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Prices versus Quantities versus Bankable Quantities

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Abstract

Welfare comparisons of regulatory instruments under uncertainty, even in dynamic analyses, have typically focused on price versus quantity controls despite the presence of banking and borrowing provisions in existing emissions trading programs. This is true even in the presence of banking and borrowing provisions in existing emissions trading programs. Nonetheless, many have argued that such provisions can reduce price volatility and lower costs in the face of uncertainty, despite any theoretical or empirical evidence. This paper develops a model and solves for optimal banking and borrowing behavior with uncertain cost shocks that are serially correlated. We show that while banking does reduce price volatility and lowers costs, the degree of these reductions depends on the persistence of shocks. For plausible parameter values related to U.S. climate change policy, we find that bankable quantities eliminate about 20 percent of the cost difference between price and nonbankable quantities.

Key Words: welfare, prices, quantities, climate change

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Contents

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Introduction

Under the presence of uncertainty, welfare comparisons of regulatory instruments have typically focused on price versus quantity instruments (Weitzman 1974; Roberts and Spence 1976; Hoel and Karp 2001; Newell and Pizer 2003). Neglected by this debate is an increasingly common trend in which regulators allow quantities to be banked and/or borrowed throughout time—where the regulated quantity can either be saved for future use or borrowed from future periods, respectively. This is true for the majority of tradable permit markets, such as the federal SO_2 and NO_x trading programs in the United States, the Regional Greenhouse Gas Initiative program for CO_2 in the northeast United States, the CO_2 Emissions Trading Scheme in the European Union and, in a broader context, the Kyoto Protocol.[1] Yet, although bankable quantity regulation is becoming increasingly common, there is still an inadequate understanding of how firm behavior responds to banking opportunities in the presence of uncertainty and, in turn, how this bankable quantity regulation compares to both ordinary quantity and price controls in terms of expected welfare.

This paper presents a model of optimal behavior with a quantitative emissions limit, the flexibility to bank allowances, and uncertainty about costs. We then use this modeled behavior to examine the welfare implications for price, quantity, and bankable quantity regulatory choices. We find bankable quantity regulation improves welfare over a nonbankable system but does not achieve welfare improvements over a price policy. We also find the equilibrium bank chosen by firms is relatively small and positive where persistent (and correlated) baseline emissions shocks have the potential to raise costs and maintain price volatility (even in the presence of an initially

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[1] See http://www.epa.gov/airmarkets/basic.html, http://www.rggi.org/, http://ec.europa.eu/environment/climat/emission.htm, and http://unfccc.int/essential_background/kyoto_protocol/items/1678.php (article 3, paragraph 13) for information on these programs, respectively.

large bank). Further, allowing for either permit borrowing or abatement and marginal cost growth improves expected welfare compared to the banking-only case.

In our analysis we extend the scope of the well-known price versus quantity dichotomy first initiated by Weitzman (1974). Weitzman (1974) was able to show that differences in the relative efficiency between price and quantity controls were a result of the marginal benefit and cost slopes as well as the degree of uncertainty. This framework has been extended by Hoel and Karp (2001, 2002) and Newell and Pizer (2003) to consider stock externalities (pollutants) accumulating over time; they find price policies tend to produce larger net benefits than quantity controls. Yet, with respect to the problem of climate change, the political difficulties of implementing price policies have resulted in a greater emphasis on quantity controls. As a result, recent studies such as Pizer (1999, 2002) and Newell et al. (2005) have begun to focus on how existing quantity regulations can be reconciled to efficient price policies. Using “safety valves” or “trigger” prices for quantities appears to be an option as they allow a ceiling on the price of the quantity. However, the distinction between price and quantity regulation has yet to consider the welfare implications of bankable quantities.

The motivation for including banking and borrowing provisions in quantity regulation reflects an extension of the fundamental idea behind tradable permit markets. The idea of tradable permit markets allows a regulator to allocate pollution rights to firms where the rights are freely traded. As a consequence of competitive trading, abatement effort among regulated firms is efficiently distributed (Montgomery 1972). Additionally, allowing firms the option of exchanging permits between different time periods further reduces social costs by allowing abatement choices to be efficiently distributed between different time periods (Cronshaw and Kruse 1996; Rubin 1996; Kling and Rubin 1997; Leiby and Rubin 2001).

Another commonly discussed justification for allowing banking and borrowing provisions is the ability of firms’ permit inventories to dampen the consequences of unexpected shocks and reduce price volatility within the market. Indeed, the intertemporal reallocation of permits may improve production scheduling and allow for speculation or hedging against possible price movements [for similar inventory models see Williams and Wright (1991) and Blinder and Maccini (1991)]. Godby et al. (1997) developed an experiment to consider the consequences of permit banking and found, in the presence of uncertainty, that banking improves permit price stability. Also, Jacoby and Ellerman (2004) and Ellerman (2005) suggested that tradable permit programs that allow banking significantly reduce price volatility compared to nonbanking schemes. Despite these discussions, until now there has been little theoretical or empirical analysis of such stabilizing potential. Our modeling results, while lending some credibility to these claims, show that price volatility may still be a problem even in the presence of banking (and borrowing). When shocks to the market are correlated and persistent, the value of banking is diminished because—in the limit—shocks verge on being permanent and not amenable to stabilization.

An initial attempt at investigating banking and uncertainty is given by Schennach (2000), who identified the expected price and emissions paths for the U.S. SO_2 market. However, this study does not focus on the incentives behind optimal banking behavior under the presence of uncertainty, steady state behavior, or welfare. Recently Feng and Zhao (2006) considered alternative structures of permit markets with uncertain abatement costs and the possibility to bank and borrow permits. In a two-period model, they found that whether a banking regime is welfare improving compared to nonbanking regime depends on the extent of asymmetric information. When firms know more about current abatement shocks than the regulator, banking can be welfare improving; however, as the level of asymmetry is decreased, the gains in banking similarly reduce, and emissions uncertainty has no effect on welfare. In their treatment of bankable quantities, Feng and Zhao (2006) do not make comparisons between price, quantities, and bankable quantities and simply focus on the case of banking and no-banking regimes. Furthermore, as the model is restricted to only two periods, only small inferences can be made about the correlation and persistence in shocks through time—something that turns out to have a significant impact on banking behavior and welfare.

For our benchmark analysis, we create an infinite-period tradable permit market in which the "representative" firm is allowed to bank allowances in each period. We consider costs and benefits associated with cumulative emissions reductions as in Newell and Pizer (2003). By using discrete dynamic programming, we establish a value function for a single representative firm. In each period the firm, in order to maximize the net present discounted value of negative costs, simultaneously chooses a level of emissions to pollute and a level of permits to bank. In our model, the bank chosen in the current period equals the previous period's bank, plus the current-period allocation, minus the choice of current-period emissions. Uncertainty in emissions is modeled by the inclusion of a stochastic shock in the current period that either increases or decreases the firm's baseline level of emissions and, as a result, may alter the cost of abatement. Further, the benchmark model is extended to cases where (i) firms have ability to borrow permits from future compliance periods and (ii) where there is abatement and marginal cost growth.

Our numerical simulation, which uses realistic parameters for U.S. climate policy, shows that under the presence of uncertainty an incentive exists, on average, to bank permits in each period. We find that a larger initial positive bank and more favorable baseline emissions shocks lower the net present value of expected costs.[2] Relative to Schennach (2000) we show that, even with an initial bank of zero and no shock, an incentive to bank permits exists. When firms hold a zero initial bank, there is an expectation that the bank will grow; for larger bank values, the expectation is that the bank will decline—this defines a stable equilibrium bank. Lower correlation among shocks and a lower discount rate also tend to increase banking behavior. That is, when shocks are highly correlated firms add to their banks more slowly in favorable shock periods and draw their banks down more slowly in unfavorable shock periods compared to the case when shocks exhibit low serial correlation. This is analogous to the permanent income hypothesis result: a more persistent shock to income induces less savings than an idiosyncratic shock (Friedman 1957). Bankable quantities, although welfare improving on nonbankable qualities, generally achieve less than half the cost improvements associated with a price policy. The main reason for the lower expected welfare is due to the persistent shocks that encourage deviations from average prices and raise costs. Furthermore, due to the persistence of shocks throughout time, price volatility may continue to pose a problem; although a large positive bank will dampen price movements, there is a tendency for firms to draw down the bank and, as a result, price volatility continues. Similar findings occur when permits can additionally be borrowed, yet the net present value of costs tends to be smaller than those experienced in the banking-only case. Finally, we also show that a model with growth can be transformed into a solvable stationary model, analogous to the Ramsey (1928) growth model. We find allowing for growth produces larger expected welfare gains compared to the banking-only case.

Our contribution to the literature is thus twofold. To date, research has either investigated the simple price versus quantity dichotomy as a form of regulation or has attempted to reconcile quantity regulation with supplementary mechanisms to obtain results similar to that of price policy. However, we are able to investigate the welfare consequences of price, quantity, and bankable quantities. Although our main focus is on climate change policy, our model can be used to compare the welfare of regulating stock externalities through a price, quantity, or bankable quantity control instrument. Furthermore, we are able to provide insights into the incentives of

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[2] To the extent that we are primarily concerned with cumulative emissions (as is the case with CO_2) or that early reductions are preferred to later reductions (as is the case with relatively constant marginal emissions consequences, as arises with SO_2 and NO_x), these reduced costs are not associated with any reduction in benefits (and, in fact, might yield higher benefits).

firms when they select a level of bankable quantities; given this, we also show the potential for sustained price volatility under the presence of uncertainty in a tradable permit market.

The paper is organized as follows. Section 2 outlines the underlying cost–benefit model and reviews previous welfare results for prices and nonbankable quantities. Section 3 develops the banking model and derives results for the case with growth. Section 4 introduces the numerical analysis. Section 5 discusses the policy implications and Section 6 concludes.

Model and Previous Results

Our underlying model is based on Newell and Pizer (2003), hereafter NP, who compared the welfare consequences of price and (nonbankable) quantity controls for the case of a stock externality. They consider a “representative” firm responding to alternate price or quantity controls set by a regulator where shocks are observed by the firm (but not by the regulator).

Following their approach, we assume firm costs are given by

$$C_t(q_t,\theta_t)=\frac{c_t}{2}(q_t-\overline{q}_t-\theta_t)^2$$

where q_t is the quantity of emissions, $\overline{q}_t$ is the average cost-minimizing level of emissions in the absence of regulation (i.e., the baseline emissions level), c_t is the slope of marginal costs, and θ_t is a baseline emissions shock to the cost-minimizing emissions level.[3] Potential changes in c_t and $\overline{q}_t$ allow for cost reductions and growth in uncontrolled emissions. The cost shock has an autoregressive form $\theta_t=\rho\theta_{t-1}+\varepsilon_t$ with correlation $|\rho|\le 1$ and mean zero error $\varepsilon(t)\sim(0,\sigma_\varepsilon^2)$. We assume costs are convex ($c_t > 0$) so that costs are minimized at $\overline{q}_t+\theta_t$ (ignoring the potential benefits). Any reduction in emissions below this level leads to increasing costs at an increasing rate.

Also, following the approach of NP, we allow for emissions to accumulate in the environment:

$$S_t=(1-\delta)S_{t-1}+q_t$$

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[3] NP, in turn following Weitzman (1974), specify θ_t as a shock to marginal costs; the only difference is a scaling factor c_t. If c_t is unchanging, there is no consequence; however, if we allow c_t to change and assume the distribution of θ_t is time invariant, we are choosing between a shock whose distribution remains invariant in \$/ton (NP) versus constant in tons (here). We choose the latter because it will allow us to solve the problem with growth.

where S_t is the accumulated stock of emissions at time t, which accumulates with decay rate δ. The decay rate can take on values representing cases ranging from a "pure stock externality" that persists forever ($\delta = 1$) to a "flow externality" ($\delta = 0$) that replicates the traditionally analyzed case. "Benefits" associated with the stock of emissions are given by

$$B_t(S_t) = -\frac{b_t}{2}\left(S_t - \overline{S}_t\right)^2$$

where $\overline{S}_t$ represents a benefit-maximizing level of the stock (possibly zero, possibly a background level), and $b_t \geq 0$.

NP use this model to derive the welfare difference between optimal price and quantity controls. Assuming constant growth g_b in b_t, they show that this welfare difference in any period t equals

$$\Delta_t = \frac{\sigma_t^2}{2c_t^2}\left(c_t - b_t\Omega_\delta\Omega_{\rho,t}\right) \tag{1}$$

where

$$\Omega_\delta = \frac{1+r}{1+r-(1+g_b)(1-\delta)^2}$$

r is the interest rate, and $\Omega_{\rho,t}$ captures the correlation of shocks today with previous shocks and, under a price policy, deviations from the expected level of the accumulated pollution stock. Note that when the decay rate equals 1, these two Ω terms equal 1, and the expression reduces to the original Weitzman (1974) expression for comparing price and quantity controls. Summing this Δ_t expression over time, for example, $\sum_t (1+r)^{-t}\Delta_t$, we can estimate the net present value of using price versus quantity controls over many periods.

It is useful to note that (1) can be decomposed into two effects associated with prices: a decrease in expected costs given by $\sigma_t^2 c_t / (2c_t^2)$ and a decrease in expected benefits given by $\sigma_t^2 b_t \Omega_\delta \Omega_{\rho,t} / (2c_t^2)$. Applied to climate change, the effect on benefits is sufficiently small to be negligible because $b_t\,\Omega_\delta\,\Omega_{\rho,t}$ is small relative to c_t (NP). This would suggest that welfare analyses of bankable quantities applied to climate change could similarly neglect the benefits. However, even if this term were not negligible, banking—to the extent that it introduces variability in emissions relative to nonbankable quantities—does not diminish benefits because in all cases emissions reductions occur earlier than required when banking is not allowed. For that reason, while the benefit–loss term is relevant for comparing quantity and price controls (where variability will diminish benefits), our discussion of the welfare effects of bankable quantities versus prices and quantities can neglect the benefit term and leave, at worst, a conservative estimate of the bankable quantity advantage.

The Banking Problem

We retreat from the optimal price and quantity discussion in NP to consider, for a moment, the banking problem facing the representative firm. Ordinary price and quantity controls pose a relatively simple behavioral problem for the regulator to understand. In the case of quantity controls, there is the challenge of choosing the optimal quantity, but the regulated firm actually faces no choice: it simply emits the regulated volume of emissions (technically, the firm could choose to emit less but, given positive marginal costs of abatement and no financial benefit to emitting less than the given quantity, it would never choose to do so). In the case of price controls, the firm matches marginal cost to the regulated price each period; for a model with linear marginal costs, this is a trivial problem.

The opportunity to bank (borrow) poses a trickier challenge to understanding the firm's behavior. As before, the firm faces the quadratic cost function given above where the firm is given a set emissions allocation each period, which we now label y_t to distinguish from actual emissions. Unlike the no-banking regulation, where the firm would always choose $q_t = y_t$, the firm now has the flexibility of choosing emissions q_t anywhere between 0 and $y_t + B_t$, where B_t is the start-of-period bank, and where any excess emissions allocation can be saved for the next period. In the most general case, this choice of emissions results in a bank at the beginning of the next period equal to

$$B_{t+1} = R_t \left(B_t + y_t - q_t \right) \tag{2}$$

where R_t is a trading ratio between periods. In other words, the bank for the future period must equal the current bank with the addition of the initial allocation minus the choice of current-period emissions, all multiplied by the trading ratio between periods.[4]

We can now write the firm's optimization problem as

$$V_t\left(B_t, \theta_t\right) = \max_{q_t} \left\{ -\frac{c_t}{2}\left(q_t - \overline{q}_t - \theta_t\right)^2 + \beta E_t\left[V_{t+1}\left(B_{t+1}, \theta_{t+1}\right)\right] \right\} \tag{3}$$

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[4] Trading ratios are typically set to one if the bank is positive and greater than one if the bank is negative. For instance, the trading ratio is 1.1 for borrowed permits in the proposed climate change bill S. 2191 (Lieberman–Warner).

subject to (2). We have defined $V_t(B_t,\theta_t)$ recursively as the negative expected net present of costs in period t, conditional on the current bank B_t and baseline emissions shock θ_t, and assuming optimal behavior in every future period. This is a value function. To the extent there is a final period, (1) can be solved backward from the final period. If we want to consider an infinite horizon, however, we need to further specify the model to eliminate the time dependence of the value function. A simple approach would be to make c_t, $\overline{q}_t$, y_t, and R time invariant, removing the time dependency and simplifying (3) to

$$V\left(B_t,\theta_t\right)=\max_{q_t}\left\{-\frac{c}{2}\left(q_t-\overline{q}-\theta_t\right)^2+\beta E_t\left[V\left(B_{t+1},\theta_{t+1}\right)\right]\right\} \tag{4}$$

subject to (2).

Alternatively, suppose we assume that the marginal cost slope c_t grows at constant rate g_c and the required abatement absent from banking, $\overline{q}_t-y_t$, grows at constant rate g_a. Let R be time invariant. Note that it is possible to write the cost function in period t as

$$\frac{c_t}{2}\left(q_t-\overline{q}_t-\theta_t\right)^2=\frac{c_t}{2}\left(y_t-\overline{q}_t\right)^2\left(1+\frac{\Delta q_t-\theta_t}{y_t-\overline{q}_t}\right)^2$$

where $\Delta q_t = q_t - y_t$ is the new choice variable. This suggests redefining the bank B_t, choice variable Δq_t, and shock θ_t in terms relative to the required abatement each period, absent from banking: $\widetilde{B}_t=B_t/\left(y_t-\overline{q}_t\right)$, $\Delta\widetilde{q}_t=\Delta q_t/\left(y_t-\overline{q}_t\right)$, and $\widetilde{\theta}_t=\theta_t/\left(y_t-\overline{q}_t\right)$.[5] By changing the discount rate to $\widetilde{\beta}=\beta\left(1+g_c\right)\left(1+g_a\right)^2$ the discounted cost function becomes time invariant,

$$\beta^t\frac{c_t}{2}\left(y_t-\overline{q}_t\right)^2\left(1+\frac{\Delta q_t-\theta_t}{y_t-\overline{q}_t}\right)^2=\widetilde{\beta}^t\frac{c_0}{2}\left(y_0-\overline{q}_0\right)^2\left(1+\Delta\widetilde{q}_t-\widetilde{\theta}_t\right)^2$$

and we can then rewrite the value function as

$$V\left(\tilde{B}_t,\tilde{\theta}_t\right)=\max_{\Delta\tilde{q}_t}\left\{-\frac{c_0}{2}\left(y_0-\overline{q}_0\right)^2\left(1+\Delta\tilde{q}_t-\tilde{\theta}_t\right)^2+\tilde{\beta}E_t\left[V\left(\tilde{B}_{t+1},\tilde{\theta}_{t+1}\right)\right]\right\} \tag{5}$$

with $\tilde{B}_{t+1}=\tilde{R}\left(\tilde{B}_t-\Delta\tilde{q}_t\right)$ and $\widetilde{R}=R/\left(1+g_a\right)$.

It is useful to note that $\widetilde{\beta}^t c_0\left(y_0-\overline{q}_0\right)^2/2$ equals the net present value of costs each period under price regulation designed to yield emissions equal to y_t on average. Similarly,

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[5] This is similar to rewriting variables in the Ramsey (1928) growth model relative to labor or labor and total factor productivity in order to make that problem stationary.

$\tilde{\beta}^t c_0 \left(y_0 - \bar{q}_0\right)^2 E\left[\left(1+\tilde{\theta}_t\right)^2\right] \Big/ 2$ equals the net present value of costs each period under quantity regulation without banking. To the extent that banking allows $\Delta\tilde{q}_t$ to approach $\tilde{\theta}_t$, expected costs with banking will be reduced toward expected costs under price regulation.

Numerical Analysis

The recursive equations (4) and (5) must be solved numerically. In order to do this, we make a discretized approximation of the problem. Our programmed approach creates a 101 × 101 grid of discrete values for the bank and cost shock. Each iteration starts with the preceding guess of the value function defined over this grid. That value function is used to create the next-period expected value function in terms of the next-period bank and *this-period* shock.[6] We then loop over all grid values for the current-period shock and bank, and numerically solve (4) and (5) by using the given current-period cost function, this next-period expected value function, and the accumulation rule for the bank. This gives us a new estimate of the value function. To help improve convergence, our next guess is a weighted average of the previous guess and this new estimate.[7]

Our work focuses on parameter values meant to inform the debate over the design of U.S. climate policy—in particular, whether banking significantly reduces price volatility and expected costs relative to a no-banking case as well as a price policy. Our benchmark case is the no-growth model given in (4) with banking only (i.e., no borrowing). Based on recent estimates of U.S. compliance costs with S. 2191 (Lieberman–Warner), we assume $\bar{q}$ = 6.7 billion tons and y = 5.7 billion tons (about a 15 percent reduction) with a marginal cost of \$30/ton CO_2 (EPA 2008). This implies c_0 = \$30 per ton per billion tons, or \$3 × 10^{-8} \$/ton^2. We assume the standard deviation of the independently and identically distributed quantity shock is 1/3 billion tons (equivalent deviation of the marginal cost shock is \$10/ton). Based on NP, we assume an autocorrelation of 0.8 (which implies a long-term standard deviation of θ of about 5/9 billion tons or \$16/ton). Finally, we assume a discount factor of 0.95 and a uniform trading ratio R. Table 1 summarizes the "benchmark" parameter values.

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[6] For example, if shocks are uncorrelated, the next period expected value function will have the same value for any current period shock.

[7] This technique is sometimes referred to as overrelaxation when the weight on the new estimate is greater than one (and the old guess has a negative weight). See Wilmott et al. (1995) for more details.

The primary output of the numerical effort is the value function, defined over the bank value B_t and level of the baseline emissions shock θ_t. The negative of the value function defined in (4), that is, the net present value of costs resulting from our numerical optimization, is depicted in Figure 1. Costs are a positive function of the shock [which raises costs in (4)] and a negative function of the bank (which initially represents a weakening of the constraint). Recalling that the first-period standard deviation of the cost shock is 1/3 billion tons, the figure shows costs up to ±5 standard deviations (±3 standard deviations of the long-run cost shock with autocorrelation of 0.8). The bank reflects a potential accumulation equal to four times the annual abatement level of 1 billion tons (while borrowing is limited to 1 billion tons). Thus, the potential bank covers 15 standard deviations of the short-run cost shock (9 standard deviations of the long-run cost shock).

A more useful way to view the value function for the purpose of welfare comparisons among instruments is to take expectations of the net present value costs in Figure 1 over the first-period cost shock (applying a mean zero, 1/3 billion ton standard deviation, normal distribution to the baseline emissions shock in Figure 1) and then to consider the value associated with an initial bank of zero (e.g., zero value along the banking axis). This is what we would expect the program to cost before knowing the initial shock and assuming any bank must be acquired by emissions reductions in excess of the annual cap. Figure 2 shows the result of taking this expectation over the cost shock. With an initial bank of zero tons, the expected net present value of costs is $369 billion.

We can compare these expected costs to those under a tax or nonbankable permit policy. Under a nonbankable permit policy $q_t = y_t$ costs equal $\beta^t c_0 \left(y_0 - \overline{q}_0\right)^2 E\left[\left(1+\theta_t\right)^2\right]\big/2$ in each period. For our infinite horizon no-growth model with parameter values given in Table 1, the net present value of costs equals $385 billion. Under a tax policy $E[q_t] = y_t$ where costs equal $\beta^t c_0 \left(y_0 - \overline{q}_0\right)^2 \big/2$ each period, the net present value of costs equals $300 billion. These calculations are summarized along with sensitivity analysis for the discount factor β and correlation ρ in Table 2. Cost comparisons for the growth case, (5), and a system that allows borrowing as well as banking are also included in Table 2. The main conclusion from this table is that bankable quantities generally achieve less than half the cost improvement associated with a tax policy.

As noted earlier, the effect on benefits of a mean-preserving change in emissions is negligible compared to costs in the climate example because the slope of marginal benefits is so much flatter. Further, banking serves to move emissions reductions from the future to the present (and emissions from the present to the future) thereby, if anything, *increasing* benefits relative to fixed emissions constraints. For both of these reasons, the cost effects in Table 2 can also be viewed as preliminary welfare comparisons.

Looking in more detail, we see that bankable quantities achieve slightly less than one-fifth the cost improvement associated with price policies for the benchmark parameters. This jumps to roughly one-quarter with lower discount rates and considerably higher—over 40 percent—without correlation. Intuitively, lower discount rates make the future more important (after a precautionary bank is developed and welfare can be improved). Lower correlation is a different story. When correlation is high, banking in low-cost states does not pay off as much, in terms of using the bank to cover a future high-cost period, because low-cost states tend to be followed by more low-cost states. Similarly, the bank is drawn down more slowly in the high-cost states when shock correlation is high because of the expectation of persistent high costs. With no correlation, banking in a low-cost state has a 50-50 chance of paying off next period, and thus banking activity (adding to and drawing down the bank) increases with decreased shock correlation. This more aggressive use of the bank with no shock correlation drives the result that the cost savings of moving from a no-banking system to a system that allows banking is greater as the correlation declines.

In the case where borrowing is permitted, we assume that borrowed permits must be paid with 10 percent interest.[8] This alters the trading ratio in the banking state equation, (2), such that

$$R_t = \left\{ \begin{matrix} 1 & \text{if } B_t \geq 0 \\ 1.1 & \text{otherwise} \end{matrix} \right\}.$$

Additionally, we assumed that borrowing in any period is limited to one billion tons. As shown in Table 2, allowing both banking and borrowing, even with a trading ratio greater than unity for borrowed permits, further reduces the net present value of costs compared to the case of banking only. However, for our parameter assumptions, the cost savings from adding borrowing provisions to a system with banking are quite minimal. The cost savings from allowing borrowing do increase as the trading ratio for borrowed permits approaches unity and as the borrowing limit is relaxed.

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[8] This borrowing interest rate is consistent with S. 2191.

For the growth specification, (5), we assume, as in NP, that the slope of marginal cost declines at a rate of 2.5 percent ($g_c = -0.025$) and that annual abatement grows at a rate of 3.5 percent ($g_a = 0.035$).[9] As can be seen in Table 2, the growth assumption dramatically increases the net present value of costs for all regulation forms compared to the no-growth scenarios. Allowing banking in the growth case achieves about one-third the cost improvement associated with price policies for the benchmark parameters. The gain from banking on a percentage basis is roughly double compared to that of the no-growth case. Intuitively, allowing growth in the model increases the discount factor compared to the benchmark, which increases the importance of future periods (this is similar to a reduction in the discount rate).

Distinct from welfare and expected costs, one of the particular appeals of price mechanisms is their predictable economic impact in terms of price effects. Proponents of borrowing, in particular, often argue that with sufficient intertemporal flexibility, short-term price fluctuations will be substantially reduced or could even vanish. Therefore, it is useful to look at how banking affects price variability. Figure 3 shows the mean price for various levels of the bank, along with 2.5 percent and 97.5 percent quantiles, based on the initial shock distribution.[10] Note that the 95 percent confidence interval (CI) for baseline emissions shocks *without* banking would be from \$10 to \$50 per ton CO_2, with a mean of \$30 (e.g., a standard deviation of \$10 as shown in Table 1) . With no bank, banking does not help with adverse shocks: the 97.5 percent quantile is still \$50. However, as the bank builds, the upper range drops to \$40. Another interesting observation is that even with a large bank of 2 to 3 billion tons—several times the annual abatement requirement—prices still have a 95 percent prediction interval of about one-third of the original no-banking case. In the case where correlation is set to zero (not shown here), this range associated with a large bank drops to about one-tenth of the no-banking case.

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[9] Assuming a growth in baseline emissions of 0.6 percent annually, an annual abatement growth rate of 3.5 percent will approximately halve current baseline emissions levels in 50 years. This is roughly in line with S. 2191, which calls for a 65 percent reduction in current emissions levels by 2050.

[10] Note this is different from the long-term steady state distribution, but is useful for understanding likely short-term price fluctuations.

Steady State

We now turn briefly to the steady state. While useful for understanding the model behavior, it is probably less informative for real policy comparison as it focuses entirely on the extrapolated future rather than the path beginning with the present. The steady state analyses conducted here are for a system with banking only and for a system that allows both banking and borrowing. Both cases are based on no-growth (4). In our steady state simulations (Figures 4, 5, 6, and 7), we find that equilibrium-expected bank levels and prices are highly dependent on the level of persistence in the baseline emissions shocks.[11] From Figure 5, we see that the expected bank level and 95 percent CIs of the bank increase as shock correlation increases, which is not surprising as the long-run standard deviation of the emissions shocks equals $\left(1-\rho^2\right)^{-\frac{1}{2}}$. For a system with both banking and borrowing, when baseline emissions shocks are less persistent, bank levels fluctuate between positive and negative values more from period to period. This creates a steady state bank time-path that is centered around a zero mean. However, as persistence in the shocks increases, the steady state bank levels drift (more persistently) from zero. This leads to greater variation in the bank. Also, since the maximum allowable positive bank level is greater than the maximum allowable borrowing level, persistent shocks will force the bank to drift farther away from zero on the positive side than on the negative side, resulting in an increasing expected bank level as persistence in the shocks increases. The story is similar for policies that allow banking only except that $B_t \geq 0$ for all t, and thus the expected steady state bank levels for any given value of ρ are larger than those in a banking–borrowing system.

From Figure 6, we see that, regardless of shock persistence, the expected permit price in a banking-only policy is simply the expected marginal cost of abatement, $30/ton. This means that on average $y_t = q_t$, just as it would in a no-banking system. However, an interesting result, readily observable in Figure 7, is that when borrowing is allowed the expected steady state prices are slightly above the $30 no-growth marginal cost level. This means that on average, $q_t < y_t$, which seems to suggest an ever-increasing bank. However, this steady state feature is a result of a trading ratio being greater than unity in borrowing states. Since firms have to pay back more than they borrowed, firms will emit less than their allocation to cover their borrowing interest, resulting, on average, in $q_t < y_t$. Both Figure 6 and Figure 7 also show that the variability in the

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[11] With the exception of ρ, the results presented in Figures 4 through 7 are based on benchmark parameter values and $R = 1.1$ when permits are borrowed.

price increases considerably as shock persistence increases. This result is, again, due to the fact that firms more actively use the bank, in terms of adding to or drawing from the bank in any given period, as shock persistence decreases. Because firms use the bank less actively with highly persistent baseline emissions shocks, the marginal abatement costs, and hence prices, will more fully reflect the baseline emissions shocks just as they would under no banking. This directly leads to greater steady state price variability as shock persistence increases.

Comparing the steady state price variability based on the CIs, the banking-only system appears to have less variability for any given ρ value than the banking–borrowing system. This points to another interesting observation. As shown in Figure 3, expected permit prices increase as bank levels decrease. Looking at the steady state bank levels in Figures 5 and 6, we see that the system with banking and borrowing produces an upper bound bank level slightly below that of a banking-only system. Since permitting borrowing lowers the expected permit price for every bank state compared with a banking-only system and there is only a slight difference in the upper bound steady state bank levels between the banking and banking–borrowing cases, the lower bound steady state permit price is roughly equal for both the banking-only and banking–borrowing cases. However, for the banking–borrowing case the lower bound of the steady state bank is significantly below that of the banking-only case. This forces the upper bound of the steady state permit price to be much higher in the banking–borrowing case compared to that in the banking-only case. So, while allowing borrowing lowers expected costs, it does not reduce steady state price variability compared to a banking-only system. In fact, our model shows that the increased variability associated with a banking–borrowing system can be quite substantial as the persistence of the shocks increases.

Discussion

These results suggest that bankable quantities help out in terms of expected welfare and reducing price volatility, but perhaps not as much as proponents might suggest. Costs and welfare are improved by about one-fifth of the difference between price and nonbankable quantity regulations.[12] More importantly, there is no protection against adverse costs in the initial period, as evidenced by the "zero-bank" results in Figure 3.

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[12] Note that the infinite horizon expected price/nonbankable quantity welfare difference of $185 billion is about five times the 40-year estimate reported in Newell and Pizer (2003). This is a result of a higher benchmark price in the current estimates (as well as the longer, infinite, horizon).

This suggests two possible policy modifications: some mechanism to create an initial bank as well as a possible safety valve mechanism (Pizer 2002). The effect of an initial bank is relatively easy to see. A small bank equal to the equilibrium bank can be introduced without changing the expected emissions level over time (because the effect of banking, in general, is to lower expected emissions initially, as the bank is acquired). While it is still possible that over time the market will wander toward a zero bank and large price shocks, the likelihood of these events is the product of both wandering toward a zero bank *and* having an adverse shock, which is less likely than the singular probability of having an adverse shock when we know the bank is zero.

Alternatively, one could introduce a large initial bank—say equal to twice the annual abatement requirement, or about 2 billion tons, as suggested at the end of the last section. This would initially depress the price to $20 (with consequently higher average emissions), but the range of prices would be cut by more than half. As the bank is drained, the price would again wander up toward the higher range. This is, in many ways, analogous to what happened in the SO_2 market shown in Figure 8. Under that program, overcompliance in the initial phase yielded a bank roughly equal to the annual emissions level. This bank was slowly being drawn down until 2004, when the policy was reformed with tighter targets beginning in 2010—leading to higher prices and renewed banking.

Evidence to suggest that prices continue to fluctuate even with a large bank can be found in the history of SO_2 prices themselves, which wandered between $100–$200 per ton over the first decade of the program. This is consistent with our observation that as long as shocks are correlated and persistent, prices will continue to fluctuate even with a large bank. Given the large bank, the market also witnessed even more significant price escalation in 2004–2005 as the new reforms were proceeding through the regulatory process. The price rose to more than $1,500 before settling down to around $600.

We should also note that proposals to allow borrowing are, for many intents and purposes, equivalent to introducing an initial bank.[13] For a large enough borrowing limit, we would expect an equilibrium with a nonzero expected debt.

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[13] The one difference is a proposed difference in the rate of interest on negative balances (borrowing) versus positive balances (banking). Most proposals suggest interest on borrowing, but none on banking.

All of this suggests another kind of policy might be useful: a safety valve whereby the government sells additional allowances at a fixed price. While Pizer (2002) finds the "optimal" safety valve policy would be to turn the quantity control into a price policy by setting the safety valve price equal to the expected price, he also finds that a high safety valve also significantly raises welfare relative to no safety valve. Here, it might make sense to include a high-price safety valve to address the risk of an initially high price level before any bank development.

A final point is to note recent proposals for a "reserve" rather than an unlimited safety valve (Murray et al. 2008).[14] That is, the government would sell up to a fixed reserve amount into the market when the price exceeded a given threshold. Given that a relatively small volume of permits is necessary to reduce prices, the use of an unlimited safety valve is unnecessary. A limit also has the potential to appeal to a broader audience of stakeholders, many of whom are highly focused on the emissions outcome.

Conclusions and Future Directions

Comparing price and quantity instruments has long provided a basic framework to analyze efficient regulatory controls. However, it is also possible for quantities to be banked and borrowed throughout time. For example, the ability to overcomply with a tradable permit system and bank unused allowances for future use is a central part of most observed emissions trading systems. What has been less well understood is the ability of banking to provide insurance against unexpected high-cost outcomes. Despite significant claims about this potential feature, there has been little analysis of how firms ought to behave in the face of uncertain costs and the opportunity to bank. Therefore, given the presence of uncertainty, it is the aim of this paper to investigate firms' behavior under bankable quantity regulation and then compare this to both price and quantity regulation in terms of expected welfare.

This paper has developed a relatively straightforward model of a representative firm's period-to-period decision to bank allowances under uncertainty. Solving the model numerically for parameters relevant for U.S. climate policy, we have made several observations. First, banking does improve welfare versus a nonbankable system, but does not achieve even half the benefits associated with a price policy. This arises primarily because of the persistence in baseline emissions shocks. Additional improvements in expected welfare also occur when

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[14] See www.rff.org/costscontainment.

borrowing and growth are taken into consideration. Second, there is still considerable price volatility: to the extent proponents expect banking to substantially dampen high prices, this does not appear to be the case. A large initial bank dampens prices more—although a large bank does not appear to be sustainable as it is desirable to draw it down. Borrowing provisions can be expected to behave similarly to a large initial bank. This suggests there may still be motivation for considering price mechanisms in addition to banking.

These preliminary results raise many questions, some of which we have already identified. In particular, what might motivate a larger bank? Both the SO_2 and NO_x programs have larger banks than would seem to be suggested by other features. Suppose marginal costs are nonlinear, with marginal costs rising faster for adverse shocks than falling for favorable ones. Or suppose there is some probability of transition to a new regulatory state—either tighter controls (as in the SO_2 program) or confiscation of the existing bank (as in the NO_x program). Finally, our approach to including growth, which is itself completely preliminary, may be inadequate to capture important features. By solving for a future steady state with a finite-horizon transition, we should be able to capture additional features. All of these are avenues we plan to pursue.

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Table 1. Parameter Values for Benchmark Solution of Banking Problem

Description	Parameter	Value
Slope of marginal costs	c_0	\$30/ton per billion tons
Annual baseline emissions	$\overline{q}$	6.7 billion tons
Annual cap	y	5.7 billion tons
Initial s.e. of emissions	σ	0.33 billion tons
(converted to cost s.e.)		\$10/ ton
Correlation of shocks	ρ	0.8
Long-run s.e. of emissions	$\sigma \big/ \sqrt{1-\rho^2}$	0.55 billion tons
(converted to cost s.e.)		\$17/ton
Discount factor	β	0.95
Trading ratio	R	1

Table 2. Net Present Value of Costs (dollars in billions)

Case*	Tax	Quantities	Bankable Q	Banking Gain
Benchmark	\$300	\$385	\$371	16%
Low discounting	\$600	\$777	\$730	27%
No correlation	\$300	\$333	\$318	45%
Low discounting + no correlation	\$600	\$667	\$627	60%
Borrowing**	\$300	\$385	\$369	19%
Benchmark with growth***	\$1,929	\$2,516	\$2,325	33%

Notes: *Benchmark parameter values given in Table 1. Low discounting sets $\beta = 0.975$. No correlation sets $\rho = 0.0$.

**For the borrowing case, $R = 1.1$ when permits are borrowed ($B_t < 0$) and $R = 1$ otherwise ($B_t \geq 0$).

***Benchmark with growth sets $g_c = -2.5\%$ and $g_a = 3.5\%$.

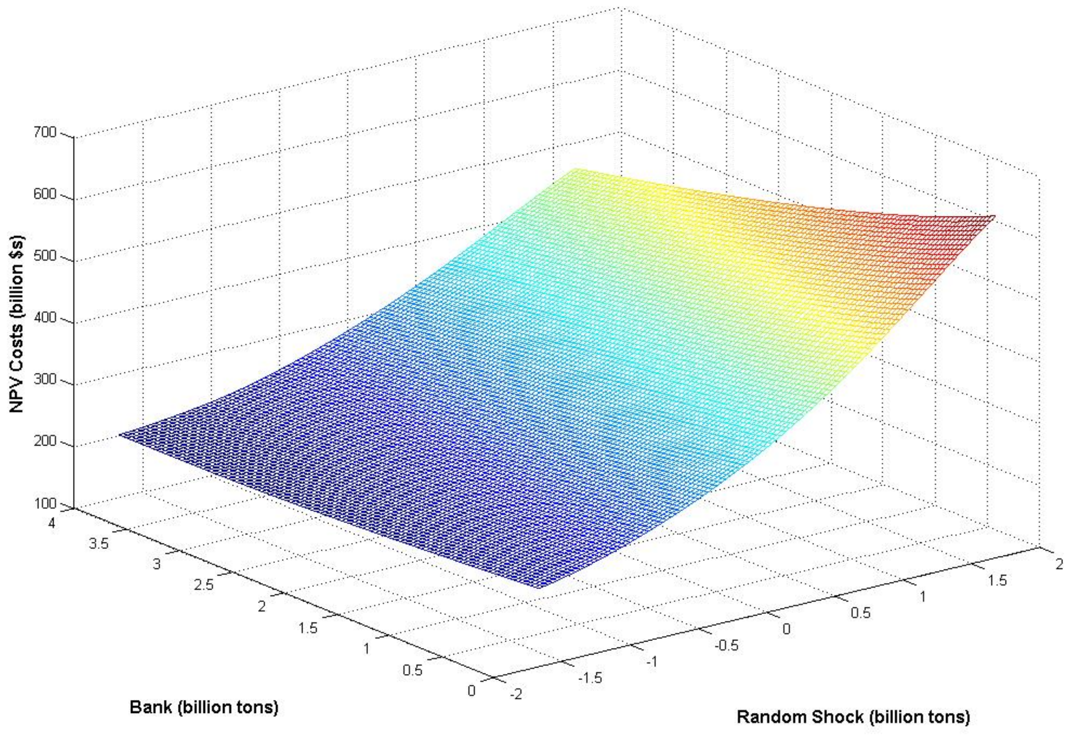

Figure 1. Value Function Based on Benchmark Parameter Values

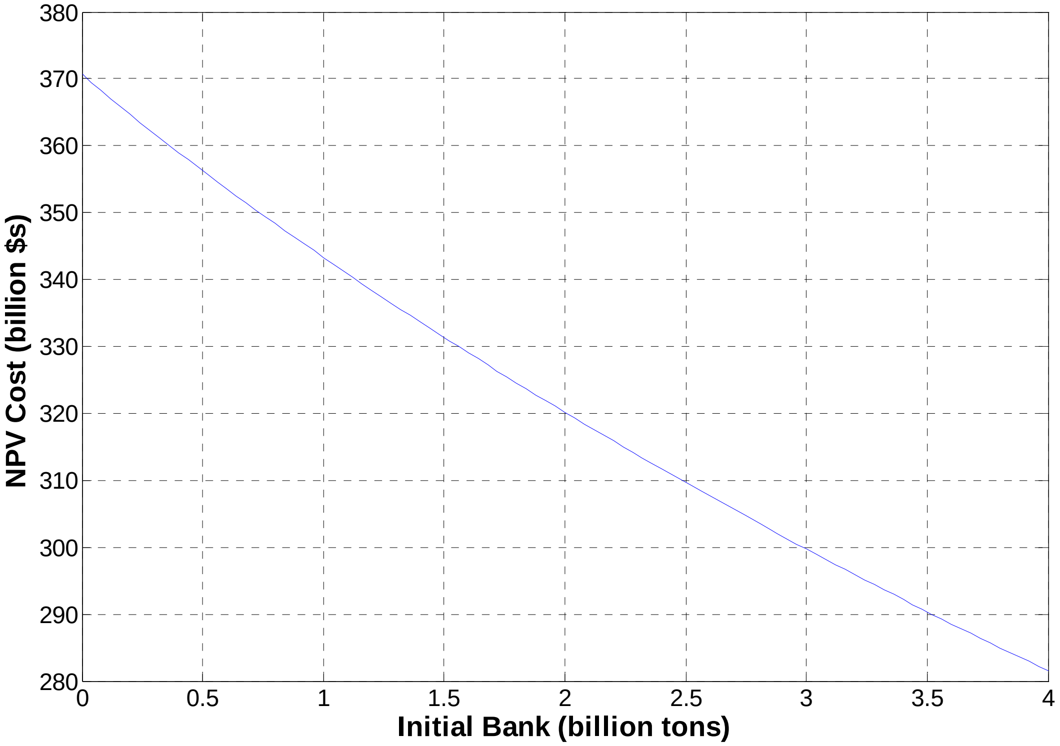

Figure 2. Value Function Averaged Over First-Period Shock Distribution

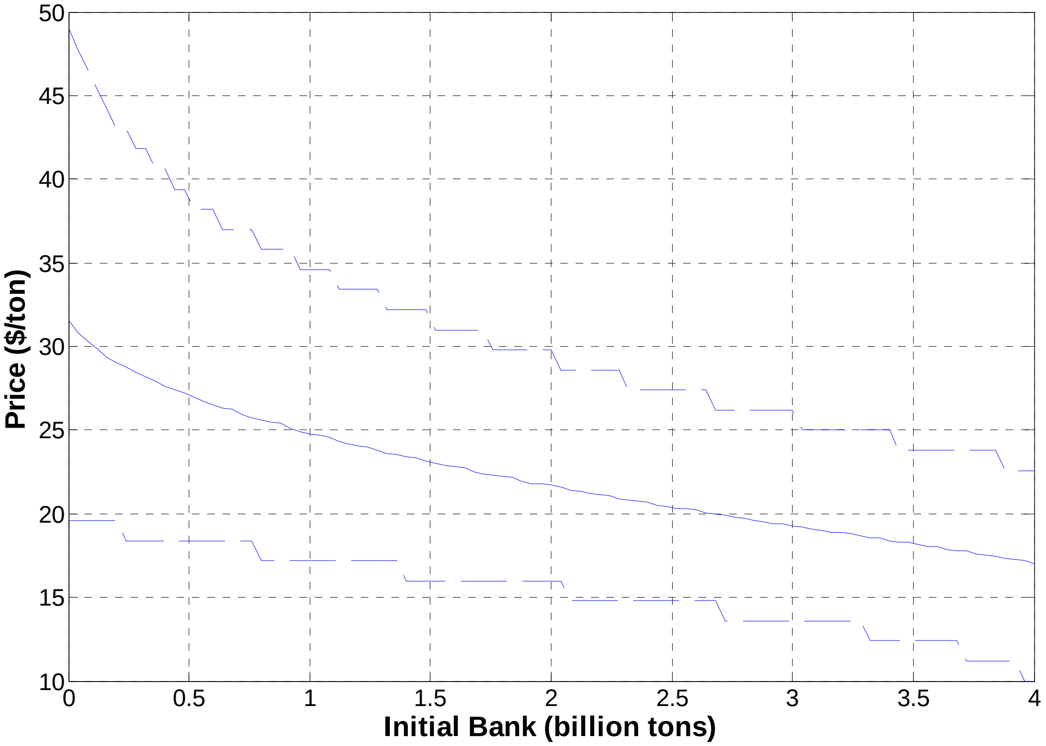

Figure 3. Mean Price and 95% CI Using Benchmark Parameters

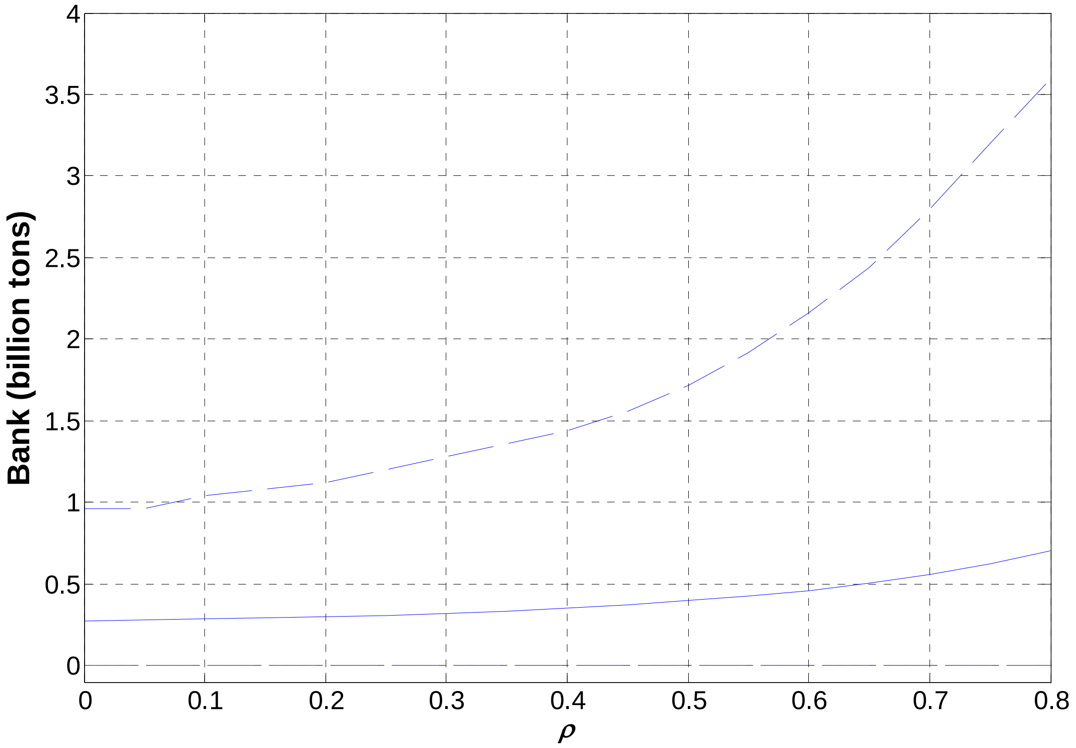

Figure 4. Steady State Expected Bank and 95% CIs with Banking Only

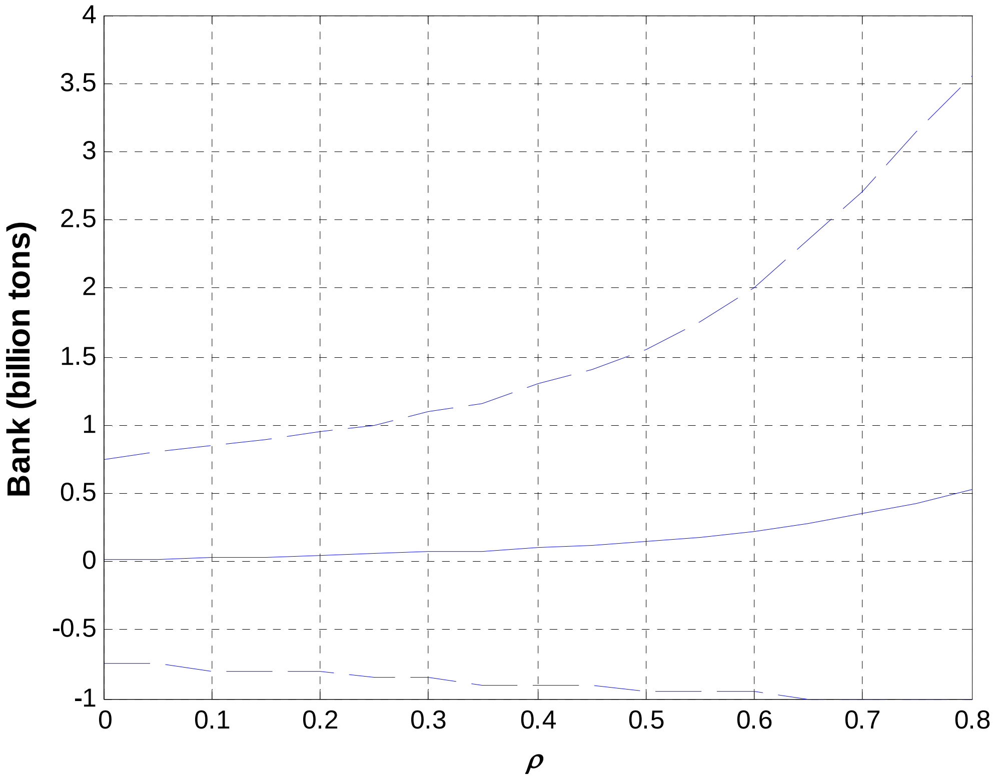

Figure 5. Steady State Expected Bank and 95% CIs with Banking and Borrowing

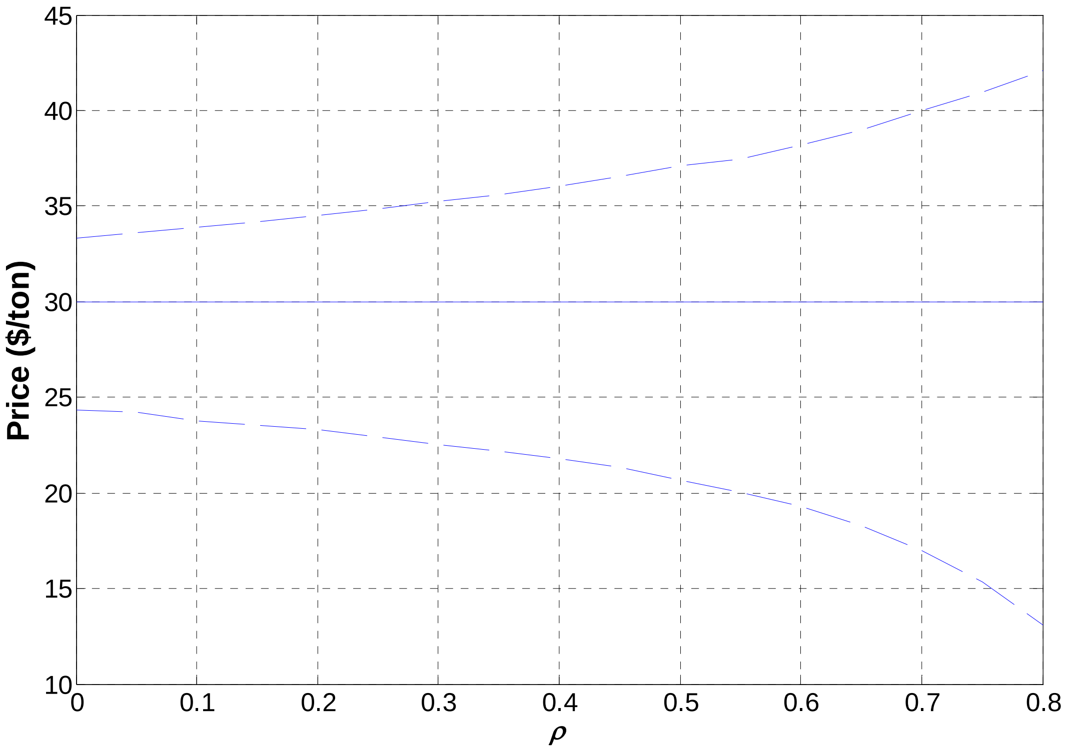

Figure 6. Steady State Expected Prices and 95% CIs with Banking Only

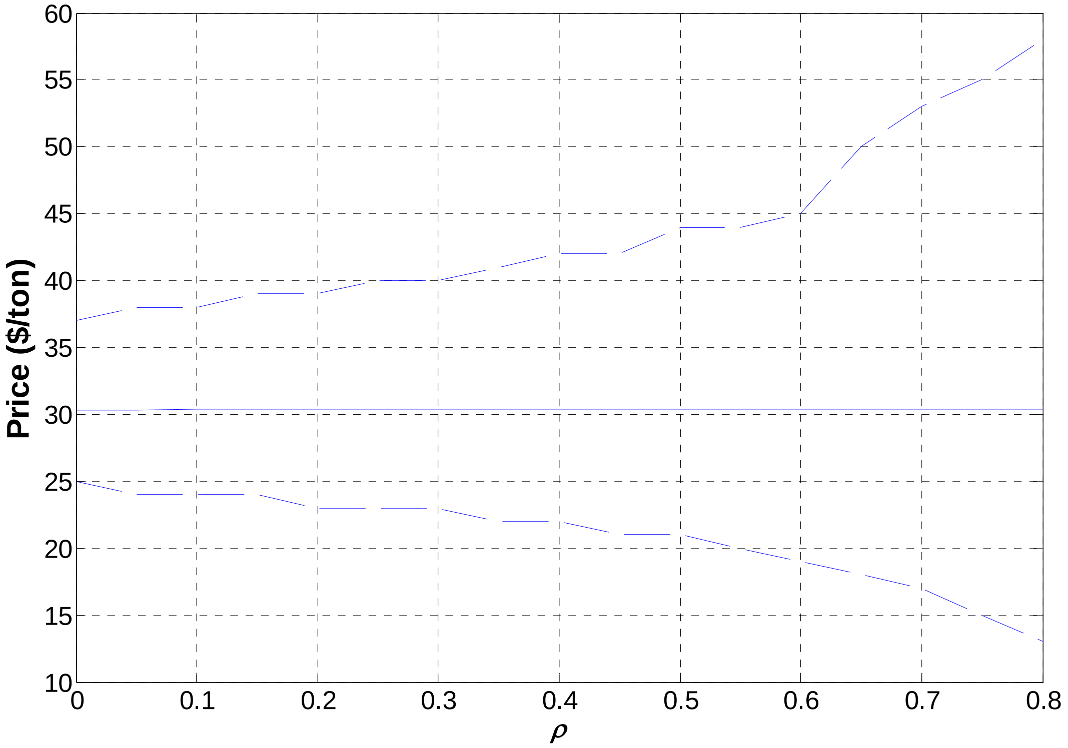

Figure 7. Steady State Expected Price and 95% CIs with Banking and Borrowing

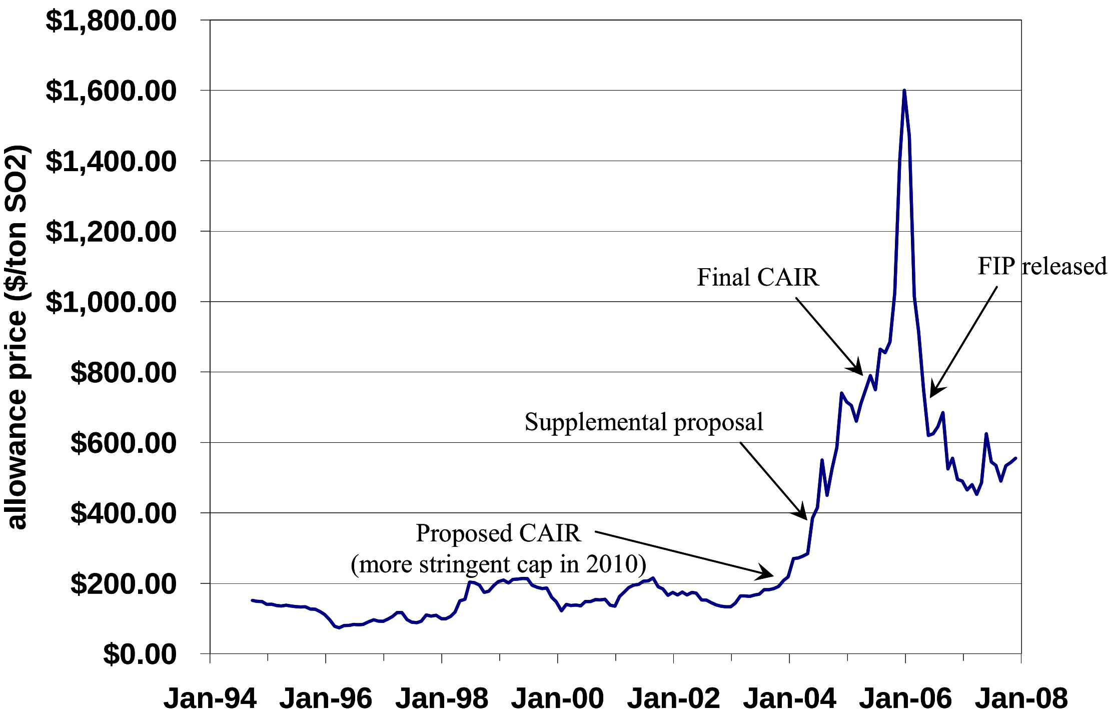

Figure 8. SO_2 Program, Current Vintage Price