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Storage Technology and the Environment

Erik Lichtenberg and David Zilberman

A dynamic framework is presented for analyzing regulations affecting the use of spoilage-reducing inputs with potential negative environmental effects, such as pesticides, growth regulators, chemical preservatives, and irradiation. Such regulations change intertemporal consumption patterns as well as total output. Consumers may benefit from restrictions on storage technology, giving them a reason to support regulation even when it may not be warranted to correct environmental externalities. Static analyses do not take into account changes in intertemporal consumption, and thus may give misleading depictions of the effects of imposing new regulations. Implications of the framework for development and trade policy are discussed, as are extensions to cases of uncertainty and multiple time periods.

Key words: irradiation, perishability, pesticides, preservatives, regulatory welfare analysis, spoilage, storage

Introduction

Because of its role in stabilizing price and consumption, commodity storage has received a great deal of attention in the economics literature (for comprehensive treatments see Newbery and Stiglitz; Gardner; and Williams and Wright). Economists have focused on the desirability of public storage and the design of public inventory holding strategies. As pointed out by Wright and Williams (1982), commodity storage is a productive activity that transfers a commodity from one period to the next. Just how productive this activity is depends on the technology brought to bear.

The perishability of commodities is affected by factors like temperature, humidity, and the presence of disease or insect pests, and can be controlled by applying inputs such as temperature control (refrigeration), drying, aeration, irradiation, and pesticides. For example, fruits, vegetables, and grains are commonly treated with chemical pesticides after harvest to reduce spoilage losses and enhance food safety. Corn is dried to lengthen storage life and reduce spoilage losses. A major motivation for the use of the growth regulator daminozide (Alar) on apples was to lengthen the storage life by reducing harvest-time maturity. A large proportion of the chemical additives used in processed foods are preservatives.

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To date, economists have paid little attention to the technological choices involved in storage and, in particular, to their economic implications. Economists have assumed either that stored commodities are perfectly nonperishable or that they are subject to spoilage at a constant rate which cannot be altered. The operations research literature similarly assumes exogenous spoilage; this literature concentrates on the impacts of spoilage on the choice of how much inventory to hold (see, e.g., Nahmias; Zipkin). Yet, measures taken to reduce spoilage losses have increasingly been bones of contention in public policy.

Some of the biggest controversies over pesticides during the past few years have involved chemicals with important uses in prolonging storage life. For instance, fruits and vegetables are commonly subjected to post-harvest treatment with fungicides, which may be carcinogenic. Methyl bromide is used to treat a wide variety of fruits and nuts, particularly for export. However, its use is being phased out worldwide due to its activity as a depleter of stratospheric ozone. A televised report on the potential carcinogenicity of the growth regulator Alar caused a sharp reduction in apple consumption.

Chemical preservatives are the subject of long-standing debates concerning food safety (e.g., the use of nitrite to preserve meats), as is the use of irradiation to preserve foods. The use of refrigeration requires electricity and is thus indirectly involved in environmental problems ranging from air pollution and global warming caused by fossil fuel-fired power plants to fishery, wildlife, and scenic damage attributable to hydroelectric power generation.

In this study, a framework is presented for analyzing storage technology choices and their impacts on resource allocation, on prices, on the environment, and on the economic welfare of consumers and producers. The analysis applies to a class of inputs which can be characterized as storage enhancing or spoilage reducing. This class includes inputs such as refrigeration, drying, pesticides, irradiation, and vacuum packing. In contrast to much of the literature on storage, we concentrate on short-term storage where commodities are stored across seasons within a year. In this context, storage is used to smooth differences in consumption between the time of production, which takes place over a short period (e.g., harvest), and time of consumption, which continues throughout the year.

Our analysis thus applies to inventory management of commodities which are relatively highly perishable—i.e., fruits and vegetables, poultry, fish, and meats. A simple two-period model is utilized in which production and environmental damage occur in one period (summer), while consumption occurs in both periods (summer, winter). The socially optimal level of spoilage-reducing input use is derived, and the effects of alternative policies for addressing environmental damage on supply, market equilibrium, and consumer and producer incomes are examined.

Because storage technology choices affect the distribution of consumption over time, the market-level welfare effects of policies affecting storage technology must be evaluated using an intertemporal model. In such a context, it becomes possible for consumers to gain from restrictions on storage technology—unlike in the static case. The intertemporal evolution of price will depend on storage technology choices, and consequently on public policies affecting spoilage-reducing inputs. The model also indicates that derived demands for spoilage-reducing inputs should include intertemporal variables such as interest rates; further, it can be used to specify demand functions for this class of inputs. Implications for specific policies, such as those regarding pesticides or energy pricing, are also discussed.

In many countries, improvements in post-harvest handling (including storage) are viewed as a low-cost means of increasing food supplies. In the former USSR, for example, it is widely believed that one-quarter to one-third of agricultural production may be lost during transport or due to spoilage. In other countries, development of certain export industries (e.g., winter vegetable production in Mexico and Central America)—and hence development strategy more broadly—depends critically on refrigerated storage and transportation, energy prices, and agro-chemicals for post-harvest use. In these countries, public policy decisions related to development of transportation infrastructure, electrification, energy pricing, and construction of storage facilities exert significant influence on storage technology.

Production and Storage in a Social Optimum

Consider a simple two-period model of equilibrium in the intertemporal market for a storable but perishable good Q, produced during the first period by a price-taking industry with a convex cost function $C(Q)$. We assume the industry is characterized by decreasing returns to scale, as is typical of perishable agricultural commodities due to scarcity of land with good soils, appropriate climate, and sufficient growing-season moisture. Total industry production is Q_T. An amount Q_1 is consumed in the first period. The remaining output, $Z = Q_T - Q_1$, is placed in storage at a cost, $S(Z)$ (with $S_Z > 0$, $S_{ZZ} > 0$), to be consumed in the second period. (Derivates are denoted by subscripts.)

The amount of spoilage occurring during storage is $H(X, Z)$, where X is an input (e.g., a pesticide) that reduces perishability and is purchased at a price w. We assume spoilage exhibits constant returns to scale, so that $H(X, Z)$ can be written as $Z\delta(x)$, where $x = X/Z$ is the amount of the spoilage-reducing input X used per unit of output placed in storage ($\delta_x < 0$, $\delta_{xx} > 0$). Consumption in the second period is $Q_2 = [1 - \delta(x)]Z$.

Two interpretations of consumption in periods 1 and 2 are possible. First, the stored commodity available in period 2 is identical to the freshly produced commodity in period 1; that is, the model treats optimal allocation of stored, fresh product over time. This interpretation applies to fruits like apples or pears sold from storage during the off-season. A second possible interpretation is that the freshly produced commodity is consumed in period 1, and a processed form is consumed in period 2. Under this interpretation, our model depicts choices involving intertemporal allocation of consumption between the fresh form of the commodity, consumed at the time of production, and the processed form, consumed later. This interpretation applies to fruits like cherries or berries consumed fresh during the harvest season and in processed form (frozen or canned) during the remainder of the year. For simplicity, we do not address situations where there is substitution between the fresh and processed forms of the commodity during either period.

We also assume demand in the two periods to be additively separable, so that inverse demand in period i is $D^i(Q_i)$ ($i = 1, 2$). The assumption that planned consumption in either period is independent of consumption in the other period (e.g., demand for apples in the winter is independent of apple consumption in the fall) seems reasonable, especially given strong seasonality of demand for many perishable commodities.

Industry demand for the spoilage-reducing input is assumed to account for a small share of total demand for the input (or, equivalently, the input is produced under constant returns to scale), so that the industry faces a perfectly elastic supply at a fixed price w. Finally, use of the spoilage-reducing input is assumed to cause environmental damage characterized by a convex cost function, $V(X)$, representing the social value of environmental and human health damage associated with storage. Damage occurs either directly, through such pathways as occupational exposure to pesticides during treatment, unknowing exposure to pesticide residues on foods, or stratospheric ozone depletion caused by use of methyl bromide, or indirectly as a result of increased use of electric power. Because this damage may occur in either or both periods, $V(X)$ is properly interpreted as the present value of the costs of environmental damage. Markets for these aspects of environmental quality do not typically exist, so this cost is external to the industry.

Spoilage-reducing inputs may also have beneficial environmental effects, most notably enhancing food safety. For example, irradiation reduces the incidence of illness and death from microbial contaminants. Fungicides can have similar effects by reducing mold in fresh produce. Fumigants are used to prevent the spread of pests known to cause substantial economic damage (such as the Mediterranean fruit fly). These benefits are not modeled explicitly. Those not taken into account in market transactions are equivalent to reductions in environmental damage. Situations where these positive externalities dominate can be analyzed using the model by reinterpreting $V(X)$ as an addition to social welfare rather than a subtraction from it [in which case $V(X)$ would need to be concave]. Situations where the beneficial effects are taken into account in market transactions may be captured in the model to some extent by the difference between period 2 demand and period 1 demand. A more complete treatment would require explicitly modeling period 2 demand as a function of spoilage-reducing input use.

The social optimum is given by the solution to the problem of choosing Q_1, Q_T, and x to maximize the present value of consumer welfare less costs of production, storage, and environmental damage, plus expenditures on the spoilage-reducing input:

$$\text{(1)} \quad \max W = \int_0^{Q_1} D^1(q)\,dq + \frac{1}{(1+r)} \int_0^{Q_2} D^2(q)\,dq - C(Q_T) - S(Z) - wZx - V(Zx),$$

where r is the periodic discount rate. If consumption is positive in both periods, the social optimum is given by

$$\text{(2a)} \quad D^1(Q_1^e) - \frac{D^2(Q_2^e)[1-\delta(x^e)]}{(1+r)} + S_Z(Z^e) + wx^e + x^e V_X(x^e Z^e) = 0,$$

$$\text{(2b)} \quad \frac{D^2(Q_2^e)[1-\delta(x^e)]}{(1+r)} - C_Q(Q_T^e) - S_Z(Z^e) - wx^e - x^e V_X(x^e Z^e) = 0,$$

and

$$\text{(2c)} \quad \frac{-\delta_x(x^e)D^2(Q_2)Z^e}{(1+r)} - wZ^e - Z^e V_X(x^e Z^e) = 0,$$

where superscripts denote equilibrium values. These conditions are sufficient (and thus a market equilibrium with environmental costs internalized is stable) whenever demand in both periods is downward sloping and marginal production, storage, and environmental costs are increasing.

Equation (2a) is the familiar arbitrage condition requiring that there can be no marginal gain from transferring a unit for sale from one period to another. Foregoing sale of a unit of output in period 1 to sell it in period 2, for example, entails a loss equal to the period 1 equilibrium price $p_1^e = D^1(Q_1^e)$. The gain from selling in period 2 equals the present value of the period 2 price $p_2^e/(1+r)$, multiplied by $(1-\delta)$ to adjust for storage losses, less three components of cost: (*a*) marginal storage cost S_Z, (*b*) expenditure on the spoilage-reducing input per unit stored wx^e, and (*c*) the marginal environmental cost of storing an additional unit x^eV_X. The spoilage rate δ appears technically equivalent to the interest rate r in this equation, in that an increase in δ makes period 2 production relatively less remunerative and therefore serves to shift production forward in time. In contrast to the previous literature, though, the spoilage rate is endogenous and can be adjusted by using more or less of the spoilage-reducing input x.

Alternatively, equation (2a) can be interpreted in terms of the intertemporal dynamics of the price of the commodity. Rewriting equation (2a) yields the condition that the spot price of the commodity in period 2, $D^2(Q_2)$, must equal the sum of the price of the commodity in period 1, $D^1(Q_1)$, the direct marginal costs of storage, $S_Z(Z) + wx$, and the marginal environmental costs of storage, $xV_X(xZ)$, adjusted for time (divided by $1+r$) and for spoilage losses (multiplied by $1-\delta$). Thus, the spot price of the commodity must rise at a rate greater than the rate of interest because of the costs of storage and because of spoilage losses.

Equation (2b) is essentially the familiar condition stating price must equal marginal cost. In this case, the firm equates the effective real price of a unit sold in period 2, which is the present value of the period 2 price adjusted as before for spoilage losses, with the sum of the marginal costs of production, storage, and environmental damage. Again, spoilage is endogenous, and thus the real discount factor, $(1-\delta)/(1+r)$, is a function of the spoilage-reducing input.

Equation (2c) states the spoilage-reducing input (per unit of stored commodity) x should be used at a level that equates the value of its marginal product [which equals the present value of the price of a unit of the commodity in period 2, $D^2(Q_2)/(1+r)$, times the marginal product of the spoilage-reducing input, $Z\delta_x$], with its cost wZ plus the marginal cost of damage Z^eV_X.

Combining equations (2a) and (2b) gives

$$p_1^e = C_Q(Q_T^e),$$

which states the price of the commodity in period 1 equals the marginal cost of producing total output. The period 1 price will not depend directly on costs associated with storage, including environmental damage associated with the use of the spoilage-reducing input; instead, it will be influenced by storage costs only indirectly, via changes in total output.

The price of the commodity in period 2 exceeds the period 1 price, as shown by rewriting equation (2a):

$$\frac{p_2^e - p_1^e}{p_1^e} = \frac{r-\delta}{1-\delta} + \frac{1+r}{1-\delta}\left[\frac{S_Z(Z^e) + wx^e + x^eV_X(x^eZ^e)}{p_1^e}\right].$$

The rate of capital gains from storing an additional dollar's worth of the commodity should equal the rate of interest adjusted for spoilage losses, $(r-\delta)/(1-\delta)$, plus the full social marginal cost, $(S_Z + wx + xV_X)/p_1$, discounted forward one period and adjusted for spoilage losses. Therefore, the intertemporal evolution of the price of the commodity will depend on spoilage losses, spoilage-reducing input use, marginal storage cost, and the environmental cost of storage.

Internalizing Environmental Costs

Equations (2a)–(2c) represent the first-best outcome. But in most cases, environmental damage from the use of spoilage-reducing inputs will be external to both producers and consumers of the stored commodity, so the marginal cost of environmental damage is typically not taken into account in a free-market equilibrium. The conditions describing this equilibrium will be equations (2a)–(2c), with $V_X = 0$.

Government intervention is needed to attain the first-best solution. Obvious policy instruments include a Pigouvian tax imposed on the spoilage-reducing input equal to $V_X(x^eZ^e)$. Market mechanisms can be used to achieve the same effect, e.g., by implementing a system of tradable permits for the spoilage-reducing input—in which case total permits would equal x^eZ^e, and the equilibrium price of a permit would equal $V_X(x^eZ^e)$. Alternatively, regulators may use direct controls, such as restricting spoilage-reducing input use per unit of stored commodity to the socially optimal level x^e. Any of these instruments will lead to the first-best allocation in the industry.

Regulators may also impose policies that are not first-best. For example, they may impose direct controls on use of the spoilage-reducing input per unit of stored commodity at a stricter-than-privately-optimal level (say, $t < x^e$). In this case, resource allocation in this industry will be determined by the constraint $x \leq t$. Other restrictions on input use can be modeled as exogenous shifts in spoilage. This may be the case in regulations affecting the way the spoilage-reducing input is applied. For example, reentry regulation or other regulations affect the timing of pesticide application and therefore may influence spoilage.

In order to assess the impacts of regulation on the market for stored products, it is useful to distinguish three generic types: (*a*) changes in price of the spoilage-reducing input, (*b*) exogenous absolute changes in the spoilage rate, and (*c*) limitations on the use of the spoilage-reducing input. Most policies can be modeled as combinations of one or more of these types.

An increase in the price of the spoilage-reducing input comes from imposition of a corrective tax or may implicitly capture the effects of other policy actions. To illustrate, if the Environmental Protection Agency (EPA) cancels the registration of a pesticide used to prolong storage life, producers may switch to a higher-priced alternative. Changes in the operation of multipurpose water projects in order to protect wildlife, restore fisheries, or improve water quality may result in a higher price of electricity which in turn affects energy-intensive storage technologies like refrigeration or drying of grain. Imposition of air pollution-control requirements or tradable emissions permit systems on coal-fired electric power generators may have similar effects.[1] The effects of such

[1] Changes in the price of the spoilage-reducing input may also reflect a wide range of other kinds of policies. In many less developed countries, governments routinely subsidize pesticides to encourage more intensive farming methods. Regulatory approval of a new storage technology (irradiation, vacuum storage, or a new pesticide) may permit the introduction of cheaper spoilage-reducing inputs. Subsidization or taxation of energy sources will also influence the use of these technologies.

policies can be modeled as increases in the unit cost of the spoilage-reducing input from its unregulated equilibrium value of w.

Exogenous shifts in spoilage may result from policy actions such as restrictions on the use of pesticides or food additives. For example, pesticides developed to reduce spoilage by killing fungi, bacteria, or insects can only be used after approval from the EPA. The EPA may cancel the registration of currently used pesticides, resulting in greater spoilage and/or a shift to less effective pesticides. Food and Drug Administration (FDA) restrictions on food additives may have similar results.[2]

We model such exogenous change in spoilage by letting the spoilage rate be a function of x and a shifter α, $\delta(x, \alpha)$, such that $\delta_\alpha > 0$. Following the arguments of Lichtenberg and Zilberman, increased spoilage is assumed to result in nondecreased marginal productivity of the spoilage-reducing input, i.e., $\delta_{x\alpha} \leq 0$. The regularity condition $\delta_x \delta_{x\alpha} - \delta_\alpha \delta_x \geq 0$ is also assumed to hold. This condition ensures that an increase in the use of the spoilage-reducing input x decreases δ_x more than it increases δ_α; loosely, the direct effect of a change in x on its own marginal product is greater than its indirect effect on δ_α. Note, this conditions holds with equality if spoilage is exponential ($\delta(x, \alpha) = e^{\alpha - \beta x}$) or logistic ($\delta(x, \alpha) = 1/[1 + e^{\alpha - \beta x}]$).

Limitations on the use of the spoilage-reducing input (per unit of storage) reflect direct controls of the kind most commonly used in the United States. For example, the EPA typically imposes maximum allowable application rates for pesticides or irradiation in response to concern about adverse effects on human health or the environment.[3] Pesticide residue tolerances on foods are another example of this type of policy.[4]

We model the imposition of such a limit on spoilage-reducing input use as a constraint $x \leq t$, where t is the maximum allowable usage rate. Let the shadow price of this constraint be λ. If the constraint is binding, then $x^e = t$, and $\lambda^e = [\delta_x(t, \alpha)p_2^e/(1 + r) - w]Z^e > 0$.

To begin, assume the constraint on use of the spoilage-reducing input t is nonbinding, and the market ignores the marginal cost of environmental damage, i.e., $V_X = 0$. Totally differentiating the excess demand system (2a)–(2c) yields:

[2] Exogenous changes in spoilage may also be due to natural factors such as differences in perishability (for example, peaches would be characterized by a higher spoilage rate than apples), the emergence of a new disease, or differences in location (crops grown in hotter, more humid climates tend to have higher spoilage rates). Policy interventions may result in lower spoilage rates. Regulatory approval of a new spoilage reduction method such as irradiation would be an example. Reductions in effective transportation costs and elimination of trade barriers can also be viewed as exogenous absolute decreases in the spoilage rate.

[3] Limitations on spoilage-reducing input use may also arise from other sources. The availability of electricity in many areas is determined by public investment, while in other areas, electricity may be rationed, effectively limiting its use in storage facilities. Limited capacity of storage or transportation facilities may constrain the use of spoilage-reducing inputs. In less developed countries, farmers' use of purchased inputs like pesticides is often restricted by credit availability, which in turn is influenced by government lending policies.

[4] Under the terms of the Food, Drug, and Cosmetics Act, the EPA also regulates the maximum allowable concentration of pesticide residues found on foods, called a residue tolerance. Fresh produce with residue levels in excess of the tolerance cannot be sold legally, and shipments will be confiscated if they are discovered during FDA inspection. If the application rate or the half-life of the pesticide is high enough, a residue tolerance can set a binding constraint on the amount of pesticide used. Foster and Babcock present an empirical study involving tobacco exports where this phenomenon occurred.

(3)
$$\begin{pmatrix} D_Q^1 + \dfrac{D_Q^2(1-\delta)^2}{(1+r)} - S_{ZZ} & \dfrac{-D_Q^2(1-\delta)^2}{(1+r)} + S_{ZZ} & \dfrac{D_Q^2\delta_x Z(1-\delta)}{(1+r)} \\ \dfrac{-D_Q^2(1-\delta)^2}{(1+r)} + S_{ZZ} & \dfrac{D_Q^2(1-\delta)^2}{(1+r)} - (C_{QQ} + S_{ZZ}) & \dfrac{-D_Q^2\delta_x Z(1-\delta)}{(1+r)} \\ \dfrac{D_Q^2\delta_x Z(1-\delta)}{(1+r)} & \dfrac{-D_Q^2\delta_x Z(1-\delta)}{(1+r)} & \dfrac{\delta_x^2 D_Q^2 Z^2 - \delta_{xx} p_2 Z}{(1+r)} \end{pmatrix}$$

$$\times \begin{pmatrix} dQ_1^e \\ dQ_T^e \\ dx^e \end{pmatrix} = +\begin{pmatrix} -x \\ x \\ Z \end{pmatrix} dw + \begin{pmatrix} \dfrac{-\delta_\alpha p_2 - D_Q^2\delta_\alpha Z(1-\delta)}{(1+r)} \\ \dfrac{\delta_\alpha p_2 + D_Q^2\delta_\alpha Z(1-\delta)}{(1+r)} \\ \dfrac{\delta_{\alpha x} p_2 Z - D_Q^2\delta_\alpha\delta_x Z^2}{(1+r)} \end{pmatrix} d\alpha.$$

Solving the system of equations (3) gives the following set of results.

- PROPOSITION 1. *Imposition of a tax on the spoilage-reducing input will decrease spoilage-reducing input use per unit of stored commodity* ($\partial x/\partial w < 0$), *total spoilage-reducing input use* ($\partial X/\partial w < 0$), *and period 2 consumption* ($\partial Q_2/\partial w < 0$), *and will increase the period 2 price of the commodity* ($\partial p_2/\partial w > 0$). *Total output* ($\partial Q_T/\partial w$), *period 1 consumption* ($\partial Q_1/\partial w$), *and storage* ($\partial Z/\partial w$) *may increase or decrease; period 1 consumption rises (falls) only when total output and storage fall (rise). An increase in total output and storage and a decrease in period 1 consumption are more likely with (a) inelastic period 2 demand, (b) an inelastic marginal product of the spoilage-reducing input, and (c) a larger gap between the marginal and average products of the spoilage-reducing input.*

The intuition behind Proposition 1 is as follows. Imposing a tax on the spoilage-reducing input makes it more expensive, and consequently makes transferring consumption from period 1 to period 2 more costly. Spoilage-reducing input use per unit of storage and period 2 consumption both fall, and the period 2 price of the commodity rises. The increase in the period 2 price in turn increases the return to selling in period 2, and thus the attractiveness of storage, counteracting the increased marginal cost of transferring consumption to period 2.

The net effect on period 1 consumption, total output, and storage in equilibrium therefore depends on the relative sizes of these cost and price effects. If the price effect is large relative to the cost effect, the return to selling in period 2 will rise. Greater storage will substitute for lower spoilage-reducing input use as a means for transferring consumption from period 1 to period 2. As a consequence, output will rise and some consumption will be transferred from period 1 to period 2 in order to compensate for larger spoilage losses. However, the reduction in spoilage-reducing input use will exceed the increase in storage, and so total spoilage-reducing input use will fall. If the price effect is small relative to the cost effect, the opposite will occur. In this case, total output will decrease because of reduced storage and period 2 consumption, but the savings in spoilage losses permit increased period 1 consumption even though total output decreases. Total spoilage-reducing input use will fall because both storage and spoilage-reducing input use per unit of storage will fall.

Highly elastic period 2 demand implies a small price effect. A large gap between the marginal and average productivity and a low elasticity of marginal productivity of the spoilage-reducing input imply less rapidly declining marginal productivity, and thus a smaller cost effect.[5]

Imposing a Pigouvian tax, $dw = V_X(x^eZ^e)$, on the spoilage-reducing input will induce the market to replicate the social optimum. Based on Proposition 1, in a market where damage from use of spoilage-reducing inputs remains external, period 2 consumption, spoilage-reducing input use per unit of storage, and total spoilage-reducing input use are higher than socially optimal. One cannot tell unambiguously whether period 1 consumption, total output, and storage are higher or lower than socially optimal. Period 1 consumption is likely to be too high, and total output and storage too low, whenever the price effect is greater and/or the cost effect is smaller.

- PROPOSITION 2. *An exogenous increase in spoilage will decrease total output* ($\partial Q_T/\partial\alpha < 0$), *storage* ($\partial Z/\partial\alpha < 0$), *total spoilage-reducing input use* ($\partial X/\partial\alpha < 0$), *and period 2 consumption* ($\partial Q_2/\partial\alpha < 0$), *and will increase period 1 consumption* ($\partial Q_1/\partial\alpha > 0$) *and spoilage-reducing input use per unit of storage* ($\partial x/\partial\alpha > 0$). *The period 2 price will increase* ($\partial p_2/\partial\alpha > 0$), *while the period 1 price will fall* ($\partial p_1/\partial\alpha < 0$).

An exogenous increase in the spoilage rate always leads to lower returns to selling in period 2, and therefore lower period 2 consumption, storage, and total output, as well as greater period 1 consumption. In contrast to the previous case, though, greater exogenous spoilage leads to more intensive use of the spoilage-reducing input, even if the marginal product of the spoilage-reducing input is unaffected ($\delta_{x\alpha} = 0$). This occurs because the reduction in period 2 consumption means a higher period 2 price, and thus a higher value of marginal product for the spoilage-reducing input, while the price of the spoilage-reducing input w remains unchanged. However, the decrease in storage will always exceed the increase in spoilage-reducing input use per unit of storage, and so total spoilage-reducing input use will fall.

Proposition 2 further implies that producers of storable but highly perishable commodities are likely to make more intensive use of spoilage-reducing inputs like pesticides, other chemical additives, or refrigeration than producers of less perishable commodities. For example, fungicide use per unit of output should be heavier on peaches than apples. Also, spoilage-reducing inputs will be used more intensively in areas having higher spoilage rates because of climatic and other exogenous conditions. Accordingly, firms located in warm, humid areas will tend to use more spoilage-reducing inputs per unit of output than those in cooler, drier areas. Therefore, pesticide regulation may alter the regional distribution of crop production. For example, stricter pesticide residue tolerances on foods would probably have a greater effect on Mexico and Central America than on the United States.

[5] Proposition 1 has additional implications for development policy. Consider the likely effect of policies (e.g., trade liberalization or subsidies) that lower prices for pesticides in developing countries. Lower prices for post-harvest pesticides will make storage more attractive, and thus shift consumption from harvest-time to later periods. This may result in improved nutritional status by making fruits and vegetables available over a longer time period. Development of new energy sources will have similar effects by making refrigeration less expensive or lowering drying costs.

The impact of imposing a limit on the maximum allowable use of the spoilage-reducing input per unit of storage is found by differentiating the excess demand equations for consumption in periods 1 and 2 with x^e equated to t and λ^e inserted. We obtain the following result.

- PROPOSITION 3. *Decreasing the maximum allowable use of the spoilage-reducing input will decrease total output* ($\partial Q_T/\partial t < 0$), *storage* ($\partial Z/\partial t < 0$), *period 2 consumption* ($\partial Q_2/\partial t < 0$), *and spoilage-reducing input use per unit of storage* ($\partial x/\partial t < 0$) *and in total* ($\partial X/\partial t < 0$), *and will increase period 1 consumption* ($\partial Q_1/\partial t > 0$). *The period 2 price will rise* ($\partial p_2/\partial t > 0$), *while the period 1 price will fall* ($\partial p_1/\partial t < 0$).

A decrease in the maximum allowable use of the spoilage-reducing input per unit stored, t, when it constitutes a binding constraint on x, increases spoilage and thus lowers the return to selling in period 2. In contrast to the case of exogenous increases in absolute spoilage, use of the spoilage-reducing input per unit of storage must fall. Total spoilage-reducing input use falls because both storage and spoilage-reducing input use per unit of storage fall. Consequently, lower tolerances for pesticide residues on foods should lead to greater harvest-time consumption and reduced pesticide use, storage, and consumption both in later periods and in total.[6]

According to Propositions 1–3, alternative approaches for addressing externalities associated with storage technologies can have notably different effects on the intertemporal allocation of consumption. We have considered three generic instruments, a first-best tax on the spoilage-reducing input and two quantity controls: (*a*) limits on the intensity of use of a spoilage-reducing input, corresponding to a residue tolerance or constraint on a pesticide application rate, and (*b*) absolute increases in spoilage rates, which correspond to actions like banning the use of specific spoilage-reducing inputs (e.g., pesticides, food additives, or irradiation).

All three instruments lead to lower period 2 consumption and reductions in total spoilage-reducing input use. Both quantity instruments and the tax on storage induce unambiguous shifts in the intertemporal distribution of consumption, resulting in lower storage and total output plus higher period 1 consumption. Unlike limits on spoilage-reducing input use per unit of storage, however, an increase in absolute spoilage increases the intensity of spoilage-reducing input use. An optimal tax on the spoilage-reducing input, by contrast, may induce increases in total output and storage and reductions in period 1 consumption.

Distributional Effects of Policies Affecting Storage Technology

The effects of policies affecting storage technology on social welfare are examined in this section. Overall, social welfare can be decomposed into four categories: (*a*) consumer surplus accruing from consumption (i.e., consumer income exclusive of possible benefits to consumers from the transfer of tax revenues or from enhanced food safety); (*b*) producer surplus; (*c*) tax revenues; and (*d*) external environmental costs. Imposition of policies affecting storage technology may affect all four. We focus here on the ways such

[6] In contrast, greater credit availability may relax constraints in the use of spoilage-reducing inputs in many countries, leading to increased storage and later-period consumption and, likely, improved diets.

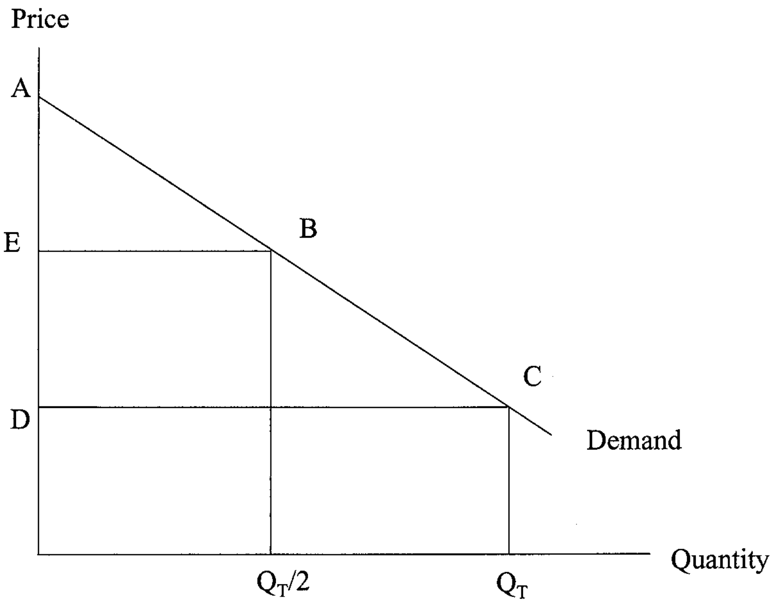

Figure 1. Impact of eliminating storage on consumer welfare with costless production and storage

policies affect consumer and producer surpluses, because these effects may be counter-intuitive. External environmental costs are a monotonic function of spoilage-reducing input use; hence, the effects of policies affecting storage technology on these costs can be derived straightforwardly from Propositions 1–3.

Both the price and quantity instruments commonly used to address externalities associated with storage alter the intertemporal distribution of consumption. They always shift consumption away from stored period 2 commodities, and frequently increase consumption of freshly harvested period 1 commodities. Such a shift makes it possible for imposition of these policy instruments to make consumers better off strictly in terms of income from the consumption of the commodity, i.e., ignoring benefits from reductions in external damage. This result differs markedly from the static case, in which regulatory measures of these kinds always force consumers to bear at least part of the cost of correcting the externality.

To see why this is so, consider first the simplest possible case. Suppose that $r = \delta = 0$, storage is costless, total supply is perfectly inelastic, and demand is identical in both periods. In this case, half of total output will be consumed in each period, as shown in figure 1. Consumer welfare (which equals total welfare in this case) equals twice the area represented by *ABE*. Now assume a change in regulatory policy—for example, removal of a pesticide from the market—results in the elimination of storage. Total output Q_T will be entirely consumed in period 1, and thus consumer welfare will equal the area *ACD*. Because demand is downward sloping, the area *ABE* will be less than the area *EBCD*, and eliminating storage will therefore increase consumer welfare.

When r and δ are nonzero, equilibrium in the market requires that Q_2 be less than Q_1. The higher are r and δ, the greater this difference becomes. As Q_2 shifts farther to the left of Q_1, it becomes more and more likely that consumers' gain in period 1 from

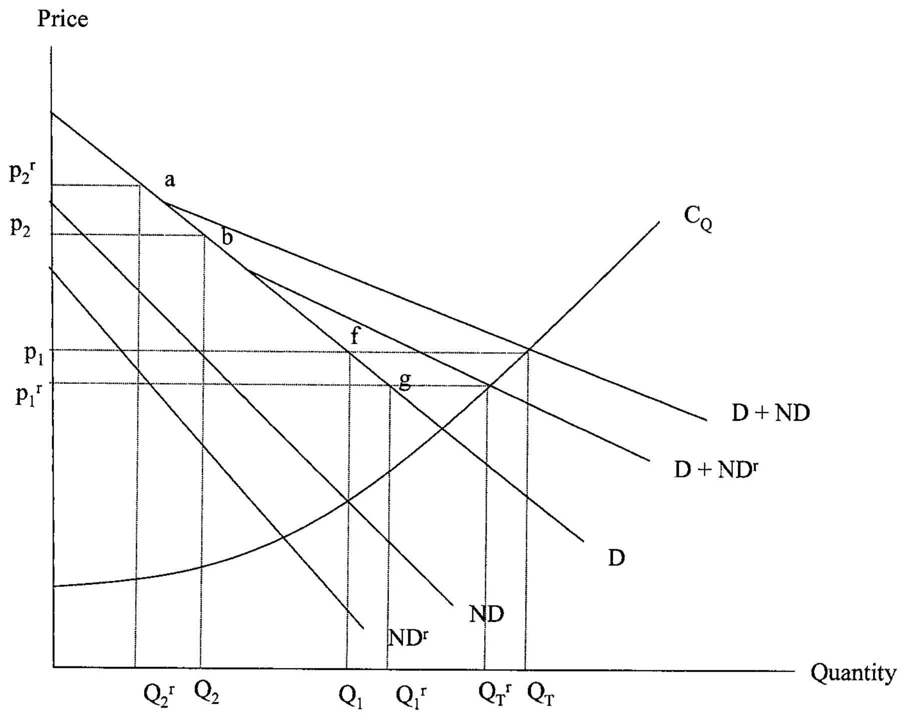

Figure 2. Impact of an exogenous increase in spoilage on consumer welfare with positive production and storage costs

eliminating storage will outweigh their loss in period 2; i.e., consumers might actually gain from policies aimed at correcting externalities associated with storage technology.

Now suppose that storage is not costless. To simplify the graphical exposition, assume demand is the same in both periods, $D^1(Q) = D^2(Q) = D(Q)$. Let

$$ND(Q_2) = \frac{D(Q_2)[1 - \delta(x)]}{(1 + r)} - S_Z\left(\frac{Q_2}{1 - \delta(x)}\right) - wx$$

denote period 2 demand (in present value terms) net of the marginal cost of storage S_Z and expenditure on the spoilage-reducing input wx associated with storing a unit of output. Total demand over the two periods can be depicted by summing period 1 demand $D(Q_1)$ and $ND(Q_2)$ horizontally, as illustrated in figure 2. Equilibrium total output Q_T and the period 1 price p_1 occur at the intersection of this total demand curve with the marginal cost-of-production curve C_Q. Period 1 consumption occurs at the intersection of the D curve with the p_1 line. Period 2 consumption occurs at the intersection of the ND curve with the p_1 line. The period 2 price equals willingness to pay at period 2 consumption, as observed from the $D(Q)$ demand curve.

An exogenous increase in spoilage δ shifts the ND curve downward to ND^r. The D curve remains unchanged, but the total demand curve shifts downward as shown. Total output, the period 1 price, and period 2 consumption decrease to Q_T^r, p_1^r, and Q_2^r, respectively. Period 1 consumption increases to Q_1^r, and the period 2 price increases to p_2^r. Consumer surplus in period 2 decreases by an amount equal to the area of the trapezoid

$p_2^r abp_2$. At the same time, consumer surplus in period 1 increases by an amount equal to the area of the trapezoid $p_1 fgp_1^r$. If the increase in period 1 consumer surplus exceeds the reduction in period 2 consumer surplus, consumers will gain from policies that lower spoilage-reducing input productivity.

The conditions under which this phenomenon occurs can be derived by examining the impacts of regulation on consumer surplus,

$$CS = \int_0^{Q_1^e} D^1(q)\,dq + \frac{1}{(1+r)}\int_0^{Q_2^e} D^2(q)\,dq - p_1^e Q_1^e - \frac{p_2^e Q_2^e}{(1+r)},$$

and producer surplus,

$$PS = p_1^e Q_1^e + \frac{p_2^e Q_2^e}{(1+r)} - C(Q_T^e) - S(Z^e) - \bar{w} Z^e x^e,$$

where the price of the spoilage-reducing input initially equals its unregulated equilibrium value. Differentiating these expressions using the envelope theorem yields Propositions 4 and 5, below.

- PROPOSITION 4. *An optimal tax on the spoilage-reducing input, an exogenous increase in absolute spoilage, or a decrease in the maximum allowable use of the spoilage-reducing input per unit of storage will increase consumer welfare if*

$$\frac{\varepsilon_2}{\varepsilon_1} > -\frac{\left(\dfrac{p_2}{(1+r)}\right)\left(\dfrac{\partial Q_2}{\partial \xi}\right)}{p_1\left(\dfrac{\partial Q_1}{\partial \xi}\right)},$$

where $\xi = \{\bar{w}, \alpha, -t\}$, and $\varepsilon_1, \varepsilon_2 < 0$ are the respective elasticities of demand in periods 1 and 2.

- PROPOSITION 5. *A tax on the spoilage-reducing input, an increase in absolute spoilage, or a decrease in the maximum allowable use of the spoilage-reducing input will increase producer welfare if increased revenue outweighs the increased cost of period 2 consumption. Thus, a decrease in consumer welfare is a necessary, but not sufficient, condition for an increase in producer welfare.*

To prove Proposition 4, differentiate consumer surplus using the envelope theorem to obtain:

$$(4)\qquad \frac{\partial CS}{\partial \xi} = -Q_1^e\left(\frac{\partial p_1^e}{\partial \xi}\right) - \left(\frac{Q_2^e}{(1+r)}\right)\left(\frac{\partial p_2^e}{\partial \xi}\right)$$
$$= -\left(\frac{p_1^e}{\varepsilon_1}\right)\left(\frac{\partial Q_1^e}{\partial \xi}\right) - \left(\frac{p_2^e}{(1+r)\varepsilon_2}\right)\left(\frac{\partial Q_2^e}{\partial \xi}\right).$$

The first term on the right-hand side of this expression is positive, while the second is negative. Rearranging yields:

(5)
$$\frac{\partial CS}{\partial \xi} = -\left(\frac{p_1^e}{\varepsilon_2}\right)\left(\frac{\partial Q_1^e}{\partial \xi}\right)\left[\frac{\varepsilon_2}{\varepsilon_1} + \frac{\left(\frac{p_2}{(1+r)}\right)\left(\frac{\partial Q_2}{\partial \xi}\right)}{p_1\left(\frac{\partial Q_1}{\partial \xi}\right)}\right],$$

where the sign of the change in consumer surplus equals the sign of the term in square brackets.

To prove Proposition 5, differentiate producer surplus with respect to α to obtain:

(6)
$$\frac{\partial PS}{\partial \alpha} = Q_1^e\left(\frac{\partial p_1^e}{\partial \alpha}\right) + \left(\frac{Q_2^e}{(1+r)}\right)\left(\frac{\partial p_2^e}{\partial \alpha}\right) - \frac{p_2^e \delta_\alpha Z^e}{(1+r)}.$$

Differentiating producer surplus with respect to the maximum allowable use of the spoilage-reducing input t gives:

(7)
$$\frac{\partial PS}{\partial t} = Q_1^e\left(\frac{\partial p_1^e}{\partial t}\right) + \left(\frac{Q_2^e}{(1+r)}\right)\left(\frac{\partial p_2^e}{\partial t}\right) - \frac{p_2^e \delta_x (1-\delta) Z^e}{(1+r)} - wZ^e.$$

Differentiating producer surplus with respect to the tax on the spoilage-reducing input gives:

(8)
$$\frac{\partial PS}{\partial \bar{w}} = Q_1^e\left(\frac{\partial p_1^e}{\partial \bar{w}}\right) + \left(\frac{Q_2^e}{(1+r)}\right)\left(\frac{\partial p_2^e}{\partial \bar{w}}\right) - x^e Z^e.$$

The first two terms in each of these expressions represent the change in revenue, and the remaining term(s) the change in the cost of period 2 consumption, as discussed more fully below.

Proposition 4 states that imposition of a tax on the spoilage-reducing input use (when it leads to an increase in period 1 consumption), an exogenous increase in spoilage, or a reduction in the maximum allowable use of the spoilage-reducing input leads to a lower period 1 price and a higher period 2 price, indicating consumers may actually gain from an increase in spoilage.[7] It can be seen from the proof of the proposition that consumer welfare will increase when the ratio of the elasticity of period 2 demand relative to period 1 demand exceeds the ratio of the increase in period 2 expenditure relative to period 1 expenditure. This finding suggests consumer welfare is more likely to increase when period 1 demand is highly inelastic and/or period 2 demand is highly elastic—an intuitive result, because highly elastic period 2 demand implies a small welfare loss from reduced period 2 consumption, and highly inelastic period 1 demand implies a large welfare gain from increased period 1 consumption.

Further insight into the conditions under which consumers gain or lose from these three types of policy measures can be obtained by rewriting the changes in consumer welfare as:

(9)
$$\frac{\partial CS}{\partial t} = \left(-\frac{p_1^e}{\varepsilon_1} - \frac{p_2^e(1-\delta)}{(1+r)\varepsilon_2}\left[\frac{1}{\varepsilon_1 \eta \sigma_1} - 1\right]\right)\frac{\partial Q_1^e}{\partial t} + \left(\frac{p_2^e Z^e \delta_x}{(1+r)\varepsilon_2}\right)\left(\frac{\partial x^e}{\partial t}\right),$$

[7] This result is analogous to those obtained by Wright and Williams (1984) in their analysis of the welfare effects of the introduction of storage. Specifically, the unanticipated introduction of storage can be modeled as an unexpected reduction in the spoilage rate from 100% to less than 100%.

$$(10)\quad \frac{\partial CS}{\partial \alpha} = \left(-\frac{p_1^e}{\varepsilon_1} - \frac{p_2^e(1-\delta)}{(1+r)\varepsilon_2}\left[\frac{1}{\varepsilon_1\eta\sigma_1} - 1\right]\right)\frac{\partial Q_1^e}{\partial \alpha} + \left(\frac{p_2^e Z^e}{(1+r)\varepsilon_2}\right)\left(\delta_\alpha + \delta_x\left(\frac{\partial x^e}{\partial \alpha}\right)\right),$$

and

$$(11)\quad \frac{\partial CS}{\partial w} = \left(-\frac{p_1^e}{\varepsilon_1} - \frac{p_2^e(1-\delta)}{(1+r)\varepsilon_2}\left[\frac{1}{\varepsilon_1\eta\sigma_1} - 1\right]\right)\frac{\partial Q_1^e}{\partial w} + \left(\frac{p_2^e Z^e \delta_x}{(1+r)\varepsilon_2}\right)\left(\frac{\partial x^e}{\partial w}\right),$$

where $\eta = C_{QQ}Q_T/C_Q$ is the elasticity of total supply, and $\sigma_1 = Q_1/Q_T$ is the share of period 1 consumption in total consumption. The first term on the right-hand side of expressions (9)–(11) is the intertemporal reallocation effect of shifting consumption from period 2 to period 1. The second term is the damage effect, the impacts of increased spoilage, and changes in spoilage-reducing input use on consumer welfare. We generally expect the damage effect to be negative, so that any of these three regulatory measures will increase consumers' commodity market income only when the intertemporal reallocation effect is positive. The intertemporal reallocation effect is more likely to be positive when period 1 demand is highly inelastic, period 2 demand is highly elastic, total supply is highly elastic, and/or period 1 consumption makes up a large share of total consumption.

The change in producer welfare from any of these three policies can be decomposed into two effects. The first is a revenue effect,

$$Q_1^e\left(\frac{\partial p_1^e}{\partial \alpha}\right) + \left(\frac{Q_2^e}{(1+r)}\right)\left(\frac{\partial p_2^e}{\partial \alpha}\right),$$

consisting of a transfer of income from consumers to producers. The second is a cost effect [$-x^e Z^e$ for an increase in w, $-(p_2^e\delta_\alpha Z^e)/(1+r)$ for an increase in α, and $(p_2^e\delta_x(1-\delta)Z^e)/(1+r) + wZ^e$ for a decrease in t], reflecting the fact that transferring a unit of the commodity from period 1 to period 2 has become more expensive due to higher spoilage.

The net effect of imposing any of these three policies depends on the signs and relative sizes of these two effects. If consumers gain from an absolute increase in spoilage or a reduction in the maximum allowable level of spoilage-reducing input use, then producers lose, and lose more than consumers gain. Thus, producers are more likely to lose when period 1 demand is highly inelastic, period 2 demand is highly elastic, total supply is highly elastic, and/or period 1 consumption makes up a large share of total consumption.

Situations in which the elasticity of period 2 demand is high while the elasticity of period 1 demand is low are likely to be common. For example, if demand is linear, demand elasticity will be low when consumption is high and price low, such as one would expect to occur during harvest season (period 1 in our model). In this case, the elasticity of demand rises as price rises and consumption falls. Consequently, a higher elasticity of demand would be expected during the off-season (period 2). When such situations occur, one would expect to find strong grower opposition to regulatory measures aimed at spoilage-reducing input use. The 1989 Alar situation may be a case in point, because growers believed their losses to be substantial enough to warrant lawsuits against the environmental organizations responsible for a precipitous drop in consumption due to a health scare and for the ultimate removal of this chemical from the market.

These results reveal the importance of recognizing the specific role of spoilage-reducing inputs—transferring production and consumption across time. For example, a standard analysis treating spoilage-reducing inputs as generic factors of production in a static production context would predict that an exogenous increase in spoilage would always lead to lower equilibrium consumption and a higher equilibrium price, and thus reduced consumer welfare. When intertemporal reallocation of consumption is taken into account, however, it becomes evident there are conditions under which consumers would prefer lower productivity in storage. For instance, it is possible consumers would be better off without food irradiation, even ignoring potential health and safety risks of the technology.

Similarly, a standard static analysis would find that regulation can serve as a mechanism for controlling supply and making producers better off, and that a decrease in consumer welfare is a necessary, but not sufficient condition for an increase in producer welfare. In contrast to the static case, it is not enough that demand be inelastic in order for producer welfare to increase. Furthermore, a standard static analysis would miss the critical importance of the relative elasticities of demand in periods 1 and 2, as well as producing erroneous quantitative estimates of welfare effects.

Extensions: Uncertainty and Multiple Production Periods

The results of the preceding sections can be generalized to cases where period 2 demand is uncertain and where production occurs in multiple time periods.

Consider first the case of uncertain period 2 demand. Let inverse demand in period 2 be a function of the quantity consumed and a random factor $u \in [u_0, u_1]$, i.e., $D^2(Q_2, u)$. Let $f(u)$ be the probability density of u. If agents in the industry are risk neutral, the social optimum is found by choosing Q_1, Q_T, and x ex ante to maximize the expected present value of consumer welfare minus the costs of production, storage, environmental damage, and spoilage-reducing input use:

$$\max E(W) = \int_0^{Q_1} D^1(q)\,dq + \frac{1}{(1+r)} \int_{u_0}^{u_1} \int_0^{Q_2} D^2(q,u) f(u)\,dq\,du - C(Q_T) - S(Z) - \bar{w}Zx - V(Zx). \tag{12}$$

As before, the competitive equilibrium in the absence of regulation is found by choosing Q_1, Q_T, and x to maximize the expected present value of consumer welfare minus the costs of production, storage, and spoilage-reducing input use.

The necessary conditions characterizing the social optimum are analogous to conditions (2a)–(2c), with the expected period 2 price,

$$E(p_2) = \int_{u_0}^{u_1} D^2(Q_2) f(u)\,du,$$

replacing the actual period 2 price. Thus, the discounted expected period 2 price should equal the period 1 price plus marginal storage cost plus expenditures on the spoilage-reducing input plus (in the social optimum) the marginal cost of environmental damage from use of the spoilage-reducing input use. The actual period 2 price, in contrast, will clear the market at the realized level of demand. It is readily seen that Propositions 1–5 will hold ex ante.

If consumers are risk averse rather than risk neutral, the value of period 2 consumption is measured by expected utility rather than expected consumer surplus. The necessary conditions characterizing the social optimum and unregulated competitive equilibrium can be found by amending conditions (2a)–(2c) to incorporate risk aversion by replacing the expected period 2 price $E(p_2)$ with a certainty equivalent of the expected marginal utility of consumption.

Express this certainty equivalent as a proportional reduction in the expected period 2 price $(1 - \rho)E(p_2)$, where the proportional markdown from expected willingness to pay, ρ, is increasing in the degree of risk aversion. As should be apparent from examination of conditions (2a)–(2c), an increase in risk aversion has an effect similar to an exogenous increase in the spoilage rate. Therefore, the changes in total output, spoilage-reducing input use, consumption in periods 1 and 2, and period 1 price enumerated in Proposition 2 also hold for increases in risk aversion. As in the case of risk neutrality, the actual period 2 price will clear the market at the realized level of demand. Furthermore, since $\rho = 0$ corresponds to the case of risk neutrality, the aforementioned results from Proposition 2 can be interpreted as a comparison of risk-averse consumers to risk-neutral consumers.

It is similarly straightforward to show that the analysis of the preceding sections holds for the case of multiple production periods. Consider the case where production occurs in odd-numbered periods (1, 3, ...) and consumption is possible in even-numbered periods only via storage of the commodity. Standard arguments for backstop technologies in exhaustible resource problems suggest it will always be optimal to plan to consume all of the stored commodity in each even-numbered period, thereby reducing the multiple-period problem to a series of two-period problems, as with the series analyzed in the preceding sections.

Intuitively, it will be optimal to carry over some of the commodity in storage from, say, period 2 to period 3 only if the period 3 price exceeds the period 2 price. But under certainty, the period 3 price will equal the marginal cost of production in period 3, and so will be less than the period 2 price. Thus, it will be optimal to exhaust the supply of the commodity in storage in period 2. Even if future production is uncertain, it will be optimal to carry over some of the commodity in storage from period 2 to period 3 only if random factors are expected to keep period 3 production sufficiently low such that the expected period 3 price exceeds the period 2 price. Analysis of such cases is beyond the scope of this investigation.

Final Remarks

To date, economists have studied storage from the point of view of stabilization policy, ignoring choices among storage technologies. These technologies play a critical role in storage policy, and in public policy debates more generally, and their role in environmental policy debates has grown markedly in recent years. Spoilage-reducing inputs such as pesticides, growth regulators, chemical preservatives, and irradiation have become controversial because of actual and putative damage they inflict on human health, wildlife, and ecosystems. The availability and price of electricity (a key input in refrigeration) are functions of environmental damage from the construction and operation of hydroelectric systems and from air pollution due to coal-fired power plants.

In this study, a framework for analyzing regulations affecting storage technology is presented. In contrast to most of the literature, we consider a somewhat different form of storage. Here, the type of storage focuses on managing differences between time of production and times of consumption within a year rather than smoothing randomness in production and demand and stabilizing consumption and price over several years. Our findings show the storage technology choices affect total output as well as the temporal distribution of supply, consumption, and prices. Decisions about quantities to place in storage are linked to decisions about storage technology. Policies which alter the effectiveness of spoilage-reducing inputs or raise their cost will unambiguously reduce social welfare, but may make either consumers or producers worse off.

Most studies assessing the impacts of regulations affecting storable commodities have ignored the specific role played by spoilage-reducing inputs in changing the intertemporal distribution of production and consumption. Instead, they have employed static approaches, modeling the effects of absolute increases in spoilage or increases in the cost (reductions in the marginal effectiveness) of spoilage-reducing inputs as generic increases in production cost. An example is the 1991 study by Zilberman et al. on the impacts of broad-scale pesticide bans on California agriculture. The findings obtained here suggest the results of such earlier studies may be quite misleading. In a standard, static context, for instance, consumers can never gain from regulation; however, once the dynamic nature of spoilage-reducing input productivity is recognized, it becomes clear they can.

The model developed here can also be applied to broader questions involving storage of perishable commodities. A number of questions arise in the context of development policy. Reductions in post-harvest losses have significant promise for increasing food production in many areas of the world. Investments in storage infrastructure and in production capacity for key spoilage-reducing inputs (electricity, pesticides) are critical policy issues relevant to these global areas.

The model presented here does not consider the implications of capacity constraints. Extending the model to examine optimal investment in such capacity would be of interest. More generally, as yield increases become more difficult to achieve because of limitations on genetic capability and because of concerns about pollution from agricultural chemicals, the importance of reducing storage losses will grow. The tradeoffs involved in such issues can be analyzed by expanding the model to incorporate effects of storage on nutritional status, and thus public health, food security, and similar items of interest.

This framework also yields some insights into issues involving international or interregional trade. For example, foreign production can substitute for storage of domestically produced commodities (e.g., winter imports of Southern Hemisphere fruits and vegetables into the United States). Reductions in effective transportation costs and elimination of trade barriers can be viewed as exogenous absolute decreases in the spoilage rate. From this perspective, liberalizing trade in off-season produce can improve both the welfare of produce consumers and environmental conditions in the importing country by substituting imports for pesticides and other spoilage-reducing inputs known to cause environmental damage. The model is also quite similar to one involving trade between exporting and importing countries in cases where losses incurred during transportation can be altered by exporters' actions. The results obtained here thus apply to cases involving regulation of transportation-loss-reducing technologies that cause negative externalities.

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