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OIL SUPPLY SHOCKS AND INTERNATIONAL POLICY COORDINATION*

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This paper examines the value of international cooperation in an oil supply disruption. The perspective is that of oil-importing countries; since the oil market is integrated internationally, the actions of one have spillover effects on the others. We focus on buffer stock policies, with each player maximizing the present value of national income less the cost of operating the stockpile program. We contrast cooperative and Cournot–Nash solutions to the dynamic game, paying special attention to the asymmetries between small and large countries. The principal results are reviewed to assess the viability of current international agreements.

1. Introduction

The past decade has been one of the violent fluctuations in international commodity markets. The 'commodity boom' has been most pronounced in the oil market, where supply shocks in 1973–1974 and in 1979 have dislocated established trading patterns, inflicted substantial damage on the OECD economies, effected enormous wealth transfers to oil-exporting countries, and resulted in large and persistent increases in oil prices. The average price of a barrel of crude oil stood at roughly $2 in 1970, $12 in 1975, and $30 in 1980.

Economists have proposed and examined policies to alleviate the adverse shocks of supply shocks [Gordon (1975), Gramlich (1979), Mork and Hall (1980)], but have relatively little to say about mitigating the shocks them-

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selves.[1] Inasmuch as macroeconomic costs are related to the magnitude of the shocks, the use of policies designed to act directly on oil prices suggests itself. Our focus here is on one such policy – the use of a national oil stockpile. The United States has had such a stockpile (known as the Strategic Petroleum Reserve) since 1975.

Since the oil market is internationally integrated, the use of a buffer stock by one country has spillover effects on others. The possibility of international policy coordination thus becomes important in attempting to reduce the economic impacts of oil shocks. Our investigation parallels a recent strand of the macroeconomics literature [Johansen (1982), Canzoneri and Gray (1983), Miller and Salmon (1983), Sachs (1983)] that compares international coordination of stabilization policies with non-cooperative (Cournot–Nash) equilibria.

In a policy context, issues of the optimal size of public oil stockpiles have been discussed,[2] and empirical estimates of the impact of stockpile releases on world oil prices have been made [see Hubbard and Weiner (1983b) and U.S. General Accounting Office (1983)]. However, unlike the case of agricultural stockpiling behavior in a single country [for which optimizing models have been elaborated in Gustafson (1958), Goreux (1978) and Newbery and Stiglitz (1981)], virtually no attention has been paid to optimizing public stockpile behavior in the oil market. Second, while empirical studies have found merits (in terms of lower prices) of international stockpile coordination, issues of whether such an outcome would occur in the absence of an agreement and of what types of institutional mechanisms might facilitate cooperation have been largely ignored.

The goal here is to characterize optimal stockpiling behavior of consuming countries in a market subject to supply shocks, and to examine the ability of coordinated agreements to enhance the benefits of such behavior. Toward those ends, the paper is organized as follows. Section 2 of the paper reviews the institutions of international cooperation in the oil market as embodied in the International Energy Agency (IEA) and addresses the basic policy issues of stockpile coordination. Section 3 develops intertemporal optimizing models of private and public stockpiling, comparing their motivations and implications. Since our focus is on market behavior in the short run, our formulation of supply neglects the exhaustible nature of the resource. Stockpiles held by consumers, however, are similar to reserves, lending a Hotelling flavor to the problem.

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[1] Surprisingly, the substantial recent literature devoted to modeling the oil market has virtually ignored short-run issues and has been characterized as ill-suited to capturing the effects of supply disruptions [Stanford University Energy Modeling Forum (1982)].

[2] Some earlier analyses of the size and management of public stockpiles can be found in Hogan (1983), Teisberg (1981), Wright and Williams (1982), and Hubbard and Weiner (1983b). Nichols and Zeckhauser (1977) review some of the motivations for establishing public strategic stockpiles.

We find that the extent of serial correlation of shocks is particularly important. Knowledge of the intertemporal correlation of the impacts of shocks is central to the analysis of optimal stockpiling schemes.[3] Treating public stockpile behavior as an international game, we contrast non-cooperative and cooperative solutions. In general, whether the response for a given country is greater under a collusive agreement than in the Cournot–Nash equilibrium depends on the oligopsony potential generated by collusion and on the persistence of a transitory shock's effects on prices. With significant serial correlation, the non-cooperative drawdown will be 'too small'; that is, each country will draw down less than the Pareto-optimal amount.

Section 4 reviews the principal results of the paper in assessing the validity of proposed international agreements. Conclusions and directions for future research are given in section 5.

2. Institutional considerations: The International Energy Program

This section offers a brief description and interpretation of the existing agreement on international energy cooperation.

The provisions are codified in the International Energy Program, signed in 1974 by the major OECD countries except France (though there is some indication that France is a de facto signatory). This agreement, which is up for review in 1986, is administered through the International Energy Agency (IEA), an organ of the OECD.[4]

The agreement is successor to informal cooperation in the oil market among the industrialized countries, first through the OEEC, and later through the OECD. Frankel (1958) discussed the role of the OEEC's Oil Committee in the rerouting of tankers from the western hemisphere to Europe during the Suez Crisis of 1956. The OECD Oil Committee and EEC Energy Committee were ineffective during the 1973 oil embargo, however. The members did little collectively but argue among themselves, while scrambling for oil supplies individually, thus serving to bid up the price of oil. This was the impetus for the formal cooperative agreement.

Details of the agreement are too involved to present in entirety [see U.S. Senate Committee on Interior and Insular Affairs (1974)], but the salient points are three. First, countries are required to hold buffer stocks in proportion to their imports. Second, the agreement is dormant until a determination of emergency is made – referred to as 'triggering'. The

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[3] This finding is related to Blinder's (1982) study of optimal inventory behavior in the presence of serially correlated demand shocks, in which he determined that shocks elicit smaller (in absolute value) responses of inventory investment.

[4] The OECD econonies consume 75 to 80 percent of petroleum traded outside the communist bloc, and hold nearly 100 percent of the inventories.

emergency is signalled as a quantity shock, which must be sufficiently large in absolute value to reduce supply by 7 percent compared to its preshock value.[5] Third, the agreement calls for countries to 'restrain demand' by 7 percent (e.g., through taxes, tariffs, regulation, exhortation – not just reductions stemming from world price increases) and substitute buffer stock releases in making up any remaining loss in supply (e.g., a 10 percent reduction in quantity supplied calls for 3 percent to be made up by stockpile releases in addition to the 7 percent demand restraint).[6] The scheme's monopsonistic intent is clear.[7]

That cooperation can reap benefits begs the question of how it might be achieved. Regulation at the international level is difficult to enforce. Since there is no regulator with the power to require compliance, the incentive question naturally arises. While import restriction is clearly in the interest of the group as a whole, the effectiveness of the regulatory rules in attaining the cooperative outcome is not evident.

Numerical estimates of the benefits are useful in gauging whether cooperation is worth the effort. There is a small literature on this subject; the estimated value of cooperation varies due to the diverse modeling techniques and assumptions used. Although the estimated benefits are difficult to compare across studies, a consensus exists that the value of such action is substantial.[8] For example, Manne (1982) employed a static model with no uncertainty to examine a 25 percent permanent loss of oil production capacity. He compared the optimal OECD joint tariff with the optimal tariff for the United States acting alone, finding gains of roughly $40 billion (1980 dollars) to the United States, and $60 billion to the OECD, from the former to the latter. Hogan (1983) generated numerical solutions using a dynamic programming model, and found even larger benefits from coordinated stockpile releases.

These studies [see also Rowen and Weyant (1982), Chao and Manne (1982)] did much to delineate the importance of the issue, but little to expose

[5] In practice, the pre-shock value is a moving average of the previous four quarters. The agreement can also be triggered when one member country loses 7 percent of its base-period consumption, but the IEA as a whole does not. Given the rigidities present in the oil market, this 'specific trigger' situation is far more likely to occur than the 'general trigger' described above, wherein countries are assumed to be affected equally. Given, however, that more is always available to those willing to pay, it is difficult to assign a meaningful interpretation to this case, and it will not be discussed further.

[6] A reduction in quantity supplied of at least 12 percent obliges members to reduce demand by 10 percent.

[7] For a detailed critique of the IEA on technical, rather than economic grounds, see U.S. General Accounting Office (1981). In addition to its 'emergency provisions', the agreement calls for cooperation in longer-term energy policies, e.g., conservation, fuel-switching, and research and development of alternative energy sources. Although they scarcely mention economics, the regulations can be viewed as designed to facilitate cooperation on the demand side of the oil market.

[8] Hickman and Huntington (1984) analyze the differences among estimates reported by various simulation models of oil-disruption caused economic damage.

the economic structure of the problem. The next section develops a model designed to illuminate the 'cartel problem' in this market. The model is specified in terms of inventory behavior, although in the agreement market power is exercised through both buffer stock releases and demand restraint. The reasons for doing so are twofold. First, the two are equivalent from the standpoint of the world market. Second, inventory fluctuation has played an important role in price determination during past supply shocks, whereas demand regulations have proved difficult to monitor and enforce.[9]

3. Intertemporal optimizing models of stockpile behavior

Stockpile policy is inherently more complex to analyze than are tariffs and quotas, since it requires an explicitly intertemporal model; in a one-period framework, it is always optimal to liquidate the entire stockpile. We simplify the analysis by taking the stockpile size as given at the time of disruption, and utilize the dynamic methods recently popularized in macroeconomics [Sargent (1979)], to examine drawdown decisions.[10]

3.1. Optimal private stockpiling

As a point of reference, we begin with a model of private stockpile behavior. The emphasis is on speculative stockpiling, that is, inventory acquisition for the purpose of a future sale on the anticipation of price appreciation. We assume that firms maximize the present value of expected future profits. Inventory adjustment is assumed to be costly – in fact, increasingly costly – in the size of the adjustment due to rising payments to factors fixed in the short run, in this case storage facilities, tankers and pipelines. Thus changes in price expectations cannot be fully acted upon instantaneously. We follow the literature in modeling these costs as quadratic, the simplest specification of 'diminishing returns'.

The notation is as follows: Stock levels are measured at the end of period t. Firms (assumed to be price-takers) buy oil in period t at price p_t, and expect to sell at price p_{t+1} next period. The stream of expected future profits is discounted at rate δ. Holding costs have a linear component at a constant rate c; the cost of adjustment parameter is denoted by h.

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[9] A case in point was the IEA decision to restrain demand by 5 percent in March 1979, which was widely ignored. In contrast, consensus credits stockpile behavior with turning the 1978–1979 disruption into a catastrophe, while smoothing the effects of the 1980–1981 disruption, which were of similar magnitude; about 5 percent of world production capacity was lost on each occasion. Verleger (1982) contains an empirical investigation of the role of inventories in oil-price behavior; Bohi (1983) discusses the problems with such empirical work.

[10] Calculations of optimal stockpile size entail solving a dynamic programming problem. While analytically intractable, the problem has been solved numerically by assuming that the oil market can be characterized by a small number (two or three) of Markov states. Hogan (1983) has extended to two countries the single-country case analyzed by Teisberg (1981) and Chao and Manne (1982).

The firm's optimization problem in period t can be written

$$\max_{I_{t+i}} \mathrm{E}_t \left\{ \sum_i (1+\delta)^{-i} [(1+\delta)^{-1} p_{t+i+1} I_{t+i} - p_{t+i} I_{t+i} - c I_{t+i} - \frac{h}{2}(I_{t+i} - I_{t+i-1})^2] \right\}, \tag{1}$$

$i=0,\ldots,\infty$, subject to $I_{t+i} = I_{t+i-1} - R_{t+i} + X_{t+i}$, where R and X are the firm's sales and purchases respectively. E_t denotes the expectation operator (conditional on the information set in period t).

Differentiation of (1) with respect to I_{t+i} yields the Euler equation

$$\mathrm{E}_t \left\{ (1+\delta)^{-i} \left[\frac{p_{t+i+1}}{1+\delta} - p_{t+i} - c - h(I_{t+i} - I_{t+i-1}) + \frac{h}{1+\delta}(I_{t+i+1} - I_{t+i}) \right] \right\} = 0. \tag{2}$$

This is a second-order linear inhomogeneous difference equation in inventories, with boundary conditions given by the size of the initial stock and the requirement that

$$\lim_{t\to\infty} (1+\delta)^{-t} [(1+\delta)^{-1} p_{t+1} - p_t - c - h(I_t - I_{t-1})] = 0.$$

The two roots are 1 and $1+\delta$, so the particular solution is given by[11]

$$I_{t+i} - I_{t+i-1} = h^{-1} \sum_{k=0}^{\infty} (1+\delta)^{-k} \mathrm{E}_t [(1+\delta)^{-1} p_{t+i+k+1} - p_{t+i+k} - c]. \tag{3}$$

Thus, inventory changes are a function of adjustment costs (through the parameter h) and of expected profits, with geometrically declining weights into the future.

3.2. Optimal government stockpiling

Understanding the motives for public stockpiling is important not only for a realistic analysis of the response of public reserves to price movements in the world oil market, but also for evaluating the viability of particular

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[11] Sargent (1979) contains a discussion of linear-quadratic optimization problems and solution techniques.

international agreements. Agreements whose provisions run in opposition to the optimizing behavior of the various nations involved are unlikely to prove workable and successful in a crisis.

The public stockpile is to be used in accord with each country j's assumed economic policy of maximizing the present discounted value of real income (output less imported intermediate goods). In each country j, output (y_j) of a single final good is produced from oil (Q_j) and other factors ($\bar{X}_j$) according to the production function

$$y_{jt}=F_j(Q_{jt},\bar{X}_j);F_{j1},F_{j2}>0 \quad \text{and} \quad F_{j11},F_{j22}<0. \tag{4}$$

Each nation imports all of its oil, which is the only imported intermediate input. Non-oil factor supplies are fixed. Oil use depends negatively on its relative price $p/\bar{p}$, where p and $\bar{p}$ are the prices of (imported) oil and output. For simplicity, we make the produced good the numeraire, so that $\bar{p}$ equals unity. Hence,

$$Q_j=Q_j(p), \qquad Q_j'<0. \tag{5}$$

We introduce price uncertainty through an additive disturbance term in the inverse supply equation,

$$p_t=p\left(\sum_n Q_{nt}-\sum_n S_{nt}\right)+\eta_t, \qquad p'>0, \tag{6}$$

where $S_{nt}=I_{nt}-I_{n,t-1}$ represents the net release of stockpiled oil from the public inventory by country n.

The stockpile authority's objective is to maximize the discounted presented value of real income (by minimizing oil price increases)[12] less the cost of carrying out the stockpile program and of adjusting stockpile levels, subject to the constraint that stockpile releases not exceed the amount of oil held in the reserve.[13] The problem for each country j is to choose the stockpile level I_j (or, equivalently, the net stockpile release S_j) in period t so as to

$$\max_{I_{j,t+i}}\sum_i \mathrm{E}_t\left\{(1+\delta_j)^{-i}\left[y_{j,t+i}-p_{t+i}Q_{j,t+i}+(1+\delta_j)^{-1}p_{t+i+1}I_{j,t+i}\right.\right.$$
$$\left.\left.-p_{t+i}I_{j,t+i}-c_jI_{j,t+i}-\frac{h_j}{2}(I_{j,t+i}-I_{j,t+i-1})^2\right]\right\}, \tag{7}$$

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[12] Note that countries do not increase only their own oil supplies by releasing by releasing stored oil. Since the market is integrated, the effect of a stockpile release will be on the world price.

[13] Optimizing models of agricultural stockpiles consider the distribution of income between producers and consumers and the benefits to *producers* of price stabilization [Newbery and Stiglitz (1981)]. In the model presented here, attention is focused solely on consumers, as oil is assumed to be imported.

subject to the constraint that

$$I_{j,t+i} = I_{j,t+i-1} - S_{j,t+i}, \qquad I_{j,t+i} \geqq 0, \tag{8}$$

where δ_j is the discount rate in the jth country.[14] Again, the quadratic term is a proxy for the cost of adjusting stock levels.

There are clear distinctions between the optimization problem for the public stockpile authority and the problem for the private firm stated earlier. First is the attention paid by the public authority to aggregate output. Private firms do not consider the macroeconomic effects of their stockpiling behavior; that is, do not consider the impact of their transactions on the world oil price. Second, the behavior of other countries is important. Because the stockpiling decisions of other countries affect the oil price, they can affect the optimal release strategy of the domestic authority.[15]

Because the market for oil is a world market, price outcomes from one country's stockpile movement depend on the actions of other countries. The problem is inherently game-theoretic. As a base case, we consider the non-cooperative solution, wherein players do not consider the beneficial impact of their own actions on the others.[16] Each country takes the stockpiling decisions of the others as given, then selects its own stockpile level. As a result, this solution does not fully exploit the positive externalities associated with stockpile policy. That is, strategic stockpiles take on the character of a public good.

[14] In the literature on agricultural commodity price stabilization [see especially the discussion in Newbery and Stiglitz (1981)], the objective is usually to optimize the flow of consumption from a serially uncorrelated sequence of harvests, that is to

$$\max \mathrm{E} \sum_{t=0}^{T} (1+\delta)^{-t} U(Q_t, M_t - \gamma I_t),$$

where U denotes utility, $M = Y - pQ$ is money expenditure on all other goods (whose prices remain constant), and γ is the per unit storage cost. In our formulation of the problem, since oil is an intermediate good, utility is derived from total national income $Y_t - p_t Q_t$, which is itself a function of p and Q. Net storage costs in (7) take into account price changes, real costs of maintenance and adjustment, and opportunity costs. Because wages and the prices of other goods are not perfectly flexible in industrial economies, relative prices can change with the price of the stored commodity (oil), so that the competitive market will not supply the socially optimal level of storage, even if consumers are price risk-neutral as in (7). Merely subsidizing private storage does not address the incentives to *release* stocks during a crisis, the subject of this paper.

[15] We can see that a stockpile release by the jth country, ceteris paribus, lowers the world oil price, increasing domestic output because

$$\mathrm{d}p/\mathrm{d}I_j = \omega \sum_m (\mathrm{d}I_m/\mathrm{d}I_j) > 0 \quad \text{and} \quad \mathrm{d}y_i/\mathrm{d}I_j = F'Q'(\mathrm{d}p/\mathrm{d}I_j) = F'Q'\omega \sum_m (\mathrm{d}I_m/\mathrm{d}I_j) < 0,$$

where $\omega = p'/(1 - p' \sum_m Q'_m)$. Note the importance of the conjectured stockpile movements of other players.

[16] The countries need not recognize the game-theoretic structure of the problem to land at the suboptimal Cournot–Nash solution. They may just employ 'reduced-form estimates' of the impact of their demand for oil on the world price. This point is made in a different context in Sachs (1983).

If we assume that the discount rates, holding costs, and stock adjustment parameters are the same across countries, so that $\delta_j=\delta,\ \forall_j; c_j=c, \forall_j; h_j=h, \forall_j$; and the non-negativity constraint does not bind, then the solution to (7) can be written as

$$I_{j,t+i}=\lambda_{1j}I_{j,t+i-1}+h^{-1}(1+\delta)\lambda_{2j}^{-1}\sum_{k=0}^{\infty}\lambda_{2j}^{-k}\mathrm{E}_t[(1+\delta)^{-1}p_{t+i+k+1}$$

$$-p_{t+i+k}-c]-h^{-1}(1+\delta)\lambda_{2j}^{-1}\sum_{k=0}^{\infty}\lambda_{2j}^{-k}\left(\frac{\mathrm{d}p}{\mathrm{d}I}\bigg|I_j\right)Q_{j,t+i+k}, \tag{9}$$

where λ_{1j} and λ_{2j} are the solutions to the Euler equation.

The difference between private and public stockpiling behavior can be seen by comparing eqs. (3) and (9). First, since $\forall_j, \lambda_{1j}<1, \lambda_{2j}>1+\delta$, both the impact and long-run effects of higher expected future oil prices on inventories are muted in the public case.[17] The dampening arises from countries' taking into account the price impact of their inventory decisions. $\mathrm{d}p/\mathrm{d}I$ is written with respect to the conjecture about the reactions of other countries; $(\mathrm{d}p/\mathrm{d}I)|_{I_j}$ denotes evaluation for changes I_j alone.

As long as stockpile authorities perceive their influence on the world price,

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[17] To see this, observe that for the firm, $\lambda_1+\lambda_2=h(1+(1+\delta)^{-1})/h(1+\delta)$, $\lambda_1\lambda_2=(1+\delta)$, implying that $\lambda_1=1$ and that $\lambda_2=(1+\delta)$. Now, for each country j,

$$\lambda_{ij}+\lambda_{2j}=(h(1+(1+\delta)^{-1})+\mathrm{d}p/\mathrm{d}I)/h(1+\delta)^{-1}, \qquad \lambda_{ij}\lambda_{2j}=(1+\delta).$$

So as illustrated in fig. 1, $\lambda_{1j}<1$ and $\lambda_{2j}>1+\delta$. Note that the λ's differ across countries because each country evaluates $\mathrm{d}p/\mathrm{d}I_j$ given *its* change in stockpile levels.

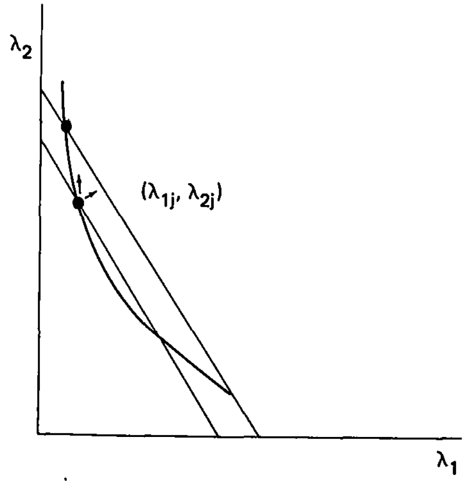

Fig. 1

however, there is another countervailing effect, reflecting the impact of price changes on inframarginal consumption. The last term in (9) captures this market power effect. Ceteris paribus, the larger the country in terms of oil consumption, the greater will be its stockpile release because of the benefits of lowering the price paid on the inframarginal barrels Q_j.

An unexpected shock in the current period (i.e., when $i=0$) affects inventory behavior as can be seen by differentiating (9) with respect to η_t. That is,

$$\frac{\mathrm{d}I_{jt}}{\mathrm{d}\eta_t}=h^{-1}\left[-\lambda_{2j}^{-1}(1+\delta)\left(1+\left.\frac{\mathrm{d}p}{\mathrm{d}I}\right|_{I_j} Q_j'\right)+(1-\lambda_{2j}^{-1}(1+\delta))\sum_{k=1}^{\infty}\lambda_{2j}^{-1}\frac{\mathrm{dE}_t p_{t+k}}{\mathrm{d}\eta_t}\right.$$
$$\left.-\lambda_{2j}^{-1}(1+\delta)\left(\left.\frac{\mathrm{d}p}{\mathrm{d}I}\right|_{I_j}\right)Q_j'\sum_{k=1}^{\infty}\lambda_{2j}^{-k}\frac{\mathrm{dE}_t p_{t+k}}{\mathrm{d}\eta_t}\right], \tag{10}$$

A *transitory* price increase this period (i.e., one for which $\mathrm{dE}_t p_{t+k}/\mathrm{d}\eta_t=0$, for all $k>0$) will induce a stockpile release by the price-taking firm, since $\mathrm{d}I_t/\mathrm{d}\eta_t=-h^{-1}<0$. The public authority, however, will build its stockpile if the country's demand is sufficiently price-responsive, i.e., if

$$-Q_j'>\left(\left.\frac{\mathrm{d}p}{\mathrm{d}I}\right|_{I_j}\right)^{-1}. \tag{11}$$

In this unlikely case, the sharp drop in consumption reduces the benefits on the inframarginal barrels sufficiently to outweigh the intertemporal price effect.[18]

What is required to determine the optimal stockpile policy is knowledge of the intertemporal correlation of prices. As a simple case, suppose that the disturbance term η_t follows a first-order autoregressive process, that is,

$$\eta_t=\rho\eta_{t-1}+v_t, \tag{12}$$

where v_t is independently and identically distributed with mean zero and variance σ_v^2. The smaller is ρ, implying that shocks exhibit little persistence, then the greater is the chance that the optimal stockpile response is a drawdown. The greater is the intertemporal correlation, the less likely is a release at the onset of a shock.

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[18] If an initial 'oil shock' at time t is expected to worsen at time $t+1$, then oil consumption at time $t+1$ falls relative to oil consumption at time t. This effect is scaled by the extent to which movements in public inventory accumulation affect the world price. For example, because of their size, small countries are unlikely to have much effect on world oil prices through their stockpiling. In the limit, they may behave like private firms, taking $(\mathrm{d}p/\mathrm{d}I)|_{I_j}$ as zero. In that case, eq. (10) reduces exactly to the 'firm' case.

3.3. Effects of cooperation on optimal public-stockpile releases

To evaluate the benefits of cooperation, we analyze the case of perfect collusion, where a single stockpile authority maximizes the joint benefits of reserve management. This case provides a measure against which alternative solutions ('agreements') can be judged. Using the assumptions that generated (9), and denoting total stock change in period t by $I_t = \sum_j I_{jt}$, the authority's problem is to choose the sequence $\{I_{t+i}\}_{i=0}^{\infty}$ so as to

$$\max_{I_{t+i}} \mathrm{E}_t \sum_{i=0}^{\infty} \Bigg\{ (1+\delta)^{-i} \Bigg[y_{t+i} - p_{t+i} Q_{t+i} + ((1+\delta)^{-1} p_{t+i+1} - p_{t+i} - c) I_{t+i} - \frac{h}{2} (I_{t+i} - I_{t+i-1})^2 \Bigg] \Bigg\}, \tag{13}$$

subject to

$$I_{t+i} = I_{t+i-1} - S_{t+i}, \tag{14}$$

where $y_t = \sum_j y_{jt}$, $Q_t = \sum_j Q_{jt}$ and $S_t = \sum_j S_{jt}$ denote total output, oil consumption and stock change in period t, respectively.

Denoting by I^{C} the cooperative inventory level for the m countries, the solution to (13) is

$$I_t^{\mathrm{C}} = \lambda_1^* I_{t-1}^{\mathrm{C}} + h^{-1} m (1+\delta) \lambda_2^{*-k} \sum_{k=0}^{\infty} \lambda_2^{*-k} \mathrm{E}_t [(1+\delta)^{-1} p_{t+k+1} - p_{t+k} - c] - h^{-1} (1+\delta) \lambda_2^{*-1} \sum_{k=0}^{\infty} \lambda_2^{*-k} \left(\frac{\mathrm{d}p}{\mathrm{d}I_j} \bigg|_{\sum_j I_j} \right) Q_{t+k}. \tag{15}$$

In general, the allocation of the stockpile change among countries depends on the costs of inventory adjustment. Here, we have assumed these costs to be the same for all countries, so that each country's release depends only on the size of its stockpile. Note that $\lambda_1^* < \lambda_{1j}$ and $\lambda_2^* > \lambda_{2j}$, $\forall_j$.[19] Because $\mathrm{d}p/\mathrm{d}I$ in the cooperative case is evaluated considering all stock changes, $((\mathrm{d}p/\mathrm{d}I_j)|_{\sum_j I_j}) > ((\mathrm{d}p/\mathrm{d}I_j)|_{I_j})$.

The question is thus the following: given an oil shock, how will stockpile behavior differ between the non-cooperative and cooperative solutions? From (9), the sum of the stocks in the non-cooperative solution is

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[19] The argument is the same as in footnote 17. Cooperation dampens price-smoothing inventory response further as as each player assumes that the others will reinforce its action.

$$I_t^{\mathrm{N}} = \sum_{j=1}^{m} I_{j,t}^{\mathrm{N}} = \sum_{j=1}^{m} \lambda_{1j} I_{j,t-1}^{\mathrm{N}} + h^{-1}(1+\delta) \sum_{j=1}^{m} \lambda_{2j}^{-1} \sum_{k=0}^{\infty} \lambda_{2j}^{-k} \mathrm{E}_t[(1+\delta)^{-1} p_{t+k+1}$$

$$- p_{t+k} - c] - \sum_{j=1}^{m} h^{-1}(1+\delta)\lambda_{2j}^{-1} \sum_{k=0}^{\infty} \lambda_{2j}^{-k} \left(\frac{\mathrm{d}p}{\mathrm{d}I_j} \bigg|_{I_j} \right) Q_{j,t+k}, \tag{16}$$

where the superscript N denotes the non-cooperative case.

Comparing (15) and (16) reveals that whether the stockpile release im response to an unanticipated shock in the current period is larger under coordination or under the non-cooperative solution depends on certain underlying parameters – the slope of the supply function (p') and the demand functions (Q_j'), and persistence (ρ). The responses of stockpiles in the non-cooperative and cooperative solutions to a shock in the current period can be gleaned from differentiating (9) and (15) with respect to v_t. That is,

$$\frac{\mathrm{d}I_t^{\mathrm{N}}}{\mathrm{d}v_t} = h^{-1} \sum_{j=1}^{m} (\lambda_{2j} - \rho)^{-1} \left[\rho - (1+\delta) \left(1 + \frac{\mathrm{d}p}{\mathrm{d}I_j} \bigg|_{I_j} Q_j' \right) \right], \quad \text{and} \tag{17}$$

$$\frac{\mathrm{d}I_t^{\mathrm{C}}}{\mathrm{d}v_t} = h^{-1} m(\lambda_2^* - \rho)^{-1} \left[\rho - (1+\delta) \left(1 + \frac{\mathrm{d}p}{\mathrm{d}I_j} \bigg|_{\sum_j I_j} \hat{Q}' \right) \right], \tag{18}$$

where $Q' = \sum_j Q_j'$ is the slope of the aggregate demand curve, and $\hat{Q} = Q/m$.

Comparing the results in eqs. (17) and (18), both the non-cooperative and cooperative responses to a transitory shock depend on the cost of adjusting buffer stock levels, the sensitivity of oil prices to incremental demand, the demand functions of consuming countries, and the intertemporal price correlation.[20] The larger is p', the more likely are the responses to be positive, that is, stock accumulation accompanying a transitive negative supply shock.

A drawdown occurs in the cooperative case when $\rho < (1+\delta)(1 + (\mathrm{d}p/\mathrm{d}I)|_{\sum_j I_j} \hat{Q}')$. In the non-cooperative case, country j draws when $\rho < (1+\delta)(1 + (\mathrm{d}p/\mathrm{d}I)|_{I_j} Q_j')$; as above, small countries are more likely to draw than large ones, ceteris paribus. Otherwise, stocks are accumulated in response to the shock. Some tedious algebra can show that $\mathrm{d}I_t^{\mathrm{N}}/\mathrm{d}v_t > \mathrm{d}I_t^{\mathrm{C}}/\mathrm{d}v_t$, so that when a drawdown is optimal, the cooperative drawdown is larger than in the non-cooperative case; when accumulation is optimal, the non-cooperative buildup exceeds the cooperative one. Increasing the persistence parameter ρ raises the absolute value of both responses but increases the non-cooperative one more, i.e., $\mathrm{d}(I_t^{\mathrm{N}} - I_t^{\mathrm{C}})/\mathrm{d}\rho > 0$.

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[20] Note that the solution form remains the same even if shocks follow an ARMA (1, 1) process, i.e., $\eta_t = \rho\eta_{t-1} + v_t + \gamma v_{t-1}$.

The benefits from cooperation are greater the higher is the serial correlation in the shocks (i.e., the higher is ρ). Changes in market structure that reduce the impact of serially correlated shocks on prices will reduce the cost of non-cooperative behavior.

4. Implications for existing petroleum agreements

What can be said about the International Energy Program in light of the preceding analysis? First, the use of current quantity loss as a regulatory signal is imappropriate. First, it ignores the critical influence on national optimizing behavior of market dynamics. Loosely speaking, whether the shock is anticipated to 'improve' or 'worsen' determines the relationship between the cooperative and non-cooperative solutions.[21] The intertemporal tradeoff of the benefits from using stockpiled oil is not as severe with a very large stockpile as it is with a small one. Stockpile decisions serve an intertemporal allocative function. In ignoring this consideration, the IEA agreement misses more than the opportunity for the most efficient response to a disruption. By calling for action counter to the interests of the individual players, it makes it unlikely that cooperation will take place at all. Supply interruptions are characterized by uncertainty over their severity and duration. The IEA agreement merely directs countries to release a specified quantity from the time that an emergency has been declared.

Creation of a viable international agreement requires a consideration of uncertainty over the future oil price trajectory in the aftermath of a shock. As pointed out in the discussion of our model, the serial correlation patterns of quantity shocks and price changes are central to the determination of optimal public stockpile responses. For example, 'persistence' can arise from the 'two-price' system in the oil market, in which long-term contracts and market-clearing spot transactions coexist. It can be shown [see Hubbard and Weiner (1983a)] that the more price-responsive is the demand for oil, the smaller is the initial increase in price caused by a supply shock and the lower is its persistence. Moreover, the larger is the fraction of trades carried out under long-term contract, the greater is the persistence. These arguments imply that changes in market structure might influence the benefits to be gained from coordination.

Moving from theory to practice, a major problem in the implementation of policy coordination is the design of an agreement without incentives to cheat. If stockpile levels could be perfectly monitored, sufficiently stiff penalties can be imposed for breach. Unfortunately, stockpile levels (and, a fortiori, changes in those levels) are difficult to observe in many countries. As a

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[21] This 'better' or 'worse' distinction could be explicitly considered by modeling shocks with higher-order serial correlation [AR(2), for example].

possible compromise, an agreement among the three largest members of the OECD – the United States, Japan and West Germany – may be easier to monitor. Since these countries constitute a majority of OECD demand, such an agreement may capture the bulk of the benefits, even if all the other countries (the non-signatories) act in their own self interest.

A tradeoff between ease of implementation and ease of negotiation may be achieved by an agreement which stipulates beforehand the *ratios* of the members' drawdowns, but allows the amount (a single parameter) to be negotiated after a disruption hits. This approach follows the spirit of the 'perfect collusion' case of the model, and allows the actors to incorporate information that becomes available at the onset of the shock into the drawdown strategy.

5. Conclusion

During the past decade, oil supply shocks have caused significant economic damage in terms of lost output and increased inflation in the industrial countries of the OECD. To the extent that the macroeconomic costs of shocks are a function of the magnitude of the oil price increases, domestic policies or internationally coordinated efforts to restrain oil price increases during disruptions can be beneficial. One such policy initiative is the release of oil held in public stockpiles.

In the second section of the paper, we addressed the motivations for private and public stockpiling behavior in an intertemporal optimizing model. The benefits to one country from public stockpile releases during an oil shock depend on the stockpiling behavior of other countries. By contrasting non-cooperative and cooperative solutions to the optimization problem, we illustrate the conditions for beneficial cooperation and develop conditions under which public stockpile authorities are likely to release oil during a crisis.

Uncertainty over the path of future oil prices plays an important role in explaining inventory behavior. Ceteris paribus, after a negative supply shock, the anticipation of higher oil prices in the future (i.e., serial correlation of the shock) leads to a higher rate of public inventory accumulation (lower optimal stockpile release) in the current period. During a crisis in which the (now higher) oil price is expected to decline, countries are willing to draw down their stockpiles at the onset of a shock, even in the absence of a coordinating agreement. If the oil price is expected to increase further, however, a drawdown in the current period mandated by a stockpile coordination agreement is not in the interests of the individual members.

In the fourth section of the paper, we reviewed our results in the context of current energy policy, particularly with respect to the agreements by the International Energy Agency. The optimal stockpile rules of section 3 indicate that the focus of the IEA agreement on the period in which a shock occurs ignores the more important role of the uncertainty over future oil prices.

Two directions for extension of the results presented here are immediately suggested by the analysis. First is the foundation of persistence in supplier behavior. In a related paper (Hubbard and Weiner, 1983a), we have considered the impact of contract rigidities on price adjustment in response to shocks. By deriving the spot-contract mix from optimizing behavior, we can consider the effects of changes in structural parameters on pricing behavior over time, and the implications for optimal stockpiling. A second extension is to analyze the role of simultaneous coordination of macroeconomic and stockpile policies in reducing the costs of large oil increases. (Even within the context of examining stockpiling policies, the exchange rate is obviously a factor in determining the 'price of oil' outside the U.S.) The benefits of coordinated fiscal and monetary policies probably greatly exceed those generated from stockpile cooperation, though achieving the former is likely to be even more difficult than achieving the latter.

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