values of capital life expectancy and rate of efficiency decay τ were determined based on field research observations and expert consultations, in years: arable land with irrigation (120), storage facilities and reservoirs (55), tractor (65), machinery (50), groundwater wells (55), drip irrigation equipment (20) In concordance with the literature β_τ equals 0.5, with the exception of machinery where 0.75 was used. Capital stock is composed of machinery, infrastructure and land connected to grapevine production. The value of the stocks was formed considering the capital endowment at the time of the survey, accounting for market prices and their respective age.

References

Aigner, D., Lovell, C. A. K., & Schmidt, P. (1977). Formulation and estimation of stochastic frontier production function models. *Journal of Econometrics*, *6* (1), 21–37. https://doi.org/10.1016/0304-4076(77)90052-5

Andrieu, J., Miranda, O., Gatti, N., & Novello, R. (2014). Riego y acción colectiva: impacto en la eficiencia técnica de la producción vitícola de San Juan. *Asociación argentina de economía agraria*, 1–23. Retrieved from https://goo.gl/A6NdDe

Ashenfelter, O., & Storchmann, K. (2014). *Wine and climate change* (p. 44). https://doi.org/2166-9112

Ball, V. E., Butault, J. P., & San Juan Mesonada, C. (2004). Measuring real capital input in OECD agriculture. *Canadian Journal of Agricultural Economics*, *52*(3), 351–370. https://doi.org/10.1111/j.1744-7976.2004.tb00374.x

Battese, G. E. (1992). Frontier production functions and technical efficiency: a survey of empirical application in agricutural economics. *Agricultural Economics*, (7), 185–208.

Bravo-Ureta, B. E., Moreira, V. H., Troncoso, J. L., & Wall, A. (2020). Plot-level technical efficiency accounting for farm-level effects: Evidence from Chilean wine grape producers. *Journal of Agricultural Economics*.

Coelli, T. J., & Sanders, O. (2013). The Technical Efficiency of Wine Grape Growers in the Murray-Darling Basin in Australia. In *Wine economics* (pp. 231–249). https://doi.org/10.1057/9781137289520_12

Conradie, B., Cookson, G., & Thirtle, C. (2006). Efficiency and farm size in Western Cape grape production: Pooling small datasets. *South African Journal of Economics*, *74*(2), 334–343. https://doi.org/10.1111/j.1813-6982.2006.00061.x

COVIAR, & OVA. (2018). *Impacto de la Vitivinicultura en la Economía Argentina* (p. 134). Retrieved from Corporación Vitivinícola Argentina (COVIAR). Observatorio Vitivinícola Argentino (OVA); COVIAR website: https://goo.gl/A9AUDQ

de Sousa Henriques, P. D., da Silva Carvalho, M. L., & de Sousa Fragoso, R. M. (2009). Technical efficiency of portuguese wine farms. *New Medit*, *8*(1), 4–9.

Diaz Araujo, E., & Bertranou, A. (2004). *Systemic Study of Water Management Regimes: Mendoza, Argentina* (pp. 1–102). Global Water Partnership (GWP).

FAO, & PROSAP. (2015). *Estudio del potencial de ampliación del riego en Argentina* (pp. 1–170). Buenos Aires: Organización de las Naciones Unidas para la Agricultura y la Alimentación (FAO). Programa de Servicios Agrícolas Provinciales (PROSAP).

Farrell, M. J. (1957). The measurement of productive efficiency. *Journal of the Royal Statistical Society*, *120*(3), 253–290.

Foster, S., & Garduño, H. (2005). *Gestión sustentable del agua subterránea. Argentina: Enfoque de gestión integrada para la conservación del agua subterránea en los acuíferos de Mendoza* (p. 16). Retrieved from World Bank website: www.worldbank.org/gwmate

Foster, S., & Garduño, H. (2006). *Integrated approaches to groundwater resource conservation in the Mendoza aquifers of Argentina*. Washington, D.C.: World Bank.

Gibbons, M. A., Maffioli, A., & Rossi, M. A. (2016). *Money for Wine? Complementarities in the provision of private and public goods to wine producers*. Inter-American Development Bank.

Guesmi, B., Serra, T., Kallas, Z., & Gil Roig, J. M. (2012). The productive efficiency of organic farming: the case of grape sector in Catalonia. *Spanish Journal of Agricultural Research*, *10*(3), 552. https://doi.org/10.5424/sjar/2012103-462-11

Hernández, J., Martinis, N., & Fornero, L. (2012). *Modelación hidrológica de la cuenca norte de Mendoza*

(No. 146; p. 113). Mendoza, Argentina: Instituto Nacional del Agua (INA).

INV. (2018). *Anuario vitivinícola*. Retrieved from Instituto Nacional de Vitivinicultura website: https://goo.gl/D4FBPZ

INV. (2019). *Informe Anual de Cosecha y Elaboración* (p. 90). Retrieved from Instituto Nacional de Vitivinicultura (INV) website: https://www.argentina.gob.ar/inv/estadisticas-vitivinicolas/cosecha/anuarios

Kumbhakar, S. C., & Knox Lovell, C. A. (2000). *Stochastic Frontier Analysis* (First, p. 276). Cambridge: Cambridge University Press.

Kumbhakar, S. C., & Wang, H.-J. (2015). Estimation of Technical Inefficiency in Production Frontier Models Using Cross-Sectional Data. In *Benchmarking for performance evaluation* (pp. 1–73). https://doi.org/10.1007/978-81-322-2253-8_1

Kumbhakar, S. C., Wang, H.-J., & Horncastle, A. P. (2015). *A Practitioner's Guide to Stochastic Frontier Analysis Using Stata*. https://doi.org/10.1017/CBO9781139342070

Latruffe, L., & Nauges, C. (2014). Technical efficiency and conversion to organic farming: the case of France. *European Review of Agricultural Economics*, *41*(2), 227–253. https://doi.org/10.1093/erae/jbt024

Maffioli, A., Ubfal, D., Baré, G. V., & Cerdán-Infantes, P. (2011). Extension services, product quality and yields: the case of grapes in Argentina. *Agricultural Economics*, *42*(6), 727–734. https://doi.org/10.1111/j.1574-0862.2011.00560.x

Meeusen, W., & van Den Broeck, J. (1977). Efficiency Estimation from Cobb-Douglas Production Functions with Composed Error. *International Economic Review*, *18*(2), 435. https://doi.org/10.2307/2525757

Moreira, V. H., Troncoso, J. L., & Bravo-Ureta, B. E. (2011). Technical efficiency for a sample of Chilean wine grape producers: A stochastic production frontier analysis. *Ciencia e Investigación Agraria*, *38*(3), 321–329. https://doi.org/10.4067/S0718-16202011000300001

OIV. (2019). *State of the Vitiviniculture World Market*. Retrieved from International Organization of Vine & Wine website: http://www.oiv.int/public/medias/6679/en-oiv-state-of-the-vitiviniculture-world-market-2019.pdf

Parmeter, C. F. (2014). Efficiency analysis: a primer on recent advances. *Foundations and Trends in Econometrics, 7*(3-4), 191–385. https://doi.org/10.1561/0800000023

Pfeiffer, L., & Lin, C.-Y. C. (2014). The effects of energy prices on agricultural groundwater extraction from the high plains aquifer. *American Journal of Agricultural Economics*, *96*(5), 1349–1362. https://doi.org/10.1093/ajae/aau020

Piesse, J., Conradie, B., Thirtle, C., & Vink, N. (2018). Efficiency in wine grape production: comparing long-established and newly developed regions of South Africa. *Agricultural Economics*, *49*(2), 203–212. https://doi.org/10.1111/agec.12409

Wang, H. J., & Schmidt, P. (2002). One-step and two-step estimation of the effects of exogenous variables on technical efficiency levels. *Journal of Productivity Analysis*, *18*(2), 129–144. https://doi.org/10.1023/A:1016565719882

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