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# Prices versus Quantities versus Bankable Quantities

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## Abstract

Welfare comparisons of regulatory instruments under uncertainty have typically focused on price versus quantity controls. This is true even in dynamic analyses of cumulative pollutants and despite the presence of banking and to some extent borrowing provisions in existing emission trading programs. Nonetheless, many have argued that such provisions can reduce price volatility and lower costs in the face of uncertainty. This paper develops a model and solves for optimal banking behavior with baseline emission shocks that are correlated across time. We show that while banking does reduce price volatility and lower costs, the degree of these reductions depends on the persistence of shocks. A large initial bank will also depress price volatility, but optimal behavior will eventually draw down the bank and lead to higher emissions and continued price volatility. For plausible parameter values related to US climate change policy, we find that bankable quantities eliminates perhaps one-fourth of the cost difference between price and non-bankable quantities. We find larger improvements when we extend the model to include expected growth abatement and marginal costs as well as borrowing of permits. This latter result suggests an opportunity for additional welfare-improving policy adjustment.

**Key Words:** welfare, prices, quantities, climate change

**JEL Classification Numbers:** Q55

## Contents

# Prices versus Quantities versus Bankable Quantities

Harrison Fell, Ian A. MacKenzie, and William A. Pizer*

## 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 U.S., 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 emission 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 associated with climate change policy. We find bankable quantity regulation improves welfare over a non-bankable system, but does not achieve welfare improvements over a price policy, reaching no more than half the difference between price and non-bankable quantity controls in virtually all cases (looking at discounting, correlation of shocks, growth, and borrowing).

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

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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.

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, and 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 has 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 free trade in pollution rights among firms once they are initially allocated by the regulator. As a consequence of competitive trading, abatement effort among regulated firms is efficiently distributed (Montgomery, 1972). Additionally, allowing firms the option to exchange permits between different time periods further reduces social costs by efficiently distributing abatement choices among 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 inter-temporal 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 which allow banking significantly reduce price volatility compared to the non-banking 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 non-banking 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 affect 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 throughout 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 emission reductions, as in Newell and Pizer (2003). 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, alters the cost associated with any emission level. Further, the benchmark model is extended to allow for (i) different correlation and discounting levels (ii) the ability of firms to borrow permits from future compliance periods and (iii) abatement and marginal cost growth.

Our numerical simulation, using 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 a larger initial positive bank and more favorable baseline emission 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 tends 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 as 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 a idiosyncratic shock (Friedman 1957).

Bankable quantities, although welfare improving over non-bankable quantities, generally achieve less than half the cost improvements associated with a price policy. The main reasons for the lower expected welfare are persistent shocks that encourage persistent deviations from average prices and raise expected costs (owing to their convexity) coupled with a small equilibrium bank (owing to its carrying cost). As noted, price volatility therefore continues to pose a problem. The small equilibrium bank could be addressed by creating a large initial bank, but there is an incentive for firms to draw down such a bank and, as a result, price volatility eventually continues. Alternatively, borrowing with interest could maintain the desired flexibility without being drawn down, as the interest rate on borrowing avoids the incentive to move outright towards the borrowing limit (which would occur without interest). While we focus on a simple model without growth, 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 plausible growth in costs and abatement lead to larger expected welfare gains (in terms of the potential gain between non-bankable quantity and price controls) compared to the benchmark no-growth 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

[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 emission 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).

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 stock externality regulation through a price, quantity or bankable quantity control instrument. Furthermore, we are able to provide insights into the incentives of firms when they select a particular bank level; 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 non-bankable 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 (non-bankable) 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

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

where $q_t$ is the quantity of emissions, $\bar{q}_t$ 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 $\theta_t$ is a baseline emission shock to the cost-minimizing emission level.[3] Potential changes in $c_t$ and $\bar{q}_t$ allow for cost reductions and growth in uncontrolled emissions over time. 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 $\bar{q}_t + \theta_t$ (ignoring the potential benefits). Any reduction in emissions below this level leads to increasing costs at an increasing rate.

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[3] NP, in turn following Weitzman (1974), specify $\theta_t$ 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 $\theta_t$ 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.

Also, following their approach, we allow for emissions to accumulate in the environment.

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

where $S_t$ is the accumulated stock of emissions at time $t$, which accumulates with decay rate $\delta$. 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

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

where $\bar{S}_t$ 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

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

where

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

$r$ 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 $\Omega$ terms equal 1 and the expression reduces to the original Weitzman (1974) expression for comparing price and quantity controls. Summing this $\Delta_t$ expression over time, e.g., $\sum_t (1+r)^{-t}\Delta_t$, 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 $\sigma_t^2 c_t / \left(2c_t^2\right)$ and a decrease in expected benefits given by $\sigma_t^2 b_t \Omega_\delta \Omega_{\rho,t} / \left(2c_t^2\right)$. 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 non-bankable quantities—does not diminish benefits because in all cases emission reductions are occurring 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 firm behavior. As before, the firm faces the quadratic cost function given above where the firm is given a set emission 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 emission 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]

[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).

We can now write the firm's optimization problem as

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

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 $\theta_t$, 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 backwards 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 without 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 $\Delta q_t = q_t - y_t$ replaces $q_t$ as the choice variable. This suggests redefining the bank $B_t$, choice variable $\Delta q_t$ and shock $\theta_t$ in terms relative to the required abatement each period, absent banking: $\widetilde{B}_t = B_t/(y_t-\overline{q}_t)$, $\Delta\tilde{q}_t = \Delta q_t/\left(y_t-\overline{q}_t\right)$, and $\widetilde{\theta}_t = \theta_t/(y_t-\overline{q}_t)$.[5] By changing the discount rate to $\widetilde{\beta} = \beta(1+g_c)(1+g_a)^2$ the discounted cost function again becomes time invariant,

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

and we can then rewrite the value function as:

[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.

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

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

It is useful to note that $\tilde{\beta}^t c_0\left(y_0-\overline{q}_0\right)^2/2$ equals the net present value of costs each period under price regulation designed to yield emissions equal to $y_t$ on average. Similarly, $\tilde{\beta}^t c_0\left(y_0-\overline{q}_0\right)^2 E\left[\left(1+\tilde{\theta}_t\right)^2\right]/2$ 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

In the previous section, we showed the firm's optimization problem in the presence of banking; however, 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 x 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 maximize (4) or (5) using the given current period cost function, this next period expected value function, and the accumulation rule for the bank (2). This gives us a new estimate of the value function. To help improve convergence, our next guess for the value function 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 non-banking case as well as a price policy. Our benchmark case is the non-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 $\overline{q}$ = 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).

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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 over-relaxation when the weight on the new estimate is greater than one (and the old guess has a negative weight). See Wilmot et al. (1995) for more details.

This implies $c_0$ = \$30 per ton per billion tons, or \$3 x $10^{-8}$ \$/ton$^2$. We assume the standard deviation of the iid 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 $\theta$ 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.

Before discussing our findings, it is useful to note that the primary output of the numerical effort is the value function, defined over the bank value $B_t$ and level of the baseline emission shock $\theta_t$. The negative of the value function defined in (4), that is, the net present value costs resulting from our numerical optimization, is depicted graphically 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).[8]

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 emission 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 emission 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 \$371 billion.

In order to provide a comprehensive discussion of expected costs associated with price, quantity and bankable quantity regulation, Table 2 summaries our findings for a number of scenarios for all three policies (columns 1-3) and with the gain from bankable versus non-bankable permits shown as a percent of the gain from prices versus non-bankable permits (column 4). That is column 4 answers the question: if we view prices as the first-best policy, how far does banking move us in that direction versus the traditional analysis of non-bankable permits? For a preliminary comparison, we investigate our benchmark values consistent with S.2191 (Lieberman-Warner), discussed in the preceding paragraph and shown in Figure 2. From

[8] 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 4 times the annual abatement level of 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).

this, we extend our simulation to include lower levels of discounting and shock correlation as well as introducing the ability to borrow and the possibility of growth in abatement and marginal costs.

From column 4 in Table 2, our main conclusion is that bankable quantities generally achieve less than *half* the cost improvement associated with a tax policy. Focusing on the benchmark values given in row 1 of Table 2, a tax policy $E[q_t] = y_t$ where costs equal $\beta^t c_0 \left( y_0 - \overline{q}_0 \right)^2 \big/ 2$ in each period results in net present value costs equal to $300 billion. Whereas for a non-bankable permit policy $q_t = y_t$ where 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, net present value costs are $385 billion. By allowing quantities to be banked, we find net present values costs are $371 billion. From this, we see that bankable quantities achieve roughly one-sixth the cost improvement associated with price policies for the benchmark parameters. 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 benefit is so much flatter—hence our cost analysis is equivalent to a welfare analysis. Further, banking serves to move emission reductions from the future to the present (and emissions from the present to the future) thereby, if anything, *increasing* benefits relative to fixed emission constraints.

By additionally allowing for lower discount rates ($\beta = 0.975$) and no correlation ($\rho = 0$), rows 2-4 of Table 2 show the cost improvements associated with bankable quantity policies in column 4 jump to 27 and over 40 percent, respectively (allowing for both low discounting and no correlation results in a 60 percent cost improvement). 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 non-banking system to a system that allows banking is greater as the correlation declines.

To explore the possibility of borrowing, we first note that borrowing without interest is isomorphic to the original banking case with an initial bank. That is, there is no difference in results between borrowing with a zero initial bank, and banking with an initial bank equal to the borrowing limit – if the interest rate on borrowing is zero. Instead, we explore the case where borrowing is permitted and must be repaid with 10 percent interest.[9] This alters the trading ratio in the banking state equation, (2), such that

$$R_t = \begin{Bmatrix} 1 & \text{if } B_{t+1} \geq 0 \\ 1.1 & \text{otherwise} \end{Bmatrix}.$$

Additionally we assume that borrowing in any period is limited to one billion tons. As shown in row 5 of Table 2, allowing both banking *and* borrowing leads to a slight improvement in column 4 versus the benchmark—achieving 19 percent of the difference between prices and non-bankable quantities, compared to 16 percent under the benchmark. We can understand what happens as the interest rate goes to zero (borrowing is equivalent to an initial bank) by recalling the initial point without interest and then looking back at Figure 2: When the initial bank is 1 billion tons, costs are about $345 billion (or almost half the price versus non-bankable quantity gain)—a much larger gain. There are also larger gains if we relax the borrowing limit, a point we come back to in the steady-state discussion.

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).[10] As can be seen in row 6 of Table 2, the growth assumption dramatically increases the net present value of costs for all regulation forms compared to the non-growth scenarios but also the relative performance of banking. Banking in the growth case achieves about one-third the cost improvement associated with price policies versus 16 percent for the benchmark parameters without growth, or roughly double. Intuitively, allowing growth in the model effectively increases the discount factor (reduces the discount rate) compared to the benchmark which increases the importance of future periods (see discussion before Equation(5)).

Distinct from welfare and expected costs presented in Table 2, 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

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

[10] 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 emission levels in 50 years. This is roughly inline with S. 2191 which calls for a 65 percent reduction in current emission levels by 2050.

useful to look at how banking affects price variability. To do this, observe Figure 3 which shows the mean price for various levels of the bank, along with 2.5 percent and 97.5 percent frequency quantiles, based on the initial shock distribution and benchmark values.[11] Note that the 95 percent frequency interval for baseline emission 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 initial bank (and no borrowing), banking cannot help with adverse shocks: the 97.5 percent quantile is still $50. However, with an initial bank, the upper range falls (a bank of 0.5 billion tons results in an upper range of $40). Another interesting observation is that even with a *large* initial bank of 2-3 billion tons—several times the annual abatement requirement—prices still have a 95% frequency interval of about 1/3 of the original non-banking case. In the case where correlation is set to zero (not shown here), this range associated with a large bank drops to about 1/10 of the non-banking case. In other words, even with a large bank, some price volatility remains when shocks are persistent (as in our benchmark case).

## 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. We focus on two cases: a system with banking only (our benchmark) and a system that allows both banking and borrowing (our borrowing case). We also specifically explore the effect of persistence, and consider correlation between cost shocks ranging from zero to our benchmark value of 0.8. Both assume no growth.

Figure 4 highlights our results. The top panels of Figure 4 show the relationship between correlation and the steady state distribution of bank level. Here, we see that the expected bank level and 95 percent confidence intervals (CIs) of the bank increases as shock correlation increases, which is not surprising as the long-run standard deviation of the emission shocks is proportional to $\left(1-\rho^2\right)^{-\frac{1}{2}}$. For a system with both banking and borrowing (the top-right panel), when baseline emission shocks are less persistent, bank levels fluctuate between roughly symmetric positive and negative values. This creates a steady state bank time-path that is

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

centered around a zero mean. However, as persistence in the shocks increase, the steady state bank levels drift (more persistently) from zero. This leads to greater variation in the bank, and, as the 1 billion ton borrowing limit becomes a constraint, the expected bank becomes positive. With banking only, the constaint that $B_t \geq 0$ is relevant even for small correlations, and the expected steady state bank level is always positive.

The lower panels of Figure 4 show the relationship between the correlation parameter and the steady state distribution of prices. Regardless of shock persistence, the expected permit price in a banking-only policy is simply the expected marginal cost of abatement, \$30/ton. This is because, on average, $y_t = q_t$ just as it would with in a no-banking system. However, an interesting result, readily observable in the lower right panel of Figure 4, 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, $q_t < y_t$ seeming 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 plots of steady-state prices also show that the variability in the price increases considerably as shock persistence increases. This result is, again, due to the fact that persistent shocks can be larger in the steady state as the standard deviation of cost shocks is proportional to $\left(1-\rho^2\right)^{-\frac{1}{2}}$.

Comparing the steady-state price variability across the cases with and without borrowing, the banking-only system has more variability for any given $\rho$ value than the banking-borrowing system. This is as expected since including borrowing allows firms to dampen the impact of adverse baseline emissions shocks and thus lowers the upper bound of steady-state prices relative to those of the banking-only system. Importantly, as noted earlier, the use of a positive interest rate for borrowing (and a zero rate for banking) is what maintains the borrowing margin. However, the reduction in steady-state price variability offered by the banking-borrowing system compared to the banking-only system decreases as the shocks becomes more persistent. The cause of this result can be seen in the top panels: With more persistence, the borrowing constraint becomes relevant and no longer provides the necessary cushion given the size of the shocks. Looking at the right edge of the lower panels, corresponding to our benchmark correlation of 0.8, we see that there is actually little reduction in the steady state price range—this explains why borrowing has a small effect compared to the benchmark without borrowing (noted earlier): The borrowing constraint we use (1 billion tons) is not sufficiently flexible to deal with the size of the steady-state cost shocks.

## Discussion

These results suggest that bankable quantities help out in terms of expected welfare and reducing price volatility, but perhaps not as much as we might have guessed. Welfare is improved by about one-sixth of the difference between price and non-bankable quantity regulations in the benchmark case, and perhaps one-fourth when we jointly consider the case with growth.[12] More importantly, Figure 3 and our discussion of borrowing point to a large potential value in either beginning with an initial bank and/or including borrowing.

For example, 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 5. Under that program, over-compliance in the initial phase yielded a bank roughly equal to the annual emission 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 so 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 $1500 before settling down to around $600.

While an initial bank provides initial flexibility, there will be pressure to draw it down even in the absence of adverse shocks. Borrowing without interest would face the same fate, but borrowing *with* interest provides an incentive to keep the borrowing option open until adverse shocks arise. However, as we saw in the steady state discussion, the borrowing limit can be too small to be effective if the *steady state* shock distribution is not considered. It is worth noting that the Dingell-Boucher draft legislation released in October 2008 contained both of these

[12] Note that the infinite horizon expected price / non-bankable quantity welfare difference of $185 billion is about 5 times the 40-year estimate reported in Newell and Pizer (2003). This owes to a higher benchmark price in the current estimates (as well as the longer, infinite, horizon).

elements. It allows interest-free borrowing of up to a year's worth of allowances (equivalent to an initial bank of 6 billion tons in our calculations) *and* borrowing up to 15 percent of the cap at 8 percent interest (equivalent to a borrowing limit of 1 billion tons in our calculations).

## Conclusions

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 over-comply with a tradable permit system and bank unused allowances for future use is a central part of most observed emission trading systems. The ability of banking to provide insurance against unexpected high cost outcomes has generally remained unexplored despite claims about this potential feature.

The aim of this paper has been to investigate firms' behavior under bankable quantity regulation and to compare this to both price and quantity regulation in terms of expected welfare. To do so, 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 non-bankable system, but does not achieve even half the benefits associated with a price policy. This arises both because of the persistence in baseline emission shocks that makes banking less valuable and the small equilibrium bank. The latter can be addressed by inclusion of borrowing with interest, which leads to further improvements. Banking is also more valuable when we consider realistic growth parameters, owing to the larger weight given to the future when the bank level has been able to equilibrate.

Second, as the welfare results suggest, 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, but a large bank is not sustainable as it is desirable to draw it down; borrowing provisions without interest would behave in the same manner. However, borrowing *with* interest creates an incentive to maintain the option until high costs arise. This suggests a desire for borrowing with interest and a large initial bank, addressing flexibility in both the short and longer run.

These results raise many questions, some of which we have already identified. In particular, what else 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 non-linear, 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). While we have sought to understand how banking *ought* to proceed, it remains for future work to more carefully compare these predictions to observed behavior.

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## Tables and Figures

**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 | $\bar{q}$ | 6.7 billion tons |
| Annual cap | $y$ | 5.7 billion tons |
| Initial s.e. of emissions | $\sigma$ | 0.33 billion tons |
| (converted to cost s.e.) | | \$10 / ton |
| Correlation of shocks | $\rho$ | 0.8 |
| Long-run s.e. of emissions | $\sigma / \sqrt{1-\rho^2}$ | 0.55 billion tons |
| (converted to cost s.e.) | | \$17 / ton |
| Discount factor | $\beta$ | 0.95 |
| Trading ratio | $R$ | 1 |

**Table 2: NPV 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*** | $1929 | $2516 | $2325 | 33% |

*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**

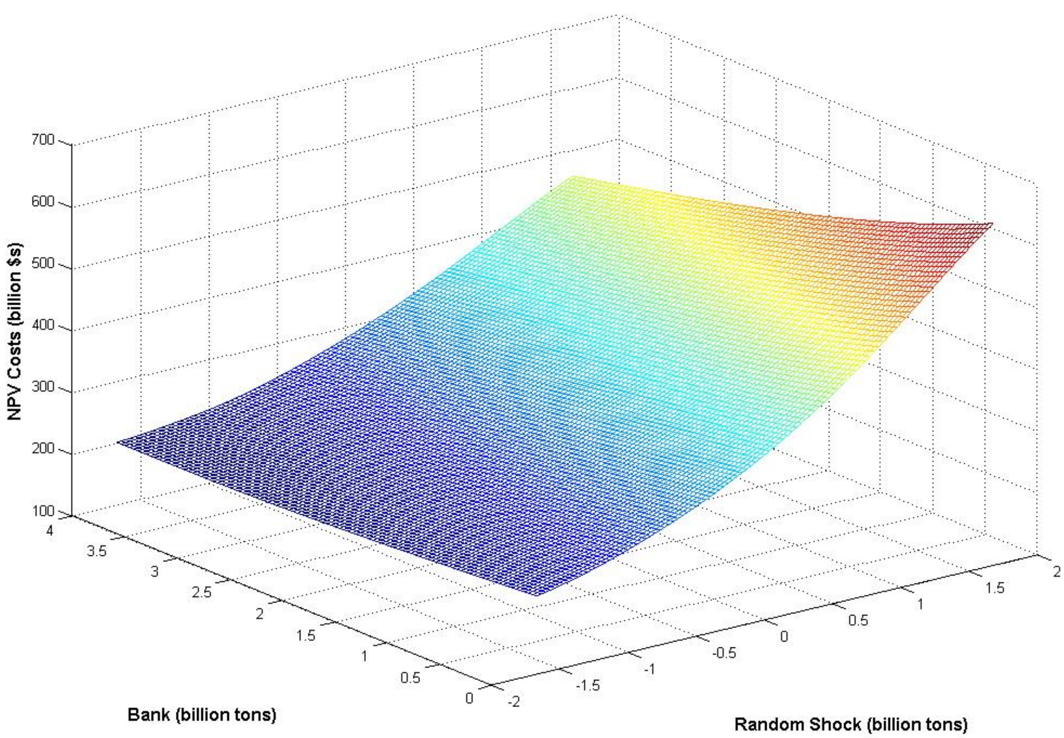

**Figure 2: Value Function Averaged Over First-period Shock Distribution**

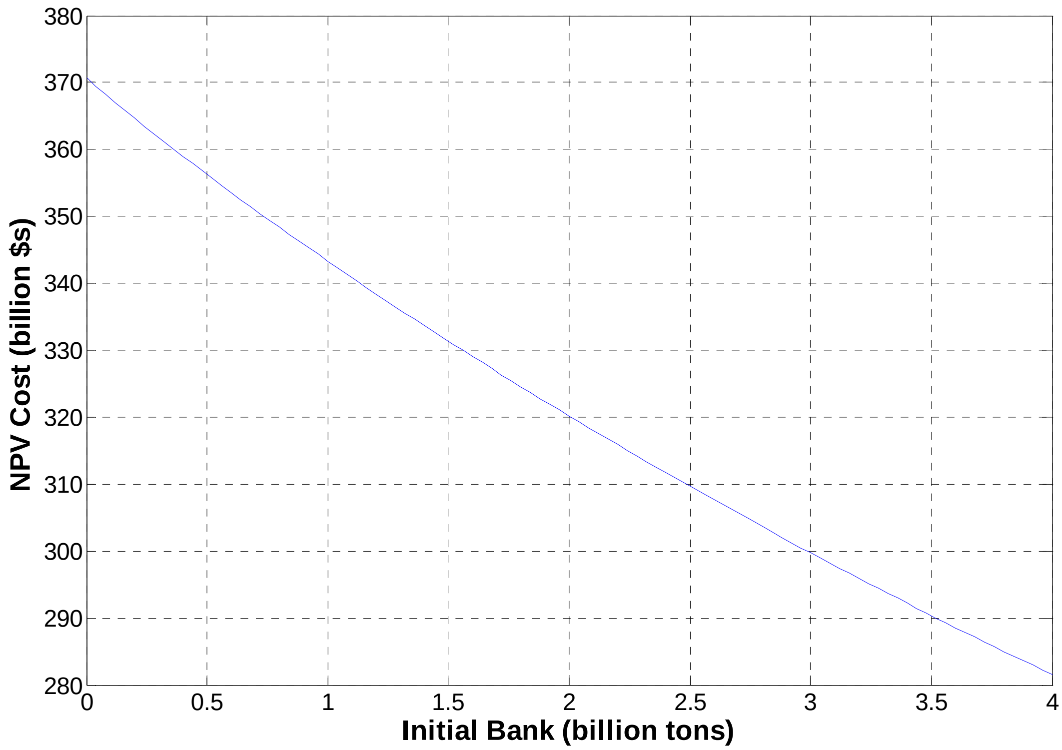

**Figure 3: Mean Price and 95% Confidence Interval Using Benchmark Parameters**

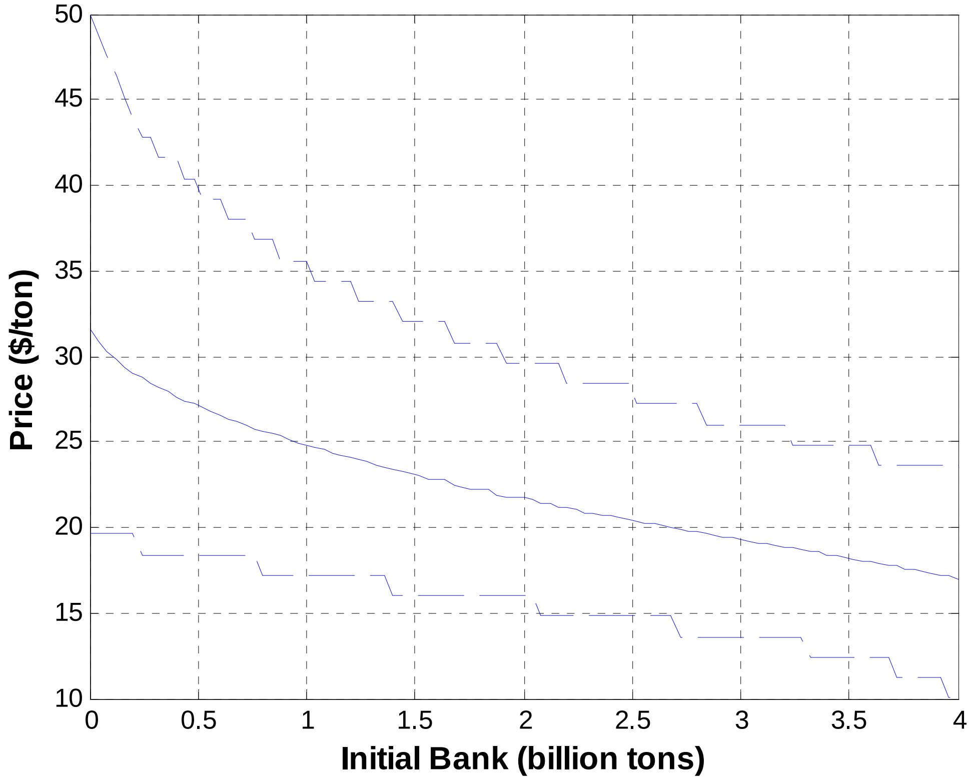

**Figure 4: Steady State Expected Banks and Prices with 95% CIs**

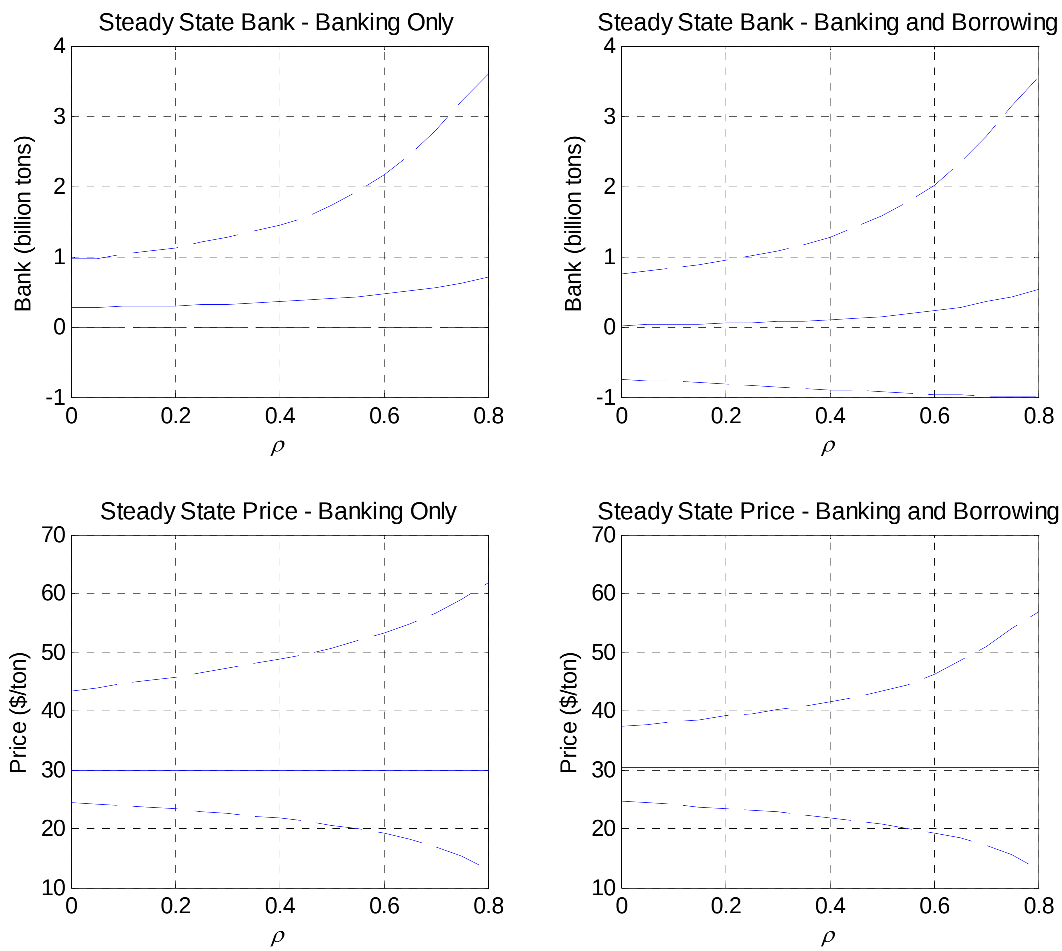

**Figure 5: $SO_2$ Program, Current Vintage Price**