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# Economic implications of a virus prevention program in deciduous tree fruits in the US

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**Abstract**

Viral diseases in fruit trees present a potential danger that could injure the fruit industry, the planting stock industry (nurseries), and consumers in the United States and abroad. Currently, the US has a virus protection program (VPP) that serves to minimize the spread of viral diseases. This paper reports research estimating the economic consequences of the loss of the program on nurseries, growers and consumers. The potential economic losses are a measure of the value of the existing program. The paper focuses on apples, sweet cherries, and Clingstone peaches.

The effects of a loss of a VPP on nurseries would include direct and indirect losses from viral diseases in the form of lower quantity and quality of planting stocks. Fruit growers would be affected by reduced plant growth and fruit yield. Consumers would be affected by higher prices and reduced quantity of fruit.

We measured benefits of the virus prevention program as changes in consumer and producer surpluses. Empirical estimates were made using the method of avoided losses. Benefit estimates to three economic sectors—nurseries (avoided change in producer surplus), producers (avoided change in consumer and producer surpluses), and consumers (avoided change in consumer surplus)—were calculated. Total benefits for all three sectors were approximately \$227.4 million a year, or more than 420 times the cost of the program. Our analysis utilizes a method that might be used to evaluate other programs that prevent the introduction of plant diseases.



*Keywords:* Virus; Losses; Economic evaluation; Fruit growers; Nursery; Consumers

## 1. Introduction

Viral diseases cause economic losses through lower yields and reduced quality of plant products. Viral diseases in perennial crop plants are more dangerous than in annual crops. Viruses can remain latent, spreading through an orchard and inflicting damage, sometimes without the growers' knowledge. Latent infestations can produce small to moderate losses in fruit production (Agrios, 1997). Often growers can maintain the productivity of diseased orchards at a profitable level by cutting infected parts and replacing dead trees to control the spread of the virus. Sometimes, however, losses are severe, and an acute viral infection can require tree removal. Between orchards, viral diseases spread thorough vegetative propagation. In tree fruit husbandry two methods are used to control viral diseases: adoption of virus-free propagation materials and eradication of contaminated trees.

The literature reports different types of damages to fruit products. Damages include: unmarketable fruits (Reeves and Cheney, 1962), substantial reduction in yields (Tables 1 and 2), and extensive tree death (Stouffer and Smith, 1971). However, the damage caused may be less dramatic and still affect profits—reduced growth, lower yields or other adverse phenomena may exist at low levels but remain unobserved by growers.

Overall, viral infections have a greater effect on crop yields and fruit quality (deformation, and loss of flavors)

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Table 1
Yield reduction effects on apple production due to viral diseases

| Apple Cultivars | Virus strain | Yield reduction (%) | References |
|---|---|---|---|
| Golden delicious | Apple mosaic virus (AMV) | 46 | Baumann and Bonn (1988) |
| | AMV, rubbery wood disease agent (RW) | 21–67 | Baumann and Bonn (1988) |
| Golden delicious | RW | 46 | Wood (1978) |
| Golden delicious | Apple stem grooving virus (ASGV), apple stem pitting virus (ASPV) & apple chlorotic leaf spot virus (ACLSV) | 12 | Meijnske et al. (1975) |
| Golden delicious | ASGV, ASPV & ACLSV | 30 | van Oosten et al. (1982) |
| McIntosh | AMV | 9 | Zawadzka (1983) |
| McIntosh | RW | 8 | Zawadzka (1983) |
| Red delicious | AMV | 42 | Zawadzka (1983) |
| Red delicious | RW | 20 | Zawadzka (1983) |

Table 2
Yield reduction effects on sweet cherry and clingstone peach production due to viral diseases

| Fruit type and cultivar | Virus strain | Yield reduction (%) | References |
|---|---|---|---|
| Sweet Cherry cv. Van, Lambert, and Burlatt | Prunus Necrotic Ring Spot Virus (PNRSV), and Prune Dwarf Virus (PDV) | 19 | Albertini et al. (1993) |
| Clingstone Peach cv. Carson | PNRSV | 18 | Uyemoto et al. (1992) |
| " | PNRSV and PDV | 30 | Uyemoto et al. (1992) |
| cv. not specified | PDV | 30 in the 1st year; 80 after | Smith and Challen, (1977) |

than on vegetative growth. With the most virulent strains, yield losses can reach 98% (Nemeth, 1986). Other viruses do not cause such heavy losses, for example the Prunus necrotic ring spot virus (PNRSV) is responsible for growth reductions that vary from 12% to 33% (Pine, 1964; Saunier, 1970).

Some viral infections cause incompatibility between rootstock and cultivar affecting yields of nurseries. A low percentage of successfully grafted trees in nurseries may be attributed to viral infection (Nemeth, 1986). For instance, reductions in bud survival have been reported from 20% up to 67% (Baumann and Bonn, 1988; Schimmelpfeng and Böhm, 1966). The degree of impact depends upon the pathogen or its strain in combination with fruit type, cultivar, rootstock, nutrient supply, and tree age.

Virus testing of imported propagation materials into the US has been the most important measure used to prevent the introduction and spread of unwanted viruses. However, financial support for the program presents a challenge because of the characteristics of the industry. The testing and use of virus-free materials has benefits for each of the three very different sectors involved (nurseries, growers, and consumers). The three sectors differ in how they benefit, how they perceive the benefits, and how they may be assessed for the benefits of a virus protection program (VPP). Growers and nurseries benefit from the service because of reduced virus yield losses and the absence of a need to invest in other virus control measures. They also benefit from reduced risk of spread of the virus. Consumers benefit from lower prices and more abundant fruit. Their major benefit is an invisible, avoided price increase in the fruit products, which would otherwise lead to a reduction in consumer welfare.

The only facility in the US that tests for viruses in fruit trees is a public agency, the National Research Support Project 5 (NRSP-5). The NRSP-5, located at the Washington State University Irrigated Research and Extension Center in Prosser, WA, is charged with responsibility for the VPP of deciduous fruit trees for the entire nation. NRSP-5 is responsible for providing sources of deciduous fruit tree propagation materials free of virus and virus-like diseases. NRSP-5 also develops, evaluates, and implements new technologies for virus detection and the elimination of viruses and virus-like agents from commercially important cultivars. In the year 2000, NRSP-5 operating costs were $541,142. NRSP-5 is supported primarily thorough public funds (75% of the operating costs), but it also receives some direct, private funds. Fees are charged to nurseries for propagation materials (16% of the total expenses of NRSP-5). Some contributions from the fruit industry also partially support the program (9%). Growers and consumers do not contribute directly to finance the program.

Prior to the establishment of NRSP-5, viruses abounded in every fruit-growing region in the US. The success of this project has resulted in a dramatic reduction in the incidence of viral diseases (NRSP-5, 1997). If NRPS-5 were eliminated, a number of consequences would follow. Virus diseases would become widely diffused, causing direct losses to growers and nurseries. The introduction of virus-free cultivar(s) would not be guaranteed, damaging the competitiveness of the US fruit industry (for example, by restricting access to specific markets). The success of NRSP-5 forms the basis for our estimates on the program's value.

This study estimates the net economic benefits of NRSP-5 for the three major sectors served by the program. Our purpose is to demonstrate the derived benefits and determine whether the program is cost-effective. Due to missing data on virus losses and the extent of spread at the orchard and nursery level, a framework was built to estimate expected losses for growers and nurseries in the case in which the VPP would be eliminated, leading to widespread virus infections. Our study is an attempt to estimate the impact of virus diseases on tree fruit production. Most existing estimates of losses caused by viruses have been reported on annual crops, such as barley (Carroll, 1980), lettuce (Yudin et al., 1990), soybeans (Damsteegt et al., 1990), rice (Abo et al., 1998), and tomatoes (Taylor et al., 2001).

## 2. Models and methods

From an economic perspective, the theoretically efficient support for a VPP occurs when the marginal benefit equals marginal program costs. Economic theory further suggests a need to account for costs and benefits under conditions of uncertainty and over time. The VPP controls the spread of dangerous viral diseases that have consequences that are hard to predict and that spread by propagation over several years in the production cycle.

We developed comprehensive models of the contributing VPP benefits to the three separate economic sectors. The empirical estimates were based on restricted models because data for comprehensive measurements were lacking. Therefore, the empirical section used commonly accepted economic methods to model the most important impacts on each sector. Analyses of the benefits were conducted for apples, sweet cherries and Clingstone peaches at the nursery, grower, and consumer levels. In the next section we describe the method used to obtain an estimate of the expected yield losses at both nursery and grower levels. Then, we examine the fruit and the planting stock markets.

### 2.1. Expected yield losses due to viruses

There are a limited number of estimates of expected yield losses from the diffusion of viruses in the fruit production and for the planting stock sectors in the published literature. To obtain such estimates we developed a framework to estimate the expected yield losses in the absence of VPP. The framework accounts for the potential spread and damage that may be expected from an extensive diffusion of virus diseases.

Expected losses depend on: (1) the rate of loss on affected acreage; (2) the proportion of acreage affected by the infestation; and (3) the probability of infection by the virus. Therefore, the expected yield losses were estimated as a percent of reduction in total yield ($\lambda$) by the following equation:

$$\lambda = \sum_{ij} d_i s_j x_{ij}, \qquad (1)$$

where $d_i$ is the crop losses (percent of losses in areas with viral diseases); $s_j$ the extent of spread (percent in acreage of orchards or tree fruit nurseries with viruses); and $x_{ij}$ the conditional probability of the event on the extent of spread.

Yield reductions for fruit production reported in the literature vary from 12% to 67% (Meijnske et al., 1975; Baumann and Bonn, 1988) for apples, 18–30% (Uyemoto et al., 1992) for Clingstone peaches, and 19% (Albertini et al., 1993) for sweet cherries. In our framework, the likely level of losses from the diffusion of viral diseases in the fruit production sector is 20% or lower. Higher losses are unlikely to occur because, if the infestation caused severe damage, growers would remove the trees and/or orchard.

In nurseries, the most common loss due to viruses is a reduction in the grafting of finished trees. This loss can range from 20% to 67% (Baumann and Bonn, 1988; Nemeth, 1986). A nursery would be unlikely to accept losses greater than 20%; if 20% losses were realized, the nursery would be forced to seek other budwood sources. Therefore, in our framework the categories of losses of 20% or lower were assumed for nurseries, which is similar to the maximum level set in the fruit production level. Specifically, we used the following categories of losses in our calculations: (1) no losses (0%); (2) low (5%); (3) medium-low (10%); (4) medium-high (15%); and (5) high (20%) (Table 3).

The next component in our framework was the extent of spread. We assumed five scenarios of the extent of spread expressed in percentage of the total acreage: (1) 1%; (2) 10%; (3) 20%; (4) 29%; and (5) 40%. The final component of the framework is to assign a conditional probability of loss to each category of crop losses (subject to the extent of spread—Table 3). A grower could have more than one infection at a time. Therefore the loss events are assumed to be independent, but not mutually exclusive. For example, a grower could face three events: (1) 5% damage in 1% of the area ($x_{11} = 48\%$); (2) 5% damage in 10% of the area ($x_{12} = 47\%$), and (3) 10% damage in 20% of the area ($x_{23} = 25\%$). Given that they are all occurring

Table 3
Conditional probabilities of virus's crop losses on the extent of spread in deciduous fruit

| Crop losses ($d_i$) | Extent of spread ($S_j$) (scope level) | | | | | |
|---|---|---|---|---|---|---|
| | Low, 1% | Medium–low, 10% | Medium, 20% | Medium–high, 29% | High, 40% | |
| No losses, 0% | 0% | 12% | 32.95% | 47.99% | 79.9898% | |
| Low, 5% | 48% | 47% | 35% | 32% | 15% | |
| Medium–low, 10% | 40% | 32% | 25% | 15% | 5% | |
| Medium–high, 15% | 10% | 8% | 7% | 5% | 0.01% | |
| High, 20% | 2% | 1% | 0.05% | 0.01% | 0.0002% | |
| Conditional probability on the extent of spread | 100% | 100% | 100% | 100% | 100% | Total Expected Losses $\sum d_i s_j x_{ij} = 3.46\%$ |

Cell values are $x_{ij}$ = conditional probabilities of loss on the indicated spread.

simultaneously, the probability of occurrence of the combined events is the product of each event's probability. In this case the combined probability amounts to 0.001%.

The framework allows for the highly likely scenario that more than one virus infestation occurs at any given time. The method used was based on an assumption of combining individual types of infections to obtain an overall value of loss. The assumptions created a hypothetical scenario with viral disease endemic at the national level. This method predicts expected losses considering the possible spread of virus diseases. Events with devastating infections and losses were excluded in the single event analysis, although they were included as combined events.

### 2.2. Welfare changes for consumer and growers due to viruses

Based on the expected yield losses we can calculate producer (growers) and consumer surplus changes. We assumed linear supply and demand functions for the fruit market, where consumers drive the demand and growers affect the supply. The demand function was assumed to be constant, but a shift of the supply curve was allowed. If VPP did not exist, viruses would become established within orchards and spread between orchards. This would cause a decrease in the quantity produced and an increase in costs for growers that will shift the supply function upward (Fig. 1). We assumed that the parallel shift upward of the initial supply curve $S_0$ was the consequence of the changing cost of production and reduced quantity produced. This assumption can be justified by hypothesizing that the increase in costs (work needed to replace plants or to eradicate infected parts) is proportional to the yield losses caused by viruses. Also, we implicitly assumed that imports did not fill the void for the demand for the fruits.

The consumer and producer losses were calculated following the methodology suggested by Alston and Norton (1995). We considered an upward shift in the supply curve, $S_0$, proportional to the market price as a consequence of the yield losses. This shift would cause higher market prices. Increased prices would create changes in consumer and producer surplus or economic well being.

The change in consumer surplus is represented in Fig. 1 by the difference between the triangle $aE_1P_1$ and the triangle $aE_0P_0$. The result is the area expressed by the sum of the rectangle $P_1E_1bP_0$ and the triangle $E_1E_0b$. Detailed algebraic steps to obtain the formula for the change in consumer surplus are reported in the appendix. The formulation used to calculate the loss in consumer surplus is shown as follows:

$$\Delta CS = -\lambda P_0 Q_0 (1 - 0.5\lambda)/\varepsilon_D, \quad (2)$$

where $\Delta CS$ is the change in consumer surplus; $P_0$ the price without viruses; $Q_0$ the production without viruses; and $\varepsilon_D$ the demand elasticity.

Similarly, the variation in producer surplus in Fig. 1 corresponds to difference between the triangle $P_1E_1I_1$ and the triangle $P_0E_0I_0$. Because of the parallel shift assumed, the two triangles $P_1E_1I_1$ and $dcI_0$ are equal, so that the loss in producer surplus is the lost surplus, triangle $P_0E_0I_0$, minus the gain in surplus represented by triangle $P_1E_1I_1$, or equivalently, triangle $dcI_0$. Therefore, the change in producer surplus can be expressed as the sum of the rectangle $P_0bcd$ and the triangle $bE_0c$. Using a calculation similar to that used for the consumer surplus calculation, we can derive the algebraic expression to calculate the change in producer surplus (appendix) as follows:

$$\Delta PS = \lambda P_0 Q_0 (1 - 0.5\lambda)/\varepsilon_S, \quad (3)$$

where $\Delta CS$ is the change in producer surplus; and $\varepsilon_S$ the supply elasticity.

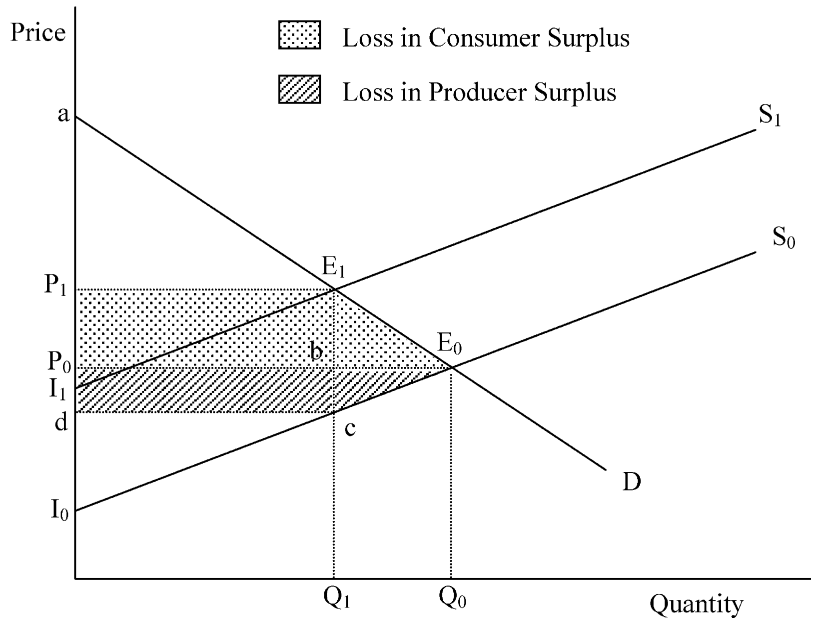


Fig. 1. Graphical analysis of the change in consumer and producer surplus in one market.

To calculate both consumer and producer surplus we used values of demand and supply elasticities reported in the literature. The demand elasticities of −0.374 (Roosen, 1999) for apples, −0.48 (George and King, 1971) for Clingstone peaches, −0.558 for California sweet cherries, and −0.381 for the other cherries in Washington, Michigan and Oregon (Schotzko et al., 1989) were used. Only the supply elasticity for apples was available, 0.713 (Roosen, 1999), and it was used for the other fruits since they are all tree fruits with some similarities as to nonbearing years during establishment of orchards and expected life of trees.

### 2.3. *Welfare changes for nurseries and growers due to viruses*

The planting stock market would be affected by a spread of viruses. The spread of viruses would create losses in the nurseries' production of planting stock that would influence prices of the grafted trees sold. In this analysis we used an analogous method to that for the fruit market.

The shift in the nursery supply curve caused by the losses due to viruses is similar to the one described before for the fruit market. In addition, all the assumptions considered for the fruit market hold for the planting stock market as well. The formulations used to calculate the consumer (growers) and producer (nurseries) are the same.

The only information regarding losses for nurseries reported in the literature was about the reduction in viable buds (Schimmelpfeng and Böhm, 1966; Baumann and Bonn, 1988). In this analysis it was assumed that the nurseries were subject to losses in grafting that lead to losses in the quantity of grafted trees supplied to the market. In the same way as in the fruit industry, the same category of losses of planting stock (0%, 5%, 10%, 15%, and 20%) and extents of spread (1%, 10%, 20%, 29%, and 40%) were analyzed. The probability value attributed to each event was different (Table 4). As stated before, those events are independent but not mutually exclusive.

This framework was used to determine losses due to viruses for the nursery industry in absence of a VPP. The planting stock prices of $3.60, $3.90, and $5.50 for apples, Clingstone peaches, and sweet cherries, respectively, were used in the analysis (Vossen et al., 1994; Hasey et al., 1998; Grant et al., 1999). Information on the elasticity of demand and supply for planting stock material was not available in the literature. As a proxy, the same elasticity values as were used in the fruit market were used in the case of the nursery sector.

## 3. Results

### 3.1. *Benefits for growers*

Growers benefit from the VPP in the form of losses not incurred because of the effect of the VPP. These losses include lost sales in the fruit market which are measured by the losses in producer surplus and losses from shortages and higher costs of planting materials in the stock market which are measured as a loss in consumer surplus (because growers are consumers of plant materials). The total avoidable losses due to viruses for US apple fruit and planting stock industries

Table 4
Occurrence of crop losses and extent of spread for viral diseases in the planting stock sector in the scenarios considered

| Crop losses ($d_i$) | Extent of spread ($S_j$) (scope level) | | | | | |
|---|---|---|---|---|---|---|
| | Low 1% | Medium–low, 10% | Medium, 20% | Medium–high, 29% | High, 40% | |
| No losses, 0% | 16.99% | 43.995% | 59.4999% | 71.8995% | 79.9898% | |
| Low, 5% | 50% | 35% | 25% | 20% | 15% | |
| Medium–low, 10% | 30% | 20% | 15% | 8% | 5% | |
| Medium–high, 15% | 3% | 1% | 0.5% | 0.1% | 0.01% | |
| High, 20% | 0.01% | 0.005% | 0.001% | 0.0005% | 0.0002% | |
| Conditional probability on the extent of spread | 100% | 100% | 100% | 100% | 100% | Total Expected Losses $\sum d_i s_j x_{ij} = 2.06\%$ |

Cell values are $x_{ij}$ = conditional probabilities of loss on the indicated spread.

Table 5
Avoidable losses to growers, nurseries, and consumers from a viral disease reduction of apple, sweet cherry, and clingstone peach ($1000)

| Industry | Avoidable losses to growers | Avoidable costs to nurseries | Consumer surplus reduction |
|---|---|---|---|
| Apple | 63,406.7 | 417.7 | 119,361.6 |
| Sweet cherry | 11,191.5 | 48.2 | 19,138.1 |
| Clingstone peach | 5580.9 | 22.5 | 8240.3 |
| Total for selected sectors | 80,179.1 | 488.4 | 146,740.0 |

for growers were estimated at $63,406,789 (Table 5). Likewise avoidable losses estimates for the US sweet cherry and Clingstone peach industries were $11,191,460 and $5,580,877, respectively, with an overall total of $80,179,126 for all three tree crops fruit and planting stock industries.

### 3.2. Benefits for nurseries

Avoided losses for nurseries involved in the production of apple, sweet cherry and Clingstone peach trees were estimated at $488,430 (Table 5). Avoidable costs in apple tree production alone totaled $417,715. The avoided losses in the production of sweet cherry and Clingstone peach trees were lower compared to apple tree production (Table 5). Avoidable losses for sweet cherry planting stock production totaled $48,202. Viral diseases in the production of Clingstone peach trees could potentially negatively affect nurseries costs by $22,513.

### 3.3. Benefits for consumers

If viral diseases in US orchards cause decreased production of 3.46% (Table 3), it would result in a total consumer's surplus reduction of $146,740,252 (Table 5). This cost to society is mainly due to the misallocation of resources, to growers' higher per unit costs and to higher retail prices for the consumers. Note that the losses to consumers from higher prices are partly offset by higher returns to growers. For this study, producer gains from higher prices were accounted for in the calculation of producer net losses.

The reduction in consumer surplus to fruit consumers in case of viruses' losses for apples is estimated to be equal to $119,361,635. The estimated reductions in consumer surplus for the sweet cherry and Clingstone peach markets were not as large. In the sweet cherry market and Clingstone peach market consumer surplus would be reduced by $19,138,125 and $8,240,252, respectively, if a VPP did not exist (Table 5).

## 4. Discussion

The potential danger from viral diseases in fruit orchards in the US is enormous. From 1940 to 1950 tree and crop losses were wide spread. NRSP-5's work has effectively limited these losses in the US fruit industry. In this study, avoided costs were used to estimate program benefits in three economic sectors: nurseries (avoided increased production costs), producers (avoided yield reductions), and consumers (avoided price increases).

Benefits from the NRSP-5 program were estimated at \$80,179,126 to growers, \$488,430 to nurseries, and \$146,740,012 to consumers for a total of \$227,407,569. These benefits clearly and considerably outweigh program's costs of \$541,142 in 2000. Based on these figures the ratio of benefits to costs is greater than 420 to 1. The exact numerical results depend on some of the specific numerical assumptions (concerning, for example, prices, elasticities). The benefit-cost ratio might be a little different if alternative assumptions were made. However, in view of the large margin by which benefits exceed costs, any small changes in assumptions would not affect the substantive results.

In addition to the benefits estimates, the analysis evokes a number of interesting observations. In particular, it is ironic that the nursery sector, which benefits the least in absolute dollars, is the only sector that pays directly into the program. However, they benefited through higher grafting and quality in finished trees. It is for that reason the nursery sector has been willing to pay.

While consumers and growers have much greater potential benefits, they have an incentive to pay or support such a program through public funds generated through taxes. To consumers, the VPP represents an intermediate cost. If costs were to increase because of viral diseases, consumers would either pay the higher price or forego the purchase of the fruit.

The problem is most acute at the critical grower level. Each grower has incentive to invest in virus protection only to protect him or herself. Yet, the overall industry gains enormously from reduced infection. Left to growers, there would be a weak viral protection program at best—and the history of the industry supports this hypothesis. However, our results clearly show that benefits to growers far exceed the cost of the program.

In summary, since the benefits are more than 420 times the direct costs of the VPP, the program should be continued (assuming only that cost efficiency is a desirable goal for all the society). Given the difficulty in directly charging growers and consumers for their full benefits from the program, if a VPP is to exist, public support of the program will remain necessary.

## Appendix

This appendix provides all the algebraic steps necessary to derive the expressions for the change in consumer and producers surplus.

Consider $\lambda \geqslant 0$, and the change in quantity expressed as $\Delta Q = Q_0 - Q_1 = \lambda Q_0$.

Using the arc elasticity of demand, $\varepsilon_D = (\Delta Q/\Delta P)(P_0/Q_0)$, we can calculate the new equilibrium price:

$$\Delta P = (\Delta Q/\varepsilon_D)(P_0/Q_0),$$
$$P_0 - P_1 = (\lambda Q_0/\varepsilon_D)(P_0/Q_0) = \lambda P_0/\varepsilon_D,$$
$$P_1 = P_0 - \lambda P_0/\varepsilon_D = P_0(1 - \lambda/\varepsilon_D).$$

Assuming a parallel shift of the supply curve, similarly we can calculate the value of $d$ using the arc elasticity of supply, $\varepsilon_S = (\Delta Q/\Delta P)(P_0/Q_0)$. In this case the change in price is equal to $\Delta P = P_0 - d$.

$$\Delta P = (\Delta Q/\varepsilon_S)(P_0/Q_0),$$
$$P_0 - d = (\lambda Q_0/\varepsilon_S)(P_0/Q_0) = \lambda P_0/\varepsilon_S,$$
$$d = P_0 - \lambda P_0/\varepsilon_S = P_0(1 - \lambda/\varepsilon_S).$$

The loss in consumer surplus ($\Delta CS$) is equal to the sum of the areas of the rectangle $P_1E_1bP_0$ and the triangle $E_1E_0b$ as follows:

$$\begin{aligned}\Delta CS &= (P_1 - P_0)Q_1 + 0.5(P_1 - P_0)(Q_0 - Q_1)\\ &= (-\lambda P_0/\varepsilon_D)(1 - \lambda)Q_0 + 0.5(-\lambda P_0/\varepsilon_D)\lambda Q_0\\ &= -\lambda P_0 Q_0(1 - 0.5\lambda)/\varepsilon_D.\end{aligned}$$

In the same way, the loss in producer surplus ($\Delta PS$) is equal to the sum of the areas of the rectangle $P_0bcd$ and the triangle $bE_0c$ that is equal to:

$$\begin{aligned}\Delta PS &= (P_0 - d)Q_1 + 0.5(P_0 - d)(Q_0 - Q_1)\\ &= (\lambda P_0/\varepsilon_S)(1 - \lambda)Q_0 + 0.5(\lambda P_0/\varepsilon_S)\lambda Q_0\\ &= \lambda P_0 Q_0(1 - 0.5\lambda)/\varepsilon_S.\end{aligned}$$

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