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THE ECONOMICS OF STORAGE TECHNOLOGY

Erik Lichtenberg
Department of Agricultural and Resource Economics
University of Maryland at College Park

David Zilberman
Department of Agricultural and Resource Economics
University of California at Berkeley

Storage

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University of Maryland
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Because of its role in stabilizing price and/or consumption, commodity storage has received a great deal of attention in the economics literature (see for example Newbery and Stiglitz, Gardner, Wright and Williams). Economists have focused on the desirability of public storage and the design of public inventory holding strategies. Little if any attention, though, has been paid to technological choices affecting storage.

As Wright and Williams point out, commodity storage is a productive activity that transfers a commodity from one period to the next. Just how productive that 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), 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. 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.

Supply and Market Equilibrium in a Two-Period Model

Consider a simple two-period model of production and consumption of a storable but perishable good, produced by a perfectly competitive industry with a convex cost function $C(Q)$. Total production is Q_T. An amount Q_1 is offered for sale in the first period at a price p_1. The rest, Q_T-Q_1, is placed in storage at a cost $S(Q_T-Q_1)$, $S' > 0$, $S'' > 0$, to be sold in the second period. Spoilage occurs during storage at a rate $\delta(x)$, where x is

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an input reducing perishability ($\delta' < 0$, $\delta'' > 0$) purchased at a price w. The amount remaining at the beginning of the second period, $Q_2 = (1-\delta(x))(Q_T-Q_1)$ is offered for sale at a price $p_2/(1+r)$, where r is the periodic interest rate.

The profit maximization problem of the industry is to choose Q_T, Q_1 and x to

$$\max\ p_1Q_T + p_2(1-\delta(x))(Q_T-Q_1)/(1+r) - C(Q_T) - S(Q_T-Q_1) - wx.$$

The necessary conditions for a maximum can be written

(1a) $p_1 - C'(Q_T) \le 0$

(1b) $p_2(1-\delta(x)) - (1+r)(C'(Q_T) - S'(Q_T-Q_1)) \le 0$

(1c) $-\delta'(x)p_2(Q_T-Q_1) - (1+r)w \le 0.$

with the strict equality holding if Q_1, Q_T and x respectively are positive.

Condition (1a) says that, if industry output is positive, the industry should adjust total supply to equate the marginal cost of production with the price of the good in period 1 alone. In other words, only the harvest-time price should be considered in determining total industry output.

Condition (1b) is the familiar arbitrage condition that storage should be adjusted to equate marginal storage cost with the gain in revenue from storage, which equals the present value of the period 2 price adjusted for spoilage losses ($p_2(1-\delta)/(1+r)$) minus the period 1 price (see inequality (1a)). It is evident that reducing the spoilage rate δ is equivalent to reducing the interest rate r. Note also that marginal storage costs and the spoilage rate must be low relative to the period 2 price for (1b) to hold with equality, i.e., for storage to be positive. Thus highly perishable commodities having high spoilage rates or high marginal storage costs (e.g., stone fruits such as peaches, apricots, cherries) will be supplied only at the time of production (on harvest).

Condition (1c) is the familiar condition that the spoilage loss reduction input x should be used at a level that equates the value of the marginal product of the spoilage retardant, which equals marginal damage reduction times the present value of the stored good, with the price of the input.

If both marginal production and marginal storage cost are increasing as assumed, these necessary conditions will be sufficient as long as

$$(2)\quad S''\delta''p_2(Q_T-Q_1)/(1+r) - (\delta' p_2/(1+r))^2 \geq 0.$$

In what follows, we will assume that the inequality (2) holds and that Q_T, Q_1 and x are all positive, so that the necessary conditions hold with equality.

Characteristics of Supply and Input Demand

Total differentiation of the system of equations (1a-c) yields

$$(3)\quad \begin{bmatrix} -C'' & 0 & 0 \\ -(1+r)(C''+S'') & ((1+r)S'' & -\delta' p_2 \\ -\delta' p_2 & \delta' p_2 & -\delta'' p_2 \end{bmatrix} \begin{bmatrix} dQ_T \\ dQ_1 \\ dx \end{bmatrix} = \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix} dp_1 + \begin{bmatrix} 0 \\ -(1-\delta) \\ -\delta'(Q_T-Q_1) \end{bmatrix} dp_2 +$$

$$+ \begin{bmatrix} 0 \\ C'+S' \\ w \end{bmatrix} dr + \begin{bmatrix} 0 \\ 0 \\ 1+r \end{bmatrix} dw + \begin{bmatrix} 0 \\ \delta_a \\ 0 \end{bmatrix} da$$

$$+ \begin{bmatrix} 0 \\ 0 \\ \delta_b' p_2(Q_T-Q_1) \end{bmatrix} db + \begin{bmatrix} 0 \\ 1+r \\ 0 \end{bmatrix} dt,$$

where *a* is a shifter representing an exogenous increase in absolute spoilage alone, $\delta_a > 0$, *b* is a shifter representing an exogenous decrease in the marginal productivity of the spoilage reducing input, $\delta_b' > 0$, and t is a tax on the amount placed in storage Q_T-Q_1 (e.g., a differential tax rate on capital gains). The determinant of the Hessian is

$$\Delta = C''[(1+r)S''\delta''p_2 - (\delta' p_2)^2] > 0$$

as long as the second order condition (2) is met.

Proposition 1. An increase in the period 1 price will increase total supply and period 1 supply and decrease spoilage reducing input demand, storage and period 2 supply.

Proof. By Cramer's Rule, $\partial Q_T/\partial p_1 = 1/C'' > 0$, $\partial Q_1/\partial p_1 = [(1+r)(C''+S'')\delta''p_2-(\delta' p_2)^2]/\Delta > 0$, $\partial x/\partial p_1 = (1+r)C''\delta' p_2/\Delta < 0$, $\partial(Q_T-Q_1)/\partial p_1 = -(1+r)C''\delta''p_2/\Delta < 0$ and $\partial Q_2/\partial p_1 = (1-\delta)\partial(Q_T-Q_1)/\partial p_1 - \delta'(Q_T-Q_1)\partial x/\partial p_1 = -(1+r)p_2C''[(1-\delta)\delta''+(\delta')^2(Q_T-Q_1)]/\Delta < 0$.

Proposition 2. An increase in the period 2 price will have no effect on total output, will decrease period 1 supply and will increase spoilage reducing input demand, storage and period 2 supply.

Proof. By Cramer's Rule $\partial Q_T/\partial p_2 = 0$, $\partial Q_1/\partial p_2 = -C''[(1-\delta)\delta''p_2+(\delta')^2p_2(Q_T-Q_1)]/\Delta < 0$, $\partial x/\partial p_2 = -\delta' C''[(1+r)S''+p_2)1-\delta)]/\Delta > 0$, $\partial(Q_T-Q_1)/\partial p_2 = C''[(1-\delta)\delta''+(\delta')^2(Q_T-Q_1)]/\Delta > 0$ and $\partial Q_2/\partial p_2 = \{(1-\delta)C''p_2[(1-\delta)\delta''+2(\delta')^2(Q_T-Q_1)]-(\delta')^2(Q_T-Q_1)(1+r)C''S''\}/\Delta > 0$.

Proposition 3. An increase in the interest rate, the price of the spoilage-reducing input or a decrease in the marginal effectiveness of the input will have no effect on total output, will increase period 1 supply and will decrease spoilage reducing input demand, storage and period 2 supply.

Proof. By Cramer's Rule, $\partial Q_T/\partial r = 0$, $\partial Q_1/\partial r = -C''[(C'+S')\delta''p_2-w\delta' p_2]/\Delta > 0$, $\partial x/\partial r = -C''[(1+r)S''w-\delta' p_2(C'+S')]/\Delta < 0$, $\partial(Q_T-Q_1)/\partial r = C''[(C'+S')\delta''p_2-w\delta' p_2]/\Delta < 0$ and $\partial Q_2/\partial r < 0$ because

$\partial(Q_T-Q_1)/\partial r$, $\partial x/\partial r < 0$. Similarly, $\partial Q_T/\partial w = 0$, $\partial Q_1/\partial w = -(1+r)C''\delta' p_2/\Delta >$ 0, $\partial x/\partial w = -(1+r)^2 C''S''/\Delta < 0$, $\partial(Q_T-Q_1)/\partial w = (1+r)C''\delta' p_2/\Delta < 0$ and $\partial Q_2/\partial w <$ 0 because $\partial(Q_T-Q_1)/\partial w$, $\partial x/\partial w < 0$. It is evident from equation (3) that an increase in *b* will have the same qualitative effects.

Proposition 4. An increase in absolute spoilage or in the tax rate will have no effect on total output, will increase period 1 supply and will decrease spoilage reducing input demand, storage and period 2 supply.

Proof. By Cramer's Rule, $\partial Q_T/\partial a = 0$, $\partial Q_1/\partial a = C''\delta_a\delta'' p_2/\Delta > 0$, $\partial x/\partial a =$ $C''\delta_a\delta' p_2/\Delta < 0$, $\partial(Q_T-Q_1)/\partial a = -C''\delta_a\delta'' p_2/\Delta < 0$ and $\partial Q_2/\partial a < 0$ because $\partial(Q_T-Q_1)/\partial a$, $\partial x/\partial a < 0$. It is evident from equation (3) that an increase in *t* will have the same effects.

Proposition 1 indicates that an increase in the current value of the stored commodity relative to its future value will lead to an increase in current period supply, while storage demand, spoilage reducing input demand and period 2 supply will decrease, exactly as one would expect. Proposition 2 indicates that an increase in the future value of the commodity relative to its current value will serve to shift supply from the present to future but, interestingly, will not change total output. Propositions 3 and 4 indicate that an increase in the interest rate, the price of the spoilage reducing input, the effectiveness of the input or excess tax on storage will shift also shift the temporal structure of supply away from the present and toward the future without affecting total production.

Characteristics of Market Equilibrium

Assume that the spoilage reducing input is supplied perfectly elastically at a fixed price $\overline{w}$. Let $p_1(Q_1)$ and $p_2(Q_2)$ denote the current value inverse demand curves for the good in periods 1 and 2, respectively. Total differentiation of the system of equations (1a-c) after substitution of these inverse demand curves yields

$$(4)\begin{bmatrix} -C" & -p_1' & 0 \\ (1-\delta)^2p_2'-(1+r)(C"+S") & -(1-\delta)^2p_2'+((1+r)S" & -\delta'p_2(1+1/\epsilon_2) \\ -\delta'p_2(1+1/\epsilon_2) & \delta'p_2(1+1/\epsilon_2) & Z \end{bmatrix}\begin{bmatrix} dQ_T \\ dQ_1 \\ dx \end{bmatrix} =$$

$$+\begin{bmatrix} 0 \\ C'+S' \\ w \end{bmatrix}dr + \begin{bmatrix} 0 \\ 0 \\ 1+r \end{bmatrix}dw + \begin{bmatrix} 0 \\ \delta_a \\ 0 \end{bmatrix}da + \begin{bmatrix} 0 \\ 0 \\ \delta_b'p_2(Q_T-Q_1) \end{bmatrix}db + \begin{bmatrix} 0 \\ 1+r \\ 0 \end{bmatrix}dt,$$

where $Z = (\delta')^2(Q_T-Q_1)^2p_2' - \delta"p_2(Q_T-Q_1) < 0$ and ϵ_2 is the elasticity of period 2 demand, $(p_2/Q_2)\cdot\partial Q_2/\partial p_2$.

The determinant of the matrix on the left hand side of this system is

$$\Sigma = [(\delta')^2(Q_T-Q_1)^2p_2'-\delta"p_2(Q_T-Q_1)]$$
$$\cdot[p_1'(1+r)(C"+S")-(1+r)C"S"+(1-\delta)^2p_2'C"-(1-\delta)^2p_1'p_2'] +$$
$$[\delta'p_2(1+1/\epsilon_2)]^2\cdot[-(1+r)C"S"+(1-\delta)^2C"p_2'-(1-\delta)^2p_1'p_2'-(1+r)(C"+S")p_1']$$

which will generally be positive (always when $p_1' < 1/C" + 1/S"$). We assume $\Sigma > 0$ for the remaining analysis.

Proposition 5. An increase in the interest rate, absolute spoilage or the tax on storage will decrease total output, increase period 1 consumption and decrease spoilage reducing input use, storage and period 2 consumption.

Proof. By Cramer's Rule and using the fact that $-\delta'(Q_T-Q_1)(C'+S') = (1-\delta)w$ when the first order conditions hold, $\partial Q_T/\partial r = -p_1'p_2[\delta'w-d"(C'+S')(Q_T-Q_1)]/\Sigma < 0$, $\partial Q_1/\partial r = -C"p_2[\delta'w-d"(C'+S')(Q_T-Q_1)]/\Sigma >0$, $\partial x/\partial r = [(-\delta)p_2'(C"-p_1'+(1-\delta))w + (C"-p_1')(\delta'p_2-(1+r)S") + p_1'(1+r)C"]/\Sigma < 0$, $\partial(Q_T-Q_1)/\partial r = (C"-p_1')p_2[\delta'w-d"(C'+S')(Q_T-Q_1)]/\Sigma < 0$ and $\partial Q_2/\partial r < 0$ because $\partial(Q_T-Q_1)/\partial r$, $\partial x/\partial r < 0$. It is evident from equation (4) that the effects of an increase in absolute spoilage a or the storage tax rate t will be qualitatively the same.

Remark. An increase in the interest rate, absolute spoilage or a tax on storage not only causes a shift of consumption from the future to the present but also makes current production for future uses less attractive, leading to a decline in total output.

Proposition 6. An increase in the price of the spoilage reducing input or a reduction in the marginal effectiveness of the spoilage reducing input will spoilage reducing input use and period 2 consumption. Total output and storage will increase (decrease) and period 1 consumption will decrease (increase) when period 2 demand is inelastic (elastic).

Proof. By Cramer's Rule, $\partial Q_T/\partial w = -p_1'(1+r)\delta' p_2(1+1/\epsilon_2)/\Sigma > (<)\ 0$ when $-\epsilon_2 < (>)\ 1$, $\partial Q_1/\partial w = -C'' p_2(1+r)\delta'(1+1/\epsilon_2)/\Sigma < (>)\ 0$ when $-\epsilon_2 < (>)\ 1$, $\partial x/\partial w = [(C''-p_1')(1+r)((1-\delta)^2 p_2' - (1+r)S'') + p_1'(1+r)C'']/\Sigma < 0$, $\partial(Q_T-Q_1)/\partial w = (C''-p_1')(1+r)\delta'(1+1/\epsilon_2)/\Sigma > (<)\ 0$ when $-\epsilon_2 < (>)\ 1$ and $\partial Q_2/\partial w = (1+r)(C''-p_1')[(1-\delta)\delta' p_2 + (1+r)S''\delta'(Q_T-Q_1) - \delta'(Q_T-Q_1)p_1'(1+r)C'']/\Sigma < 0$. It is evident from equation (4) that the effects of a decrease in the marginal effectiveness of the input will be qualitatively the same.

Remark. Intuitively, when period 2 demand is inelastic, a decrease in period 2 supply will lead to a relatively small reduction in period 2 consumption. Greater spoilage losses due to lower spoilage reducing input use necessitate increases in total output and storage and decreases in period 1 consumption to meet period 2 demand. When period 2 demand is elastic, on the other hand, the decrease in period 2 supply will engender a relatively large reduction in period 2 consumption, allowing total output and storage to fall and period 1 consumption to rise.

Market Welfare Effects of Changes in Storage Technology

Storage technologies are subject to changes induced by scientific progress and by public policy. New technologies such as irradiation and vacuum storage may prolong storage life and reduce spoilage losses. Pesticide regulation may induce technological regress by removing more effective and/or less costly pesticides from use. Consider the market welfare effects in the latter type of case, for example, reductions in the storage life of apples due the removal of Alar from the market. To simplify matters, assume that spoilage is fixed and that the proposed policy will result in an exogenous increase in the spoilage rate. If period 2 demand is inelastic, the impacts of the policy on welfare in this market will be the same as those in a static situation. Consumption will fall in both periods, so consumers will lose income. The price of the good will rise in both periods as consumption falls, so that revenue earned by producers will rise. However, production and storage costs will increase because storage and total output will increase, so that producers may gain or lose from the regulation. Net social welfare will decline, because any gains realized by producers will be more than offset by consumers' losses.

If period 2 demand is elastic, though, period 2 consumption will decline while period 1 consumption will increase. If the benefits gained from increased period 1 consumption are greater than the benefits lost from decreased period 2 consumption, consumers will be better off after imposition of the regulation. Under some conditions, then, consumers may gain from a regulation resulting in increased spoilage.

For the sake of illustration, consider the simplified case where supply is perfectly inelastic and the regulation will result in a spoilage rate so high that imposing it will shift all period 2 consumption, plus spoilage losses, into period 1. Assume further that inverse demand in period i is linear and has the same slope in both periods, $p_i = \alpha_i - \beta Q_i$. Lost consumer income in period 2 will be

$$\begin{aligned}\Delta CS_2 &= \beta Q_2^2/2(1+r)\\ &= \beta(1-\delta)^2(Q_T-Q_1)^2/2(1+r)\end{aligned}$$

while the income gained in period 1 will be

$$\Delta CS_1 = \beta(Q_T-Q_1)(Q_T+Q_1)/2.$$

The net change in consumer income will be

$$\begin{aligned}\Delta CS &= \Delta CS_1 - \Delta CS_2\\ &= \beta(Q_T-Q_1)[Q_T(1+r-(1-\delta)^2)+Q_1(1+r+(1-\delta)^2)]/2(1+r) \geq 0\end{aligned}$$

since $Q_T \geq Q_1$ and $\delta \leq 1$. Two factors combine to produce this result. First, when demand is linear, consumers value an increment in consumption more than an equal decrement, because the elasticity of demand decreases as consumption rises. This is the same reason that the introduction of storage always decreases consumer welfare when demand is linear and instability comes only from the supply side (Waugh). Second, the elimination of storage eliminates spoilage losses as well, so that total consumption rises.

Generalization to n Periods

The model is easily generalized to an arbitrary number of time periods. Let Q_j be the amount sold and $\delta_j(x)$ be spoilage losses in the j^{th} period. Spoilage reducing inputs may not retard spoilage rates uniformly over time; Alar, for instance, reduces losses from late in the year (Spring), while having little effect on losses earlier on (Winter). The amount remaining in storage after i periods will be $Q_T\prod_{j=1}^{i}(1-\delta_j) - \sum_{j=1}^{i} Q_j \prod_{k=j}^{i}(1-\delta_k)$. The amount sold in the n^{th} (final) period will be

$Q_T\prod_{j=1}^{n-1}(1-\delta_j) - \sum_{j=1}^{n}Q_j\prod_{k=j}^{n-1}(1-\delta_k)$. The industry's profit maximization problem will thus be to choose total production Q_T, spoilage reducing input use x and supply in each period $Q_1, \ldots, Q_n$ to

$$\max \sum_{i=1}^{n-1}\left(p_iQ_i - S\left(Q_T\prod_{j=1}^{i-1}(1-\delta_j) - \sum_{j=1}^{i-1}Q_j\prod_{k=j}^{i-1}(1-\delta_k)\right)\right)/(1+r)^{i-1} +$$
$$p_n\left(Q_T\prod_{j=1}^{n-1}(1-\delta_j) - \sum_{j=1}^{n}Q_j\prod_{k=j}^{n-1}(1-\delta_k)\right) - C(Q_T) - wx.$$

Letting S_i' denote the marginal cost of storage in the i^{th} period, the necessary conditions are

$$\text{(5a)}\quad -C' - \sum_{i=1}^{n-1}\left(S_i'\cdot\prod_{j=1}^{i-1}(1-\delta_j)\right)/(1+r)^{i-1} + p_n\left(\prod_{j=1}^{n-1}(1-\delta_j)\right)/(1+r)^{n-1} \le 0$$

$$\text{(5b)}\quad p_i/(1+r)^{i-1} + \sum_{j=i+1}^{n-1} S_j'\cdot\left(\prod_{k=j}^{n-1}(1-\delta_k)\right)/(1+r)^{j-1} -$$
$$p_n\left(\prod_{k=i}^{n-1}(1-\delta_k)\right)/(1+r)^{n-1} \le 0,\ i = 1, \ldots, n-1$$

$$\text{(5c)}\quad \sum_{i=1}^{n-1} S_i'\cdot\left(Q_T \sum_{j=1}^{i-1}\delta_j'\prod_{k\neq j}(1-\delta_k) - \sum_{j=1}^{i-1}Q_j\sum_{k=j}^{i-1}\delta_k'\prod_{m\neq k}(1-\delta_m)\right)/(1+r)^{i-1}\ .$$
$$- p_n\left(Q_T \sum_{j=1}^{n-1}\delta_j'\prod_{k\neq j}(1-\delta_k) - \sum_{j=1}^{n-1}Q_j\sum_{k=j}^{n-1}\delta_k'\prod_{m\neq k}(1-\delta_m)\right)/(1+r)^{n-1}$$
$$- w \le 0.$$

Evaluating (5b) for $i = 1$ assuming that $Q_1 > 0$ and substituting into (5a) yieldss

$$\text{(5a')}\quad p_1 - C' = 0,$$

total production depends only on the first period price, just as in the two period model. Subtracting (5b) for Q_{i-1} from (5b) for Q_i assuming that both are strictly positive yields the arbitrage condition

$$\text{(5b')}\quad p_i - (1+r)\left(p_{i-1} - S_i'\prod_{k=i}^{n-1}(1-\delta_k) - p_n(1-\delta_{i-1})(1+r)^{i-n-2}\right) = 0,$$

the gain from storing a unit in period i-1 to sell in period i must equal the present value of the revenue forgone in period i-1 less the marginal storage cost adjusted for spoilage less the opportunity cost of the unit in the final period. It is evident from conditions (5b') and (5c) that the spoilage reducing input effectively reduces the interest rate differentially over time. In other words, the input essentially alters the *term structure* of the discount rate as well as its absolute level.

Final Remarks

To date, economists have studied storage from the point of view of stabilization policy, ignoring choices among storage technologies. However, these technologies play a critical role in storage policy and in public policy debates more generally, as spoilage reducing inputs like pesticides, irradiation, vacuum packing and cold storage have become controversial. For example, over the past few years, post-harvest uses of pesticides to reduce spoilage and prevent deterioration of quality have become increasingly important from a regulatory standpoint because of the suspected health effects of many of the chemicals (Alar, ethylene dibromide and many fungicides.

This paper presents a framework for analyzing regulations affecting storage technology. We show that the storage technology choices affect total output as well as the temporal distribution of supply and consumption. The effects of policies that alter the effectiveness of spoilage reducing inputs or raise their cost depend critically on the elasticity of demand in periods after harvest time. If this future demand is inelastic, such regulations will reduce total production and consumption in all periods. Consumer income and will decline unambiguously, although producers may gain. If future demand is elastic, future consumption will decline while harvest-time consumption will rise. It is thus possible that consumers will gain from regulation (although producers' losses will outweigh any consumer gains).

Finally, it was shown that the model is easily generalized to an arbitrary number of time periods, making it suitable for analysis of all storable commodities.

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