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Wine Taxes, Production, Aging and Quality*

Rachael E. Goodhue[a], Jeffrey T. LaFrance[b], and Leo K. Simon[c]

Abstract

We consider the impact of taxes on the quantity and quality produced by a competitive firm of goods, such as wine, for which market value accrues with age. Our analysis found the following: an increase in the volumetric retail tax collected at sale increases quality, so that the basic Alchian-Allen effect holds. However, an increase in the volumetric storage tax collected each period decreases quality, as does an increase in the ad valorem storage tax. The effect of an increase in the ad valorem retail tax on quality is indeterminate. Increases in any of the four taxes reduce the quantity of wine produced. Any two-tax system that includes a volumetric sales tax spans the full range of feasible tax revenues with positive tax rates. For any tax system that reduces quality relative to the firm's no-tax equilibrium, there is another tax system that increases tax revenues, eliminates the quality distortion, and does not increase the quantity distortion. Many wine industry observers believe that most, if not all, existing tax systems tend to result in the suboptimal provision of quality. Our results suggest that the wide variety of wine tax systems is not prima facie evidence that these systems, or most of them, are inefficient. Provided the system includes a volumetric sales tax it may be efficient, regardless of which of the other instruments, or how many of them, are used. Assertions regarding inefficiency must be evaluated on an empirical case-by-case basis. Our analysis provides a theoretical framework for such research. (JEL Classification: D2, H2, Q1)

I. Introduction

The tendency for an excise tax to increase the average quality of a consumed good is often referred to as the Alchian-Allen effect (Alchian and Allen, 1964).[1] Barzel (1976) explained this effect in terms of product attributes; an ad valorem tax is based on all product attributes, while an excise tax affects only certain product attributes. Many authors have refined and expanded these initial analyses (Gould and Segall, 1969; Borcherding and Silberberg, 1978; Umbeck, 1980; Leffler, 1982; Kaempfer and Brastow, 1985; Cowen and Tabarrok, 1995; James and Alston, 2002; Razzonlini, Shughart and Tollison, 2003).

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[a] Department of Agricultural and Resource Economics, University of California, Davis, CA 95616 and Giannini Foundation of Agricultural Economics, email: goodhue@primal.ucdavis.edu.
[b] School of Economic Sciences, Washington State University, Pullman, WA 99164, email: jtlafrance@wsu.edu.
[c] Department of Agricultural and Resource Economics, University of California, Berkeley, CA 94720 and Giannini Foundation of Agricultural Economics, email: simon@are.berkeley.edu.
[1] This result has been credited to the UCLA oral tradition prior to the publication of Alchian and Allen's textbook (Borcherding and Silberberg, 1978).

Most – though not all – of these articles focus on consumption rather than production decisions and none have addressed the time dimension of the quality-tax relationship. Many products, such as wine, aged cheese, cultured pearls, timber, and most crop and livestock production are characterized by multi-period production processes. We examine the effects of taxes on the quantity and quality decisions of competitive producers. The representative producer chooses the optimal quantity and quality to produce and sell. Quantity is determined in the initial production period, and quality is determined by the number of periods the good is aged prior to sale. The passage of time affects the value of the product, and a share of that value is captured by the tax authority.

We develop a dynamic model of the producer's profit-maximizing choices in the presence of a tax system. We evaluate four taxes: an *ad valorem retail tax* assessed as a percentage of price and collected on the date of sale; a *volumetric retail tax*, or excise tax, assessed at a fixed rate per unit and collected on the date of sale; an *ad valorem storage tax*, or ad valorem accrual tax, assessed as a percentage of each period's market value and collected each period prior to sale; and a *volumetric storage tax*, or accrual excise tax, assessed at a fixed rate per unit collected each period prior to sale. Previous analyses of the Alchian-Allen effect have restricted attention to the ad valorem and volumetric retail taxes.

We derive the effects of each tax instrument on the quantity and quality supplied, and obtain equivalency results regarding various two-tax systems. We find that an increase in any marginal tax rate unequivocally decreases quantity produced. Consistent with Alchian-Allen, an increase in a volumetric retail tax rate increases quality at the time of sale. However, because quality increases over time an increase in the ad valorem retail tax rate can either increase or decrease quality at the time of sale, depending on the level of all tax rates and other parameters. Further, the Alchian-Allen dichotomy between ad valorem and volumetric taxes does not hold for storage taxes. An increase in either storage tax rate unequivocally decreases quality at the time of sale.

We then address the behavior of tax systems with multiple tax instruments. Any two-tax system that includes a volumetric retail tax and any one of the three other taxes spans the quality/revenue feasible set. Consequently, it is possible to achieve a quality-neutral two-tax system which results in the first- best level of quality. The supply side distortions of any tax system that results in a lower quality relative to the no-tax equilibrium can be mitigated by an alternative tax system that increases tax revenues, eliminates the quality distortion, and does not increase the quantity distortion.

A volumetric retail tax is distinguished from the other taxes considered here only because it permits the construction of a full range of two-tax schemes with positive taxes. If subsidies were permitted, then any tax system with two instruments could deliver the optimal quality level. Since direct subsidies of wine production on a per-unit basis are not typically observed in practice, such schemes would be of little practical interest to policymakers. The exception to this rule is the European Union. While most of its subsidies are not on a per-unit of wine basis, under the 2000 CAP reforms there is limited aid to private storage of wine (Corsi, Pomarici, and Sardone, 2004).

II. Wine and Taxes

When examining the effects of taxes on quality, wine is a particularly interesting aged product to consider, for four reasons. First, several studies have estimated the rate of return to holding wine over time, and have established that there is a positive return to aging over at least a twenty-year time period for the subsets of wines they examine, although their conclusions regarding its rate of return relative to other assets differ (Krasker, 1979; Jaeger, 1981; Burton and Jacobsen, 2001). Byron and Ashenfelter (1995) examine determinants of wine prices, and also find that there is a positive return to aging. Because most wine is drunk soon after its purchase, tax distortions affecting the producer's aging decision potentially may have a large effect on social welfare.

Second, wine consumption and production is subject to heavy taxation in virtually every country in the world. Economic distortions are therefore widespread, globally impacting consumption, production, and wine quality. Taxes on wine can be split into three broad categories. In order of decreasing importance, wine is subject to excise taxes, value-added and retail taxes, and import duties and other related taxes. Berger and Anderson (1999) calculate that 16% of the average global cost of a bottle of wine is attributable to excise taxes or their equivalent, 6% to retail/VAT taxes or their equivalent, and 1% to import duties.

Many countries employ excise taxes, including Canada, New Zealand, England, and Japan. On the other hand, some nations, such as Mexico, choose to impose ad valorem taxes on wine premises. Some prominent wine-producing and -consuming countries have no excise or similar taxes on wineries or wholesalers, including Italy, Spain, Germany, and China. Nearly every major wine consuming country imposes a goods-and-services tax (GST) or a value-added tax (VAT).

Various other taxes are levied on the consumption, production, trade, and sale of wine. However, while quite substantial in some markets, these taxes play a significantly smaller role in the distortions of the global market. Import tariffs can be extremely high for exports to certain nations (for example, 50% of total value for Chinese imports in 2000) but tend to be less than 5% of the total value of a premium quality wine for most developed nations (Berger and Anderson 1999). And, importantly, trade levies are essentially non-existent within regions covered by trade agreements, such as NAFTA. Many other miscellaneous wine taxes exist globally, at all levels of government, and include levies such as special winery occupational taxes (US), licensing fees (US, Australia), and environmental fees (Canada).

Third, wine tax systems vary widely across countries. Three important wine-producing countries, the United States, Australia and France, have very different tax systems. In the United States, wine is subject to a volumetric retail tax (excise tax) and an ad valorem retail tax at the federal level. Many states impose additional ad valorem retail taxes. Some states tax business inventories, such as wine held by a winery. In Australia, wine is subject to an ad valorem retail tax and to an ad valorem storage tax, referred to as the Wine Equalization Tax (WET).[2] In France, wine is subject to the Value Added Tax (VAT). Wine stocks are taxed with either an ad valorem storage tax, or a quasi-volumetric storage tax based on the wine's initial declared value which does not adjust for appreciation in wine value over time. Such variation across tax systems provides an empirical motivation for our theoretical analysis of quality-neutral tax systems and their equivalence across certain tax instruments.

Fourth, trends in wine taxation are quite pronounced. Overall wine taxation has unambiguously risen in the past 2 decades and continues to do so.[3] While tariffs are decreasing with trade liberalization, the relatively more important excise taxes and goods and services taxes (or their respective equivalents) are increasing. For example, between 1985 and 1998, the United States federal excise tax on table wine increased by 238%. During the same period, 16 states increased their excise taxes by an average of 69% (Steve Barnsby and Associates, 1998).[4] More recently, the state of Illinois raised its tax rate more than 300%. The wholesale tax rate in Australia has more than doubled since the middle 1980s. New Zealand's tax rate has also increased. Volumetric excise taxes and *ad valorem* wholesale taxes, GSTs, and value-added taxes clearly play a large and increasing role in the wine industry.

Previous work has examined wine taxes. Tsolakis (1983), Buccola and VanderZanden (1997), and James and Alston (2002) have examined the empirical effects of wine-specific taxes but have not addressed the effects on aging and quality or the difference between storage taxes and retail taxes. They have not compared tax systems.

Our analysis addresses the profit-maximizing quantity and quality choices for a vintner for a single vintage. In terms of the vintner's quality decision, it identifies the optimal stopping rule. An alternative approach would evaluate the optimal rotation rule for the winery. Wohlgenant (1982) examines vintner aging decisions across vintages as an inventory problem, but does not consider taxes.

III. The Basic Model

[2] Under Australia's WET, any change in the value of wine stocks held by a vintner is treated as ordinary income. Stocks can be valued by any one of three methods, chosen by the producer –cost of production (excluding storage costs), market value, or replacement value – with the stipulation that the ending valuation method in the previous period equals the beginning valuation method in the following period. Winemakers typically choose the cost of production basis for valuation, so that aging wine does not increase the value of their stocks (and income) until the wine is sold. With a bit of algebra, it can be shown that the WET has qualitatively the same effect as each of the four considered here on quantity, and precisely the same effect on quality/age as an ad valorem retail tax.

[3] Wine and alcohol in general are generally taxed at a higher rate than most goods and services are. High taxes on alcohol are sometimes justified by the argument that there are large negative externalities due to alcohol consumption, and taxes force users to internalize these costs. However, see Heien and Pittman (1989) for a critique of the methodology of studies of the public costs of alcohol abuse. They observe that in these studies private costs internalized by alcohol consumers are included in the calculations of costs borne by society at large.

[4] 16 states lowered their excise tax rates, but by an average rate of less than 3%.

We assume a perfectly competitive market, so that the market price of wine at the date of sale is a perfect signal of quality.[5] We invoke the small country assumption, and focus on the effects of taxes through wine prices and costs on a representative winery.[6] Both the tax authority and the representative winery have rational expectations. The quantity of wine produced is determined at the initial date $t = 0$, while quality is a function of the wine's initial quality and the number of periods it is aged. Price is an increasing concave function of quality.

Consider the problem of the production, aging, and ultimate sale of wine from a single crushing by a representative winery. The winery maximizes profits by choosing the quantity of wine produced, q, and by choosing the quality of the wine through choosing its sale date t. We denote the cost of production as $c(q)$, the marginal cost of storage per unit of wine per period as p_s, and the real discount rate as r. We assume that $c'(q) > 0$ and $c''(q) > 0$ for all $q \geq 0$. The increasing marginal cost of production reflects the increased procurement costs associated with purchasing (or growing) each incremental unit of winegrapes suitable for inclusion in the vintage, and/or the cost of non-grape inputs required to control for winegrape heterogeneity. In contrast, in our single-vintage framework there is little reason to expect the marginal cost of storage per unit of wine to vary with the number of units stored. The cost of temperature control, etc. is assumed to be a fixed cost, given that any wine is stored in a given period.

The realized profit from producing q units of wine at time 0 and aging the wine until its sale at date t is

$$\pi = e^{-rt} p(t) q - c(q) - (1 - e^{-rt}) p_s q / r . \tag{1}$$

Maximizing π with respect to q implies

$$\frac{\partial \pi}{\partial q} = p(t) e^{-rt} - c'(q) - \frac{1 - e^{-rt}}{r} p_s = 0 \tag{2}$$

Equation (2) can be rewritten as

$$p(t) e^{-rt} = c'(q^*) + \left(\frac{1 - e^{-rt}}{r} \right) p_s . \tag{2'}$$

Equation (2') shows that the optimal quantity of wine q^* is the quantity for which the marginal benefit of quantity, which is its marginal discounted present value, equals the

[5] We therefore are abstracting from the potential asymmetric information issues that may arise between the producer and consumers.

[6] By invoking the small country assumption, we assume that the world price of wine as a function of its quality and quantity is unaffected by the quality and quantity decisions made by wineries subject to the tax authority. This assumption greatly simplifies our analysis without altering our qualitative results.

marginal cost of quantity, which is the sum of the marginal cost of production and the discounted present value of the marginal cost of aging for all storage periods prior to its sale at t. We refer to q* as the firm's *first-best* quantity.

The firm chooses the age at which it sells the vintage according to the following profit-maximization condition:

$$p'(t) = rp(t) + p_s \, . \tag{3}$$

That is, the firm sells the wine at time t when the marginal benefit of aging, which is the marginal increase in value from holding the wine for an additional period, equals the marginal cost of aging, which is the opportunity cost of the money obtained from selling the wine at time t plus the marginal cost of storing the wine a little longer. Hereafter, we call this date of sale the firm's *first-best* age of wine, t*. We assume that t* is a unique global maximizer.

IV. Wine Taxes, Quantity, Quality, and Tax Revenue

We now introduce taxes into the producer's profit maximization problem, focusing on comparing his long-run responses to different tax systems. A tax system includes one or more of the four tax instruments we model. We assume that once the tax system has been designed and chosen it remains in place unchanged throughout the producer's planning horizon. In this framework the discounted present value of an ad valorem retail tax paid at time t is $e^{-rt}\tau_p^r p(t)q$, where $\tau_p^r \in [0,1]$ is the ad valorem retail tax rate. The discounted present value of a volumetric retail tax paid at time t is $e^{-rt}\tau_q^r q$, where $\tau_q^r \geq 0$ is the volumetric retail tax rate. An ad valorem storage tax is collected continuously throughout the storage period.[8] Consequently, the discounted present value of the total tax is $\int_0^t e^{-rx}\tau_p^s p(x)qdx$, where $\tau_p^s \in [0,1]$ is the ad valorem storage tax rate. A volumetric storage tax is assessed as a fixed monetary amount per unit volume and is collected continuously throughout the storage period. The discounted present value of the total tax paid is $(1-e^{-rt})\tau_q^s q / r$, where $\tau_q^s \geq 0$ is the volumetric storage tax rate.

Incorporating all four tax instruments, the vintner's profit is

$$\begin{aligned} \pi(t) = e^{-rt}\left[p(t)(1-\tau_p^r) - \tau_q^r\right]q \; - \; \int_0^t e^{-rx}\tau_p^s p(x)qdx \\ -\left(\frac{1-e^{-rt}}{r}\right)(p_s + \tau_q^s)q \; - \; c(q). \end{aligned} \tag{4}$$

For future use, given the tax regime $\boldsymbol{\tau} = [\tau_p^r \quad \tau_q^r \quad \tau_p^s \quad \tau_q^s]'$ we define the *effective tax rate per unit of wine* as

[8] We abstract away from tax collection costs and other complications associated with cases where the tax authority must continuously appraise the value of wine that has not yet been sold in order to collect ad valorem

taxes.

$$v(\boldsymbol{\tau}) = e^{-rt(\boldsymbol{\tau})}\left[\tau_p^r p(t(\boldsymbol{\tau})) + \tau_q^r\right] + \int_0^{t(\boldsymbol{\tau})} e^{-rx}\left[\tau_p^r p(x) + \tau_q^r\right]dx \,, \tag{5}$$

and the value of total tax revenue as $R(\boldsymbol{\tau}) = v(\boldsymbol{\tau})q(\boldsymbol{\tau})$, where $q(\boldsymbol{\tau})$ is the optimal choice for quantity and $t(\boldsymbol{\tau})$ is the optimal age of wine.

A. *Quality Choice with Taxes*

In this section we consider the effects of changes in the tax regime on the quality of wine produced. The firm's optimal stopping rule for the age that maximizes the expected per-unit value of the wine with respect to its date of sale is

$$(1-\tau_p^r)p'(t) = r\left[(1-\tau_p^r)p(t) - \tau_q^r\right] + p_s + \tau_p^s p(t) + \tau_q^s \,. \tag{6}$$

Dividing through by $(1-\tau_p^r)$ and rearranging terms, we obtain

$$p'(t) = rp(t) + p_s + \left(\frac{\tau_p^r p_s - r\tau_q^r + p(t)\tau_p^s + \tau_q^s}{1-\tau_p^r}\right). \tag{7}$$

In the presence of taxes, the firm chooses t such that the marginal value of quality (the marginal benefit of waiting an additional period) equals the marginal cost of quality, which is now the marginal opportunity cost of waiting another period to sell the wine plus the cost of storage plus the net effect of taxes on the returns to waiting. Equation (7) illustrates several important properties of these taxes. First, in this framework the basic Alchian-Allen effect holds for a volumetric retail tax: an increase in this tax increases the profit-maximizing age at sale because it reduces the marginal cost of waiting to sell the wine. Formally,

$$\frac{\partial t}{\partial \tau_q^r} = \frac{-r}{(1-\tau_p^r)\Delta_t} > 0 \,, \tag{8}$$

where $\Delta_t = \partial^2\pi / \partial t^2 < 0$ by the second-order condition for a unique maximum.[8] Second, the volumetric retail tax has the same qualitative effect on age/quality at retail as a decrease in storage costs does because it is a constant decrease in the marginal cost per period of storage. Third, the Alchian-Allen dichotomy does not hold for a volumetric or an ad valorem storage tax. Both taxes unambiguously decrease the profit-maximizing age because they reduce the marginal benefit of waiting an additional period to sell the wine. Formally,

[8] This is equivalent to $(1-\tau_p^r)p''(t) < [r(1-\tau_p^r) + \tau_p^s]p'(t)$. A sufficient condition for this to be satisfied

for any tax system is that there exists a t_0 satisfying $0 < t_0 < \infty$ and $p''(t) < 0 \ \forall \ t > t_0$.

$$\frac{\partial t}{\partial \tau_q^s} = \frac{1}{(1-\tau_p^r)\Delta_t} < 0 \, , \tag{9}$$

$$\frac{\partial t}{\partial \tau_p^s} = \frac{p}{(1-\tau_p^r)\Delta_t} < 0 \, , \tag{10}$$

Fourth, an increase in either storage tax has the same qualitative effect on age/quality at retail as an increase in storage costs. Fifth, the impact of ad valorem retail taxes on age is indeterminate, rather than always negative, as in the single-period case. Specifically, it depends on the values of the other three taxes, the discount rate, the cost of storage, and the price of the wine. If the marginal benefit induced by an increase in the ad valorem retail tax (the reduction in marginal cost due to waiting another period to pay the volumetric retail tax) exceeds its marginal cost (the marginal cost of storage and storage taxes), then an increase in the ad valorem retail tax will increase the optimal age. Formally,

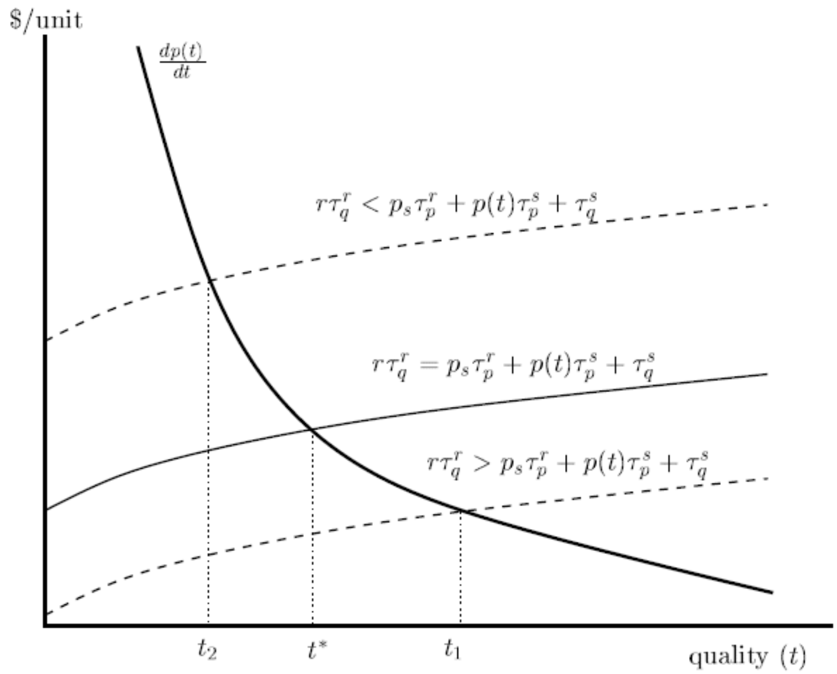
$$\frac{\partial t}{\partial \tau_p^r} = \frac{(-r\tau_q^r + p_s + \tau_p^s p + \tau_q^s)}{(1-\tau_p^r)^2 \Delta_t} \gtreqless 0 \iff r\tau_q^r \gtreqless p_s + \tau_p^s p + \tau_q^s \, . \tag{11}$$

Sixth, since the numerator of the parenthesized expression in (7) is linear in the tax rates, any given tax revenue objective can be achieved with different combinations of tax instruments. Finally, provided the second order condition for a unique maximum is met, the optimal choice for quality/age of wine exceeds, equals, or is less than the first-best age if and only if

$$-r\tau_q^r + \tau_p^r p_s + \tau_p^s p + \tau_q^s \lesseqgtr 0 \, . \tag{12}$$

This result is illustrated in Figure 1. The figure plots $p'(t)$ against the right-hand side of (7) in age-price space. The first-best age t^* and price $p(t^*)$ are obtained when $p'(t^*) = rp(t^*) + p_s$, or when the net effect of the taxes on the first-best age of wine is zero: $r\tau_q^r = \tau_p^r p_s + \tau_p^s p + \tau_q^s$. At this point, the values of the various tax instruments are such that the equilibrium with taxes is the same as the equilibrium without taxes. The intersections of the other two curves with the $p'(t)$ curve illustrate tax packages that distort age above and below its first-best level. When the effect of the volumetric retail tax dominates the joint effect of the other three taxes, then the profit-maximizing wine age exceeds the first-best age, as represented by $t_1 > t^*$ in Figure 1. When the effect of the volumetric retail tax is dominated by the joint effect of the other three taxes, then the profit-maximizing wine age is less than the first-best age, as represented by $t_2 < t^*$ in Figure 1.

Figure 1
Quality-Tax Relationship



B. *Quantity Choice with Taxes*

Next, we consider the impacts of changes in the tax system on the vintner's quantity choice. For any given tax system, the profit-maximizing quantity satisfies the first-order condition

$$\frac{\partial \pi}{\partial q} = e^{-rt}\left[(1-\tau_p^r)p(t)-\tau_q^r\right] - \int_0^t e^{-rx}\left[p_s + \tau_p^s p(x) + \tau_q^s\right]dx - c'(q) = 0\,. \tag{13}$$

The second-order sufficient condition for a unique q is simply $c''(q) > 0$. In order to evaluate the comparative statics for q with respect to each of the taxes, we first need to evaluate the cross partial derivative $\partial^2\pi/\partial q\partial t$. Differentiating the first-order condition for q with respect to t, we obtain

$$\frac{\partial^2 \pi}{\partial q \partial t} = e^{-rt}\left\{(1-\tau_p^r)p'(t) - r\left[(1-\tau_p^r)p(t)-\tau_q^r\right] - \left[p_s + \tau_p^s p(t) + \tau_q^s\right]\right\}. \tag{14}$$

From equations (2') and (7) above, we see that

$$(1-\tau_p^r)p'(t) - r\left[(1-\tau_p^r)p(t) - \tau_q^r\right] - \left[p_s + \tau_p^s p(t) + \tau_q^s\right] = 0\ . \tag{15}$$

The economic intuition for this separation property is straightforward. Once the producer has chosen how much wine to produce, each bottle of wine is simply an investment instrument. As long as the internal rate of return $(1-\tau_p^r)p'(t)$ exceeds the marginal holding cost $r[(1-\tau_p^r)p(t)-\tau_q^r]+[p_s+\tau_p^s p(t)+\tau_q^s]$ it is worthwhile to hold the bottle to capture the excess returns from further aging. This asset management decision is independent of the total quantity of wine that was produced at time $t = 0$. Hence, the firm's profit function is separable between quantity and age. This property greatly simplifies the comparative statics for the effects of different tax instruments on the quantity produced. Indeed, an increase in any of the wine taxes unambiguously decreases the quantity produced. Formally,

$$\frac{\partial q}{\partial \tau_p^r} = \frac{-e^{-rt}p(t)}{c''(q)} < 0\ , \tag{16}$$

$$\frac{\partial q}{\partial \tau_q^r} = \frac{-e^{-rt}}{c''(q)} < 0\ , \tag{17}$$

$$\frac{\partial q}{\partial \tau_p^s} = \frac{-\int_0^t e^{-rx}p(x)dx}{c''(q)} < 0\ , \tag{18}$$

and

$$\frac{\partial q}{\partial \tau_q^s} = \frac{-(1-e^{-rt})}{rc''(q)} < 0\ . \tag{19}$$

C. *Age-Quality Neutral Tax Systems*

The effects of individual tax instruments on the producer's age/quality and quantity decisions have interesting implications for the design of multi-instrument tax schemes. All four taxes reduce the quantity supplied. Equivalently, the firm's first-order condition for quantity implies that for a fixed age/quality outcome, any change in the tax system that increases the effective per unit tax rate, $v(\boldsymbol{\tau})$, decreases quantity, $q(\boldsymbol{\tau})$.[9]

[9] Formally, let $\boldsymbol{V}(\boldsymbol{\tau})$ denote the set of all non-vanishing vectors $\boldsymbol{v}$ such that the directional derivative of t with respect to $\boldsymbol{\tau}$ in the direction $\boldsymbol{v}$ is zero. Then $\forall\ \boldsymbol{v} \in \boldsymbol{V}(\boldsymbol{\tau})$,

$$\frac{\partial q(\boldsymbol{\tau})}{\partial \boldsymbol{v}} = -\frac{1}{c''(q(\boldsymbol{\tau}))} \times \frac{\partial v(\boldsymbol{\tau})}{\partial \boldsymbol{v}}\ .$$

The varying effects of individual tax instruments on the profit-maximizing choice of quality allow us to create a class of tax schemes that result in the first-best quality level. The first-order condition for the age/quality choice (13) implies that there will be no age/quality distortion if and only if the tax system satisfies the condition

$$r\tau_q^r = p_s\tau_p^r + \tau_p^s p\left(t(\boldsymbol{\tau})\right) + \tau_q^s \,. \tag{20}$$

There are three possible two-tax systems with positive tax rates that do not distort the first best wine age:

(1) retail taxes satisfying $\tau_q^r = p_s\tau_p^r / r$, so that $\boldsymbol{\tau}_1 = \tau_p^r\left[1 \quad p_s/r \quad 0 \quad 0\right]^\top$ and

$$v_1 \equiv v(\boldsymbol{\tau}_1) \equiv e^{-rt^*}\left(rp(t^*) + p_s\right)\tau_p^r/r\,;$$

(2) volumetric taxes satisfying $\tau_q^r = \tau_q^s / r$, so that $\boldsymbol{\tau}_2 = \tau_q^s\left[0 \quad 1/r \quad 0 \quad 1\right]^\top$ and

$$v_2 \equiv v(\boldsymbol{\tau}_2) \equiv \tau_q^s / r \text{ ; and}$$

(3) volumetric retail tax and ad valorem storage tax satisfying $\tau_q^r = p(t^*)\tau_p^s / r$, so that $\boldsymbol{\tau}_3 = \tau_p^s\left[0 \quad p(t^*)/r \quad 1 \quad 0\right]^\top$ and

$$v_3 \equiv v(\boldsymbol{\tau}_3) \equiv \tau_p^s\left[e^{-rt^*}p(t^*)/r + \int_0^{t^*} e^{-rx}p(x)dx\right].$$

In each case the effective tax rate v is linearly increasing in the other tax rate used to balance the volumetric retail tax to maintain age/quality neutrality. Therefore, an increase in each of these taxes increases v and decreases q.

Now consider the relationship between tax rates and tax revenues for tax schemes that maintain age/quality neutrality. It follows from the definition of tax revenue, $R(\boldsymbol{\tau}) = v(\boldsymbol{\tau})q(\boldsymbol{\tau})$, that

$$\frac{\partial R(\boldsymbol{\tau})}{\partial \boldsymbol{\tau}} = \frac{\partial v(\boldsymbol{\tau})}{\partial \boldsymbol{\tau}} q(\boldsymbol{\tau}) + v(\boldsymbol{\tau})\frac{\partial q(\boldsymbol{\tau})}{\partial \boldsymbol{\tau}} \,. \tag{21}$$

Thus, for all $\boldsymbol{v} \in \boldsymbol{V}(\tau)$,

$$\begin{aligned}\frac{\partial R(\boldsymbol{\tau})}{\partial \boldsymbol{v}} &= q(\boldsymbol{\tau}) \times \frac{\partial v(\boldsymbol{\tau})}{\partial \boldsymbol{v}} - \frac{v(\boldsymbol{\tau})}{c''(q(\boldsymbol{\tau}))} \times \frac{\partial v(\boldsymbol{\tau})}{\partial \boldsymbol{v}} \\ &= \left(\frac{c''(q(\boldsymbol{\tau}))q(\boldsymbol{\tau}) - v(\boldsymbol{\tau})}{c''(q(\boldsymbol{\tau}))}\right) \times \frac{\partial v(\boldsymbol{\tau})}{\partial \boldsymbol{v}}.\end{aligned} \tag{22}$$

Hence, maintaining age neutrality while increasing the tax rates in each two-tax system results in an increase, no change, or a decrease in tax revenue if and only if $c''\left(q(\boldsymbol{\tau})\right)q(\boldsymbol{\tau}) - v(\boldsymbol{\tau}) \gtreqless 0$. Since $c''(q) > 0$ by assumption, for all cost functions that satisfy $\lim_{q\to 0} c''(q)q = 0$ the left-hand-side of this condition is strictly positive at $\boldsymbol{\tau} = \mathbf{0}$ and $q = q^*$, eventually vanishes as v increases, and then becomes negative as v increases further and quantity decreases.

D. *Tax Equivalence of the Two-Tax Age-Neutral Systems*

We establish tax equivalence among the three two-tax age-neutral systems by deriving relationships that equate each pair of effective per unit tax rates. With no age/quality distortion, this relationship ensures that for any pair of tax equivalent systems, the quantity distortion and the tax revenue generated will be the same across tax schemes. Using the expressions for v_1, v_2 and v_3 defined in the previous subsection, it is simple to show that the per unit taxes are equal, $v_1 = v_2 = v_3$, if and only if the periodic payments from an associated perpetual annuity for each of τ_q^s, τ_p^r, and τ_p^s are equal, or

$$\tau_q^s = \tau_p^r e^{-rt^*}\left[rp(t^*) + p_s\right] = \tau_p^s\left[e^{-rt^*}p(t^*) + r\int_0^{t^*} e^{-rx}p(x)dx\right], \tag{23}$$

where, given the restriction to two taxes at any one time, $\tau_q^s > 0$ only in the first case, $\tau_p^r > 0$ only in the second case, and $\tau_p^s > 0$ only in the third age neutral two-tax case, respectively.

These conditions are intuitively appealing. Consider the first expression. The volumetric storage tax is paid every period between production and sale, and is based on quantity rather than value. The net effect here of balancing a volumetric retail tax against a volumetric storage tax is a tax scheme that is equivalent to paying the storage tax τ_q^s on each unit of wine in perpetuity.

Now consider the second expression. Because retail taxes are paid once after t^* time periods have elapsed and because there is no age distortion, $p'(t^*) = rp(t^*) + p_s$. Hence, the net effect of balancing a volumetric retail tax against an ad valorem retail tax to achieve age neutrality is a tax system that is equivalent to paying the tax $\tau_p^r e^{-rt^*}p'(t^*)$ on each bottle of wine in perpetuity.

Finally, consider the third expression. The first term reflects that the volumetric retail tax is delayed for t^* periods, and is only paid once. The second identifies the instantaneous per period effects of the ad valorem storage tax.

Thus, we have complete tax equivalence among three age-neutral two-tax systems. If we normalize on the ad valorem retail tax, then for any $\tau_p^r > 0$ the tax-equivalent systems are defined by

$$\boldsymbol{\tau}_1 = \tau_p^r \times [1 \quad p_s / r \quad 0 \quad 0]^{\top}, \tag{24}$$

$$\boldsymbol{\tau}_2 = \tau_p^r e^{-rt^*}[rp(t^*) + p_s] \times \begin{bmatrix} 0 & 1/r & 0 & 1 \end{bmatrix}^\top, \tag{25}$$

$$\boldsymbol{\tau}_3 = \left(\frac{\tau_p^r e^{-rt^*}[rp(t^*) + p_s]}{e^{-rt^*} p(t^*) + \int_0^{t^*} e^{-rx} p(x)dx} \right) \times \begin{bmatrix} 0 & p(t^*)/r & 1 & 0 \end{bmatrix}^\top. \tag{26}$$

V. Optimal Revenue Generating Tax Systems

From the first order condition for quality, if the second order condition is met, then $t(\boldsymbol{\tau}) \gtreqless t^*$ if and only if $-\tau_q^r r + \tau_p^r p_s + \tau_p^s p\left(t(\boldsymbol{\tau})\right) + \tau_q^s \lesseqgtr 0$. Differentiating the effective tax rate with respect to t results in

$$\frac{\partial v}{\partial t} = e^{-rt} \left(\frac{-\tau_q^r r + p_s + \tau_q^s + \tau_p^s p(t)}{1 - \tau_p^r} \right). \tag{27}$$

This shows that the effective tax rate increases, remains unchanged, or decreases with age/quality as the age of wine at the date that it is sold is less than, equal to, or greater than the first-best age of wine. Since there is no interaction between quantity and quality, tax revenues achieve a relative maximum with respect to age/quality at the first-best age level. In this sense, the age neutral tax systems analyzed in the previous section play a pivotal role in our analysis of optimal tax systems.

Any change in the tax regime that keeps tax revenue constant satisfies

$$\begin{aligned} 0 = dR &= \frac{\partial R}{\partial \boldsymbol{\tau}'} d\boldsymbol{\tau} \\ &= v \frac{\partial q}{\partial \boldsymbol{\tau}'} d\boldsymbol{\tau} + q \frac{\partial v}{\partial q} \frac{\partial q}{\partial \boldsymbol{\tau}'} d\boldsymbol{\tau} + q \frac{\partial v}{\partial t} \frac{\partial t}{\partial \boldsymbol{\tau}'} d\boldsymbol{\tau} \\ &= \left(v - c''(q) q \right) dq + q \frac{\partial v}{\partial t} dt. \end{aligned} \tag{28}$$

Therefore, the trade-off between quality and quantity along an iso-revenue locus has the slope

$$\left. \frac{dt}{dq} \right|_R = \frac{\left[c''(q) q - v \right] (1 - \tau_p^r)}{e^{-rt} \left[-\tau_q^r r + \tau_p^r p_s + \tau_p^s p(t) + \tau_q^s \right]}. \tag{29}$$

Recalling that $c''(q) > 0 \ \forall \ q \geq 0$ and assuming that $\lim_{q \to 0} c''(q) q = 0$, the numerator of (29) is positive for small effective tax rates. As the tax rate increases, quantity decreases, and the numerator of (29) becomes smaller, and eventually becomes negative.[10] On the other hand, the denominator is positive if $t < t^*$, zero if $t = t^*$, and negative if $t > t^*$.

These two properties imply that the revenue function for any tax system has the same general properties as the function depicted in Figure 2, which illustrates a two-tax system with an ad valorem retail tax and volumetric retail tax. Figure 2 plots tax revenues as a function of quantity q and quality t.[11] The tax revenue function has a unique interior maximum $R(t^*,q')$; the argmax levels t^* and q' are in turn functions of the values of the tax instruments. The first-best levels of quality and quantity are defined by (t^*,q^*).

Figure 3 is a contour graph of the revenue function plotted in Figure 2. Understanding the shape of these contours, or iso-revenue curves, aids us in understanding our equivalence result. To investigate Figure 3, we will trace a single iso-revenue curve, starting from a point (t^*,q), where $q^*>q>q'$. At this point, the iso-revenue curve has a zero slope. As quantity and quality both decline, moving to the left along the curve – the effective tax rate, v, must increase to support these declines – its slope becomes positive and increasingly steep, then infinite and then negative. As we progress along the same curve, increasing quality but continuing to decrease quantity, we reach the age-neutral quality t^*, at which point the iso-revenue curve again has a zero slope. That is, there are two combinations of tax rates that will induce the producer to provide the first-best level of quality and any positive level of tax revenue below $R(t^*,q^*)$. Continuing further along this same iso-revenue curve by increasing both quality and quantity, we reach another point with an infinite slope where quality is greater than the first best choice, but quantity is lower. Finally by increasing quantity and decreasing quality from this point onward we move along the iso-revenue curve back to our starting point.

Thus, Figure 3 illustrates three important points regarding the relationships among tax rates, tax revenues, quality and quantity. First, every iso-revenue curve below the maximal one includes two combinations of tax rates that result in the first-best level of quality. Second, any positive tax reduces quantity below its first-best level q^*. Finally, the revenue-maximizing combination of tax rates results in the first-best level of

[10] Available empirical evidence suggests that in practice the numerator of (29) is positive. Define δ as the proportion of the total value of wine sold that is taken by all governments in the form of taxes, so that $v = \delta p$. Then the numerator of (31) is positive, zero or negative as the price elasticity of quantity supplied, $\varepsilon_p^q = p/\left(c''(q)q\right)$, is less than, equal to, or greater than $1/\delta$. Wine taxes currently account for roughly 25% of the total value of the wine sold worldwide, so that $1/\delta \approx 4$. Information contained in James and Alston (2002) implies that the supply elasticity of wine is something less than 2. Taken together, these two conditions suggest that the numerator of (29) is strictly positive, at least for the typical current tax system imposed on the wine market.

[11] The actual tax rates generating each of these points are not reported in the figure. Figures 2-4 are created using the same parameter values and functional forms. For reasons that will become clearer later, the figures allow for positive values of only two taxes: the retail ad valorem tax and retail volumetric tax. The price function $p(t)$ has the following form: $p(t) = p(0)e^{-\alpha t} + p_{\max}\left(1 - e^{-\alpha t}\right)$ where $p(0) = 4$ and $p_{max} = 30$. The cost function $c(q)$ is $c(q) = q^2/2$. The cost of storage $p_s = 0.1$. The growth rate is $\alpha = 0.082433$.

Figure 2
Tax Revenue as a Function of Quality and Quantity

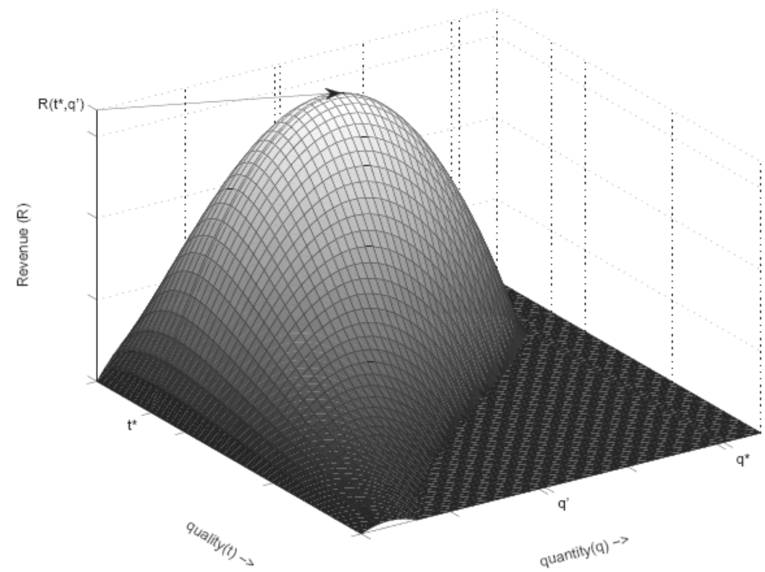
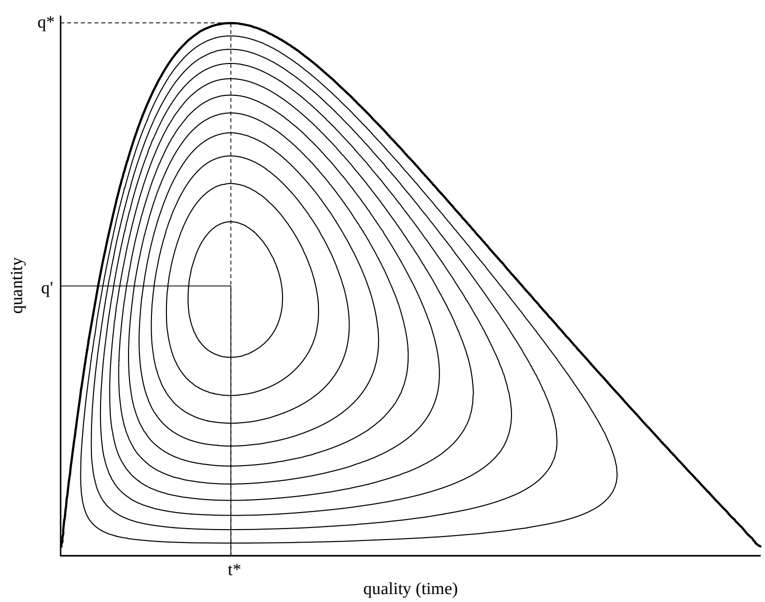
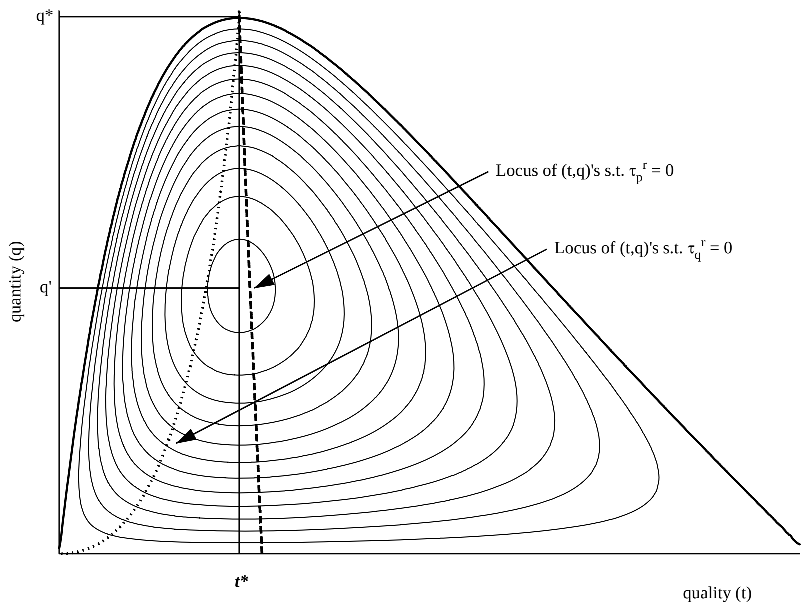


Figure 3
Contour Graph of the Tax Revenue Function



quality t^* and the quantity $q' < q^*$. Figure 4 addresses the relationship between tax rates and tax revenues. It reproduces the iso-revenue curves from Figure 3 and includes two additional lines. The dotted line beginning in the lower left-hand corner and ending at (t^*,q^*) plots t-q pairs that result from varying the ad valorem retail tax when the volumetric retail tax is zero. The slightly sloped line that begins to the right of the $t = t^*$ line and ends at (t^*,q^*) plots the t-q pairs that result from varying the volumetric retail tax rate when the ad valorem retail tax rate is zero.

Figure 4
Zero-Tax Loci and Iso-Revenue Curves



To provide some intuition for how each tax affects the producer's choice of t and q, we consider what happens when we move along each zero tax curve. Starting from the point (t^*,q^*), holding the ad valorem retail tax constant at zero, an increase in the volumetric retail tax decreases the profit-maximizing q but increases the profit-maximizing t, reflecting the fact that the volumetric retail tax subsidizes aging. Initially this increase in the per-unit tax rate raises tax revenues, but once the volumetric tax becomes sufficiently large, the effects of reducing the quantity produced and delaying the date at which the tax is received begins to dominate and tax revenues begin to decline. We now return to the point (t^*,q^*) and move down the zero volumetric tax line by increasing the ad valorem retail tax. In this case the profit-maximizing t and q both decline, as the ad valorem tax reduces the incentives to produce both quantity and quality. Again, tax revenues initially increase with the ad valorem tax rate, but for a sufficiently high ad valorem tax the effect of reducing the quantity produced dominates the increase in per-unit rates.

These results do not depend on the assumption that tax rates are non-negative. A formal comparative statics analysis readily verifies that a full range of feasible positive tax revenues can be generated with any two-tax system that includes a volumetric retail tax. These revenues also can be supported by subsidies and at least as high quality wine as the firm's first best no-tax quality level.

Summarizing, we conclude the following based on this analysis: first, the firm's first best with respect to quality is a relative maximum of tax revenues for all quantity choices; second, every positive tax revenue can be supported by a two-tax system that accommodates the first best quality outcome; and third, if the tax system results in a quality outcome that is less than the firm's first-best quality choice then more tax revenue can be raised with a smaller quantity distortion and the complete elimination of the quality/age distortion.

VI. Conclusions

We have analyzed the supply side effects of taxes on the quantity and quality of goods whose market values accrue with age, such as wine. We considered four types of taxes: a volumetric retail tax, an ad valorem retail tax, a volumetric storage tax and an ad valorem storage tax. Our analysis of the effects of these taxes on the profit-maximizing choice of quality for a representative winery found the following: an increase in the volumetric retail tax increases quality, so that the basic Alchian-Allen effect holds. However, an increase in the volumetric storage tax decreases quality, as does an increase in the ad valorem storage tax. When quality is a function of time, the effect of an increase in the ad valorem retail tax on quality is indeterminate. Increases in any of the four taxes reduce the quantity of wine produced.

Because these taxes have different effects on wine quality, multi-instrument tax systems have useful properties. We demonstrated that a two-tax system that includes a volumetric retail tax and any one of the three other taxes – an ad valorem retail tax, an ad valorem storage tax, or a volumetric storage tax – spans the quality/revenue feasible set. We derived tax equivalence for the three possible two-tax systems, and demonstrated that the producer's first-best quality is a local tax revenue-maximizing choice for any feasible tax system. Moreover, any tax system that reduces quality relative to the market equilibrium with no taxes could have its tax rates modified in a manner that would increase tax revenues and reduce the quality distortion without increasing the quantity distortion.

Our analysis contributes to the broader economic literatures regarding optimal taxation and the Alchian-Allen effect by examining the effects of taxation of a good with time-dependent quality. We establish that when quality is time-dependent a tax system can be structured so that the first-best quality level can be achieved in conjunction with the maximum amount of tax revenue. We also establish that the effects of ad valorem and volumetric taxes are more complex in this setting than under the classic Alchian-Allen dichotomy. First, an ad valorem retail tax has an indeterminate effect on quality, instead of always decreasing it. Second, both volumetric and ad valorem storage taxes reduce quality.

Apart from its contributions to the economic literature, our analysis has practical implications for policymakers and industry members. Perhaps the most important implication is that wine taxation need not reduce wine quality. In instances where that appears to be the case, policymakers could reduce the distortion by altering the relative values of the tax instruments. However, not all taxes associated with wine are wine-specific, so reducing the distortion in the wine market may increase distortions elsewhere. Accordingly, the scope for reducing the quality distortion may be limited in countries where general taxes, such as VAT, are a large share of total taxes on wine. A second implication of our analysis is that any tax system that includes a volumetric retail tax and at least one of the other three tax instruments we examine may potentially induce the first-best level of quality. Consequently, when comparing the performance of different tax systems for wine, no qualitative conclusions regarding their relative effects on quality can be reached ex ante; a quantitative evaluation is required. Furthermore, provided that an existing tax system includes a volumetric retail tax and/or includes subsidies there is no guarantee that altering the tax instruments included in the tax system will reduce any distortionary effect it has on quality; again, a quantitative analysis is required.

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