

Time Series Analysis of Market Structure

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Abstract

Previous research on market structure concludes it is difficult to empirically distinguish between various forms of imperfectly competitive behavior. However, given sufficient data describing the output of producers in a market, this ‘identification’ problem can be overcome by exploiting the time series properties of the data. Differentiation among market structures is accomplished by comparing the intertemporal dynamics embodied in a fully specified structural model to the theoretical implications of various market structures. The approach is applied to OPEC, which has been the focus of numerous studies concerning its market structure. The analysis suggests that OPEC is a loose output-based cartel wherein Saudi Arabia acts as a cartel enforcer when other OPEC members temporarily change output levels. However, Saudi Arabia acts as a swing producer or cartel stabilizer when permanent changes in other OPEC production levels occur. These results provide a synthesis of previous empirical results presented in the literature.

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1 Introduction

The seminal work by Stigler (1964) formalized the investigation of tacit and explicit cartel behavior. Unfortunately, empirical attempts to identify collusive behavior from other forms of traditional market structures such as perfect competition suffer an identification problem. While it is possible to distinguish various forms of competition from imperfect competition (see for example Al-Sultan, 1993), a general approach to differentiate amongst types of imperfectly competitive behavior has yet proven elusive.¹ This paper presents a methodology by which this difficulty can be overcome by exploiting the permanent-transitory decomposition consistent with the time-series properties of output data.

Consider a mature market with a homogeneous good and profit maximizing firms. Collusive firms “share” the market by maintaining fixed market shares consistent with joint profit maximization. Noncooperative oligopolists “share” the market by reacting strategically to output decisions of other firms, consistent with individual profit maximization. While both types of markets can be characterized by outputs that increase over time, in a collusive market temporary increases in the output by one firm, perhaps by cheating, may well be met with output increases by other firms (or a designated cartel enforcer). On the other hand, if a market is characterized by noncooperative imperfect competition, then transitory shocks, e.g., temporary increases in the production of one firm, result in short-term reductions in the outputs of other firms in the market (see Tirole, 1988).² Finally, various forms of competition imply atomistic behavior by producers, i.e., no response to temporary changes in other firms’ production. These different responses to idiosyncratic output changes imply that shocks to a steady state equilibrium will yield different qualitative responses depending on the market structure. Thus, the transition dynamics provide a means to differentiate between various market structures.

The enforcement of an explicit cartel is dependent upon detecting and punishing cheaters; therefore, an empirical test of cartel behavior requires examination of intertemporal changes in

output. The econometric technique employed herein is particularly well suited for analyzing such intertemporal dynamics. Specifically, the methodology of vector autoregressions, developed in time series econometrics, can separately test two types of shocks to a market's long-run equilibrium. The first shock is consistent with a permanent change to the output of all firms, perhaps a demand, cost, or technology shock common to all firms in the market. The second shock is consistent with only a transitory effect on the output of each producer, perhaps through cheating or other idiosyncratic cost or demand shocks.

To preview the methodology, a two-step approach helps determine the market structure supported by the data without imposing *ad hoc* restrictions on the econometric specification. Initially, test for a long-run or steady state equilibrium via cointegration. Evidence of cointegration indicates that output levels share a long-run equilibrium, a necessary condition for the producers to be in the "same" market. A negative cointegrating relationship precludes cooperative oligopoly, yet a positive cointegrating relationship is consistent with various market structures: competition, noncooperative oligopoly and cooperative oligopoly. The second step follows the structural vector autoregression (SVAR) literature by decomposing the disturbance terms of the econometric specification into permanent and transitory shocks; the former consistent with technology or demand shocks, the latter consistent with cheating or other idiosyncratic shocks to production. The qualitative responses of producers to transitory and permanent shocks to other firms' production allow for differentiation between competition, noncooperative oligopoly and cooperative oligopoly.

To illustrate the approach, the outputs of the Organization of Petroleum Exporting Countries (OPEC) members from 1965 through 1993 are examined. Some evidence points to OPEC being a successful cartel during a brief period of time in the early 1970's (citations here). Other authors suggest that OPEC has been largely ineffective in the world oil market and may not be properly characterized as a cartel, despite prevailing intuition (citations here). Still others suggest that the characterization of OPEC depends on the period investigated (citations here). These conclusions may ultimately depend upon the assumptions of the econometric techniques employed. The ap-

proach take here avoids *a priori* restrictions on the econometric specification, thereby allowing the data to reveal the appropriate market structure for OPEC.

The analysis indicates a positive long-run equilibrium between the output of Saudi Arabia and that of non-Saudi OPEC production. Therefore, OPEC producers share a long-run equilibrium during the time period investigated, as expected. Moreover, the long-run relationship is stable over the sample period implying that it may not be necessary to separately model OPEC behavior for different sub-periods, as in Griffin and Neilson (1994) and Jones (1990). Finally, the econometric evidence also suggests that Saudi Arabia acts as a cartel enforcer when non-Saudi OPEC production changes are transitory, and as a swing producer when non-Saudi OPEC production changes are permanent.

The empirical results are not consistent with the characterization of OPEC as a dominant-firm with a competitive fringe. Specifically, if Saudi Arabia were a dominant firm it would behave as a leader in the market, that is, Saudi Arabia's output would be exogenous of other OPEC outputs (Griffin and Neilson, 1994). However, Saudi Arabia's output levels are found to be entirely endogenous, therefore Saudi Arabia cannot be considered a market leader. Moreover, contrary to the traditional price-leading dominant-firm hypothesis, when non-Saudi members of OPEC temporarily increase their production levels, Saudi Arabia increases its output.³

By analyzing the responses of Saudi and non-Saudi OPEC outputs to transitory and permanent shocks, the data reveal that Saudi Arabia acts as a cartel enforcer when temporary increases in non-Saudi OPEC production occur, in a manner consistent with Osborne (1976) and Griffin and Neilson (1994). However, Saudi Arabia acts as a swing producer, or a cartel stabilizer, in response to permanent shocks to non-Saudi OPEC production levels. The results do not support the hypothesis that OPEC is consistent with perfect competition, as proposed by XXX. However, the findings here do synthesize the conflicting findings of Jones (1990) and Griffin and Neilson (1994), which are both consistent with different types of shocks to OPEC output levels.

The remainder of the paper is structured as follows. Section 2 outlines the methodology. The

discussion leads to a set of testable hypotheses with which to test across three market structures: competition, non-cooperative oligopoly and cooperative oligopoly. Section 3 outlines the estimation technique and reports the results of applying the technique to the case of OPEC. The final section offers concluding remarks.

2 An Output-Based Test for Market Structure

To understand how time series analysis may be able to differentiate between market structures, consider initially the model of price collusion with randomized demand and constrained capacity provided by Staiger and Wolack (1992). In their model, collusion is more difficult in periods of low demand relative to periods of high demand; instability in market shares is a detriment to effective collusion, which implies that a dynamic framework may be the best approach for testing collusion. Their model is appropriately set in the context of an infinitely repeated game and they find that “intertemporal instability in relative market shares...is evidence of an inability to collude effectively” (p. 295). While their model focuses on price as the target for collusive action, in this paper output is considered.

The canonical static cartel faces a market demand $P = f(X, a)$ where $X = \sum_{i=1}^N x_i$ is the total market output of N profit-maximizing producers, a is a vector of demand parameters, and f is twice continuously differentiable. Each producer incurs costs of $C_i(x_i, c_i)$ where C_i is a firm-specific cost function, x_i is firm output and c_i are firm-specific cost parameters such as technology characteristics and factor prices. The cartel determines quotas, x_i^0 , that solve $\max_{x_i} V = f(\sum x_i, a) \sum x_i - \sum C_i(x_i, c_i)$, where V is the total net value of the cartel’s output. The joint profit-maximizing solution implies N first-order necessary conditions, $\partial V / \partial x_i = f' \sum x_i + f - MC_i(x_i, c_i) = 0$.

If $MC_i(x_i, c_i)$ are not identical across members, the solution to the N -equation system yields different optimal production outputs, x_i^0 , which then lead to optimal market shares, $s_i^0 = x_i^0 / \sum_{j=1}^N x_j^0$. If something permanently affects a change in one or more marginal cost functions, the previous

optimal market shares are not necessarily valid and a new solution to the N-equation system may be necessary. After the cartel recalibrates its members' optimal outputs, market shares are reallocated accordingly. Those cartel members with lowered cost receive a larger absolute quota while those without lowered costs receive smaller absolute quotas.

Cheating on the cartel agreement can be punished by dissolution of the agreement and all firms increasing production to either Cournot or perfectly competitive levels. Therefore, the punishment for cheating is a lower price induced by increased production. However, this is not necessarily the least cost punishment (all non-cheating members of the cartel suffer the same punishment as the cheaters). Osborne (1976) suggests a cartel-rule which provides a least-cost punishment for cheating on predetermined quotas for cartel members. In the case of perfect information on output levels, the quota-rule calls for each producer to set output as

$$\max \left(x_i^0, x_i^0 + \frac{s_i}{s_j} \Delta x_j \right), \quad (1)$$

where s_i and s_j are the market shares of producers i and j , respectively, x_i^0 is the fixed quota-quantity for firm i and Δx_j is the amount of cheating by firm j . If there is more than one potential cheater, Osborne offers a modified rule of

$$\max \left(x_i^0, x_i^0 + \frac{s_i \sum_{j \in J} \Delta x_j}{\sum_{j \in J} s_j} \right), \quad (2)$$

where J is the set of cheating members. These quota rules are designed such that observed cheating by one or more cartel members is punished with proportional changes in output of non-cheating members so that market shares are stable.⁴

The quota rules imply that the output levels of cartel members should be positively related to each other over time to maintain market shares. If output levels are not positively related to each other over time, then the quota-rule enforced cartel can be dismissed as a possible market structure.

Both forms of cartel decision making are consistent with cointegration, defined as two or more trending series that exhibit a long-run relationship. However, simply finding evidence of cointegration is not enough to prove a cartel arrangement, since competition, non-cooperative oligopoly and cooperative oligopoly are all also consistent with positive cointegration. The problem of observational equivalence between the non-cooperative and cooperative outcomes discussed by Al-Sultan (1993) can be overcome by recognizing that cooperative market structures, such as an Osborne cartel, imply different responses to temporary and permanent changes in output levels than in competition or noncooperative oligopoly.

The distinction can be made using economic intuition rather than complex mathematical models. Consider a traditional quantity-setting Cournot market. Is it reasonable to expect cointegration in output levels over time? Assuming that profit functions are strictly concave in output, x_i , the Cournot equilibrium implies reaction functions for all N producers of $x_i = r_i(x_1, \dots, x_{i-1}, x_{i+1}, \dots, x_N, C_1, \dots, C_N)$, and given the appropriate stability conditions⁵ an interior solution exists such that $x_i^0 = g_i(a, c_1, \dots, c_N)$.

With identical cost structures, a symmetric outcome is obtained wherein every firm's production is the same and thus every firm has equal market shares. If cost structures differ, optimal quantities in the non-cooperative setting will likewise differ and so too will optimal market shares. The importance of this model lies in the nature of the reaction functions; they indicate that output decisions are strategic substitutes (see Bulow, et al., 1985). Thus, the comparative statics indicate that the outputs in a Cournot-in-quantity market should be inversely related to each other.

While the traditional Cournot model is static in nature, both Griffin and Neilson (1994, Appendix A) and Lewis and Shmalensee (1980) discuss a dynamic interpretation of the Cournot equilibrium. The inverse relationship between firm output levels is ultimately embodied in the (dynamic) reaction functions of the Cournot competitors. These reaction functions are "solved" simultaneously to determine output as in a one-shot game. Intertemporal responses by firms follow the same intuition as in the static Cournot model.

If marginal cost permanently rises (falls) for each firm, all firms restrict (expand) output. Hereafter, this scenario is called "Symmetric Cournot;" firm outputs move in the same direction. By contrast, if an idiosyncratic shock permanently lowers only one firm's costs, then that firm's equilibrium output increases while other equilibrium outputs decrease. Hereafter, this scenario is called "Asymmetric Cournot." In both instances *temporary* increases in the output of one firm should induce temporary reductions in the output of other firms; to reduce output is a dominant strategy. While in a cooperative oligopoly a temporary increase in one firm's output should trigger an increase in non-cheating members' output (or that of a designated cartel enforcer), in non-cooperative oligopoly the result is exactly the opposite.

The remaining market structure to be discussed is competition. The technique proposed here only focuses on quantity, therefore many of the elements of competition, either perfect or monopolistic, are not included. For example, profitability and pricing is not included in this approach. The focus is on the impact of temporary and permanent changes in other firms' outputs on the output of a representative firm. In various forms of perfect competition, short-term responses to temporary changes in others' production should elicit no response; atomistic producers do not respond to changes in other firms' production. However, if a permanent shock occurs to one firm, competition would imply that it should occur for all firms. Therefore, increases in production would be expected in response to permanent changes in other firms' production.

The preceding suggests that the output levels of producers in an industry can exhibit different intertemporal relationships. Some market structures predict output levels are positively related over time; others predict the opposite. The well-established cointegration technique, coupled with the technique of decomposing disturbances into permanent and temporary shocks, can be used to isolate the actual market structure supported by the data without requiring *a priori* restrictions that may influence the final result.

2.1 Market Structure Implications of Cointegrating Relationships

To facilitate discussion, various market structure hypotheses are presented using a representative firm, called Firm A; all other firms in the market are denoted as “other(s).” The first stage of the analysis centers on the cointegrating vector itself. The cointegrating vector provides evidence about certain market structures. If output levels fail to exhibit cointegration, there is no long-run relationship amongst output levels. This would indicate that the producers are probably not in the same market. Moreover, a lack of a long-run relationship amongst output levels would definitely preclude both cooperative and non-cooperative oligopoly and most likely competition.

However, if cointegration is evident, an inverse long-run relationship between Firm A and other firms’ output levels would preclude both competition and cooperative market structures. This is because perfectly competitive firms are identical and small relative to the overall market and cannot unilaterally influence price, thereby indicating a positive long-run relationship in which all firms’ outputs increase or decrease together. Cooperative oligopoly is precluded based upon the discussion in the previous section.

A positive cointegrating vector would be consistent with several market structures. A direct relationship may indicate a cooperative market structure as suggested by Osborne, yet the market might be characterized by competition or non-cooperative oligopoly in the presence of exogenous long-run supply or demand shocks. However the problem of observational equivalence between competition, noncooperative oligopoly and cooperative oligopoly can be overcome by analyzing the response of outputs when subjected to, alternatively, permanent and transitory shocks.

2.2 Market Structure Implications of Transition Dynamics

The empirical analysis of non-stationary time-series data allows for a decomposition of the data into permanent and transitory components and, by extension, innovations that have permanent and temporary effects on the dependent variable, in this case output. Permanent changes in output might be associated with permanent changes in demand or supply. On the other hand, transitory

shocks are, by definition, not caused by permanent changes in a market's fundamentals. In an empirical sense, the long-run or steady state effects of both shocks are the same for all producers.⁶ The market structure supported by the data is determined by the transition paths caused by the two types of shocks, i.e. the short-term response of Firm A to the various innovations.

If Firm A has no short-run response to a positive transitory shock to the output of other firms, this would only be consistent with competition, in which all agents are atomistic and do not respond to temporary changes to other firm output levels. For example, a short-run drought in one area of the country may reduce the output of farmers in that area. Although prices may increase, in the short-run farmers in non-drought areas cannot alter their production. However, if a permanent shock occurred, for example a permanent increase in market demand or a permanent decline in cost, competition implies that outputs of all existing firms should increase, *ceteris paribus*. It follows that the output of Firm A responds in a like manner.

If Firm A responds to a positive transitory shock in other firms' output by increasing output in the short run, this is consistent with cooperative oligopoly (perhaps an Osborne-cartel or a tit-for-tat cartel as described by Griffin and Neilson). A short-term decrease in output in response to temporary output changes is consistent with (dynamic) Cournot.

A positive permanent increase in other producers' output levels may elicit a corresponding increase in Firm A's output level in the short run, consistent with competition or (dynamic) Cournot.⁷ This response is not consistent with cartel enforcement because the change in other firms' output is permanent; by increasing its output, Firm A would fail to elicit the desired decrease in cheaters' production and simply depress price further. If, however, the market is characterized as (dynamic) Cournot, then an increase in Firm A's output would be expected. However, if Firm A wished to act as a swing producer, or a "cartel stabilizer," it might reduce output immediately after the permanent shock to other firms' output and slowly increase output over time in response to the permanent change in cartel quotas.

If and only if a positive cointegrating relationship exists, the identification between competition,

cooperative and noncooperative oligopoly is determined by hypotheses H1 and H2 (enumerated in Table 1), which are dependent upon the short-term responses of Firm A to permanent and transitory shocks to others' production.

Analyzing the dynamics of transitory and permanent shocks to output, a non-response to a transitory shock to output is consistent with competition, hypothesis H2a. A temporary decrease in Firm A's output after a transitory increase in other firms' output is consistent with (dynamic) Cournot, hypothesis H1b. A temporary increase in Firm A's output in response to a transitory increase in others' output is consistent with either competition or a tit-for-tat cartel strategy, hypothesis H2c.

If Firm A shows no short-term response to a permanent increase in others' output, this is consistent with competition, Hypothesis H2a. A short-term decrease in output by Firm A in response to a permanent positive shock to others' production is consistent with non-cooperative oligopoly or a swing-producer strategy, hypothesis H2b. A short-term increase in output after a permanent shock is consistent with either dynamic Cournot or competition, hypothesis H2c.

Jointly applying hypotheses H1 and H2 further differentiates between competitive, cooperative and non-cooperative market structures as depicted in the decision matrix Figure 1. If H1a holds simultaneously with either H2a or H2b, the data support competition. If both H1a and H2b hold simultaneously, the market structure is indeterminant, in this case H1a suggests competition but H2a supports swing-producer of non-cooperative oligopoly. If H1b and H2a hold simultaneously, the market structure is likewise indeterminant. However if H1b holds with either H2b or H2c, the data support (dynamic) Cournot; H2b would support Asymmetric Cournot whereas H2c would support Symmetric Cournot. If H1c holds simultaneously with either H2a or H2c, the data support competition. Finally, if H1c holds simultaneously with H2b, the data support the "cartel enforcer-stabilizer model," wherein Firm A adjusts output in the short-term to accommodate permanent shocks in others' output by decreasing its own production, but also punishes transitory increases in others' output with a tit-for-tat strategy. This final model is consistent with the loose cartel model

offered by other authors (see, for example, Jones, 1990).

The joint hypotheses outlined above, and depicted in Figure 1, allow for the identification of the market structure without the imposition of *ad hoc* restrictions, either on the empirical framework employed or on the delineation of time-based regime changes. Data requirements are the major hurdle to implementing this methodology. From the time-series literature, the frequency of the data is not as important as the sample span investigated. For a long-run relationship to become apparent, econometric theory suggests 10-15 years as a minimum. Additionally, the technique requires a sufficient number of producers in the market, although exactly how many is ambiguous. However, given sufficient data, combining cointegration analysis with the analysis of long-run and short-run dynamics may assist in identifying the market structure supported by the data. The following section applies the approach to an empirical analysis of OPEC.

3 An Empirical Application to OPEC

The methodology outlined above is applied to the Organization of Petroleum Exporting Countries (OPEC). Several authors have investigated OPEC behavior, including Al-Sultan (1993), Gilbert (1978), Hayilicza and Pindyck (1976), Salant (1976), Griffin (1985) and Griffin and Neilson (1994), to name just a few; many claim that OPEC successfully cartelized the world oil market during a brief time in the early 1970's (see Gately, 1984, for a full survey), and successfully influenced world oil prices in the early 1980s (see, for example, Gulen, 1996 and Loderer, 1985). A brief review of OPEC and the associated literature is provided in Appendix A.

Data describing monthly oil production levels of each OPEC member-country, measured in millions of barrels, were collected from *Oil and Gas Journal* for the period from January 1965 to February 1993,⁸. The data are aggregated into total production by all OPEC countries except Saudi Arabia, called non-Saudi OPEC (NSOPEC), and total production by Saudi Arabia alone (SA).⁹ This distinction facilitates a test of whether Saudi Arabia and the rest of OPEC behave consistent

with competition, non-cooperative oligopoly, or with cooperative oligopoly in which Saudi Arabia acts alternatively as a swing producer and a cartel enforcer. The data are transformed from levels to natural logs prior to the analysis; these transformations are plotted in Figure 2.

The first step in the methodology is a careful analysis of the univariate time series properties of the data. If the data are not characterized by unit roots or stochastic trends, then use of cointegration analysis in the multivariate application is not warranted. If, however, the data are consistent with stochastic trend behavior, then standard estimation techniques, i.e., ordinary least squares (OLS), instrumental variables (IV), and two-stage least squares (2SLS), are inappropriate. The next step in the analysis will be to estimate and test for a long-run equilibrium or cointegrating relationship between Saudi and non-Saudi OPEC production levels. While there are several methods for accomplishing this, the vector autoregressive maximum likelihood estimator (VAR-MLE) introduced by Johansen (1991) is employed. This procedure not only provides the most reliable estimates and test statistics, but also allows the model to be interpreted as a dynamic reduced-form while still treating all variables in the system as endogenous, a priori. Tests for exogeneity and causality can be carried out after estimation. Important disequilibrium dynamics can be discerned from the dynamic multipliers or impulse response functions (IRF) obtained by inverting the vector autoregression (VAR). In order to give the IRFs a structural interpretation some identifying restrictions will have to be imposed on the model. These will take the form of independence restrictions on the structural error terms implying a diagonal structural covariance matrix. The number of additional ad hoc restrictions, such as exclusion restrictions, necessary for structural identification is zero. The existence of cointegration and the restrictions implied by cointegration provide all the remaining identification restrictions (see Crowder, 1995).

3.1 Univariate Analysis

The potential for trends in time series data has important implications for the choice of appropriate estimators. Specifically, if the data are characterized by stochastic trends then the use of OLS, or

a variant, is inappropriate because of the non-standard distribution of the parameter estimates. Several procedures exist to test for the presence of stochastic trends in time series data. The most commonly applied is the augmented Dickey-Fuller (1979) (ADF) test defined as

$$\Delta X_t = \mu + \delta t + \rho X_{t-1} + \sum_{j=1}^k \gamma_j \Delta X_{t-j} + \varepsilon_t, \quad (3)$$

where t is a time trend and the lag truncation parameter k is chosen such that the residuals of the estimated equation are white noise statistically. The null hypothesis of a unit root or stochastic trend is $\rho = 0$, which can be tested using a t-statistic denoted by τ_ρ . If the time trend is omitted then the test statistic is denoted by τ_μ . The distribution of these test statistics is non-standard but critical values can be obtained by Monte Carlo simulation as in MacKinnon (1991). Table 1 presents the results of the ADF tests for several choices of k , the lag truncation parameter, because inference may be sensitive to the number of lags included in the regression. This is not the case for the time series examined in Table 1. The evidence strongly implies that both the Saudi and non-Saudi production series have stochastic trends and are thus non-stationary.

The inference from the ADF test can be sensitive to regime shifts in the time series as demonstrated by Perron (1989). Specifically, the presence of a structural break in the series may lead to spurious acceptance of the unit root null hypothesis. To allow for the possibility of structural breaks in the data, Zivot and Andrews (1992) have developed a recursive test for stochastic trends based upon equation (4),

$$\Delta X_t = \mu + \delta t + \theta D_t + \rho X_{t-1} + \sum_{j=1}^k \gamma_j \Delta X_{t-j} + \varepsilon_t. \quad (4)$$

The variable D_t is a dummy variable that takes a value of one when t is greater than λT (where T is the sample size), and $\lambda \in [0.1, 0.9]$, and a value of zero otherwise. The presence of the intervention dummy variable D_t changes the distribution of the ADF test statistics. Zivot and Andrews provide critical values appropriate for tests based upon equation (4). Figure 3 plots the recursive estimates

of the Zivot-Andrews test statistics derived from estimation of equation (4).¹⁰ The statistics in Figure 2 have been normalized by the appropriate 5% critical values such that values greater than one imply statistical significance.¹¹ There is no evidence that structural breaks or regime shifts are driving the non-rejection of the unit-root null hypothesis. It can be concluded with some confidence that the data are characterized by stochastic trends.

3.2 Multivariate Analysis

The non-stationarity of the data make standard OLS estimation and inference inappropriate (see Sims, Stock and Watson, 1990). A common practice is to first difference the data prior to estimation, since the first differences would be stationary implying that OLS yields valid inference. However, this practice has two drawbacks. First, by differencing the data prior to estimation all long-run or low frequency information is lost. Second, if the variables share a long-run equilibrium and are cointegrated, then first differencing prior to estimation imposes a moving-average unit root on the error terms making inference invalid once again. Since the theoretical discussion above implies that Saudi and non-Saudi production levels might be linked together in the long run or that the two series should be cointegrated, it is appropriate to test for cointegration using Johansen's (1991) maximum likelihood estimator.

Assume that the p^{th} order vector time series X_t follows a finite order vector autoregressive (VAR) process represented as

$$\Pi(L) X_t = \mu_t + \varepsilon_t, \tag{5}$$

where $\Pi(L)$ is a k^{th} order matrix polynomial in the lag operator and $\Pi(0) = I$. μ_t contains deterministic components which may depend upon time and ε_t is a vector white noise error term. The previous equation can be transformed into error-correction model (ECM) form as in equation (6) by subtracting X_{t-1} from both sides of the equation:

$$\Delta X_t = \mu_t + \Pi X_{t-1} + \sum_{j=1}^{k-1} \Gamma_j \Delta X_{t-j} + \varepsilon_t. \quad (6)$$

The long-run multiplier matrix $\Pi = -\Pi(1)$ can be decomposed into two $p \times r$ matrices such that $\alpha\beta' = \Pi$. The $p \times r$ matrix β represents the cointegrating vectors or the long-run equilibria of the system of equations, in this case Saudi and non-Saudi production levels. The $p \times r$ matrix α is the matrix of error-correction coefficients which measure the rate each variable adjusts to the long-run equilibrium. Maximum likelihood estimation of (6) can be carried out by applying reduced rank regression. Johansen suggests first concentrating out the short-run dynamics by regressing ΔX_t and X_{t-1} on $\Delta X_{t-1}, \Delta X_{t-2}, \dots, \Delta X_{t-k+1}$ and μ_t and saving the residuals as R_{0t} and R_{1t} , respectively. Then calculate the product moment matrices $S_{ij} = T^{-1} \sum_{t=1}^T R_{it} R'_{jt}$ and solve the eigenvalue problem $|\lambda S_{11} - S_{10} S_{00}^{-1} S_{01}| = 0$. The likelihood ratio statistic testing the null hypothesis of at least r cointegrating relationships in X_t is given by $-T \sum_{i=r+1}^p \ln(1 - \hat{\lambda}_i)$ and is called the trace statistic by Johansen (1991). The distribution of this statistic is non-standard and depends upon nuisance parameters. Critical values have been tabulated by MacKinnon et al. (1999) using response surface regressions.

The estimate of β , $\hat{\beta}$, is given by the eigenvectors associated with the r -largest eigenvalues $\hat{\lambda}$. Hypothesis tests on $\hat{\beta}$ can be conducted using likelihood ratio (LR) tests with standard χ^2 inference. Let the form of the linear restrictions on β be given by $\beta = H\varphi$ where H is a $p \times s$ matrix of restrictions and φ is a $s \times r$ matrix of unknown parameters. The LR test statistic is given by,

$$T \sum_{i=1}^r \ln \left[\frac{(1 - \tilde{\lambda}_i)}{(1 - \hat{\lambda}_i)} \right] \sim \chi_{r(p-s)}^2 \quad (7)$$

where $\tilde{\lambda}_i$ are the eigenvalues from the restricted MLE.

The two variables in (5) can be represented in the vector process:

$$X_t = \begin{bmatrix} NSOPEC_t & SA_t \end{bmatrix}',$$

where $NSOPEC_t$ is the non-Saudi OPEC output and SA_t is the output of Saudi Arabia at time t , respectively. The long-run relationship can be defined by $\beta' z_t$ with $\beta' = [\beta_{11} \ \beta_{21}]$.

Normalizing β so that the first element is one, denoted as $\tilde{\beta} = [1 \ \tilde{\beta}_{21}]'$, facilitates a structural interpretation of the cointegrating vector.¹² The value of $\tilde{\beta}_{21}$ helps identify which market structure is more consistent or, alternatively, which market structures are inconsistent with the data. As noted in the previous sections, if OPEC is a non-cooperative oligopoly, then $\tilde{\beta}_{21}$ should be positive. On the other hand, a necessary, but not sufficient, condition for a cooperative market structure is $\tilde{\beta}_{21}$ less than zero. If $\tilde{\beta}_{21}$ is not statistically different from -1, then the output levels of non-Saudi OPEC and Saudi Arabia are trending together, consistent with a collusive agreement to maintain relative market shares over time (this would support both the Osborne quota rule and the planned extraction rates of Lewis and Schmalensee). Therefore, the system is subjected to extensive tests to determine whether the data are consistent with a system characterized by cointegration rank one and then whether the estimated empirical representation spans the vector space described by $\tilde{\beta}$.

The test for cointegration employs Johansen's maximum-likelihood based analysis on the unrestricted bivariate VAR using 7 lags (6 lags in the VECM representation).¹³ The calculated trace statistic for the null hypothesis of $r = 0$, i.e., that there is no long-run equilibrium between Saudi and non-Saudi OPEC production, is 21.48, which has a p -value of 0.034 implying that this hypothesis can be rejected. The estimated trace statistic associated with the hypothesis that $r \leq 1$ is 6.10 which has a p -value of 0.183 suggesting that one cannot reject at conventional significance levels the hypothesis that there is at most one cointegrating relationship. The evidence supports the existence of one cointegrating relation between the two production levels which is consistent with the hypothesis that the OPEC members are in the same market.¹⁴

The estimated cointegrating vector is $\tilde{\beta} = [1.0, -0.84]'$, implying the two series are positively related to each other. This finding is consistent with Osborne's quota rule and Lewis and Schmalensee, yet also supports Al-Sultan (1993) and Dahl and Yücel (1991).¹⁵

The assumptions of various market structures imply that the two series (Saudi Arabia and non-Saudi OPEC production) move together in the long-run. Perfect competition, in its strictest form, predicts that all firms should have the same cost and demand conditions, thereby having the same output levels. Over time, the output levels of perfectly competitive firms should change in proportion with each other. Yet, both Osborne, because of the quota rule, and Lewis and Schmalensee, because of steady-state extraction rates, also predict that Saudi Arabia and non-Saudi OPEC production levels should have constant output ratios or proportional growth rates. This implies a restriction on the normalized cointegrating vector such that $\beta = [1.0, -1.0]'$. This restriction is tested using the log-likelihood ratio (*LR*) test of equation (7). The calculated test statistic of 0.13 is distributed as a χ^2 variate with one degree of freedom. Comparing this to the appropriate 5% critical value of 3.841 leads to the conclusion that this restriction on the cointegration space cannot be rejected.

One possible source of model misspecification is parameter instability. The estimated cointegration parameters are assumed to be constant throughout the sample. This may not be the case if the variables are subject to changing economic environments, policy regimes, etc. Hansen and Johansen (1993) have developed a recursive procedure to test the stability of the cointegration parameters. They suggest testing the stability of $\hat{\beta}$ using the model of equation (6) when the short-run dynamics parameters are restricted to equal their full-sample values. This simply implies using stability tests based upon the equation $R_{0t} = \alpha\beta'R_{1t} + \epsilon_t$, where R_{0t} and R_{1t} have been defined earlier. The hypothesis of interest is that $\beta_t = \beta \forall t = T_0, \dots, T$ so that $H = \beta$ and φ is the $r \times r$ identity matrix. For each period t the LR test is calculated as,

$$t \sum_{i=1}^r \ln \left[\frac{(1 - \tilde{\lambda}_i)}{(1 - \hat{\lambda}_i)} \right], t = T_0, \dots, T, \quad (8)$$

which is distributed $\chi_{r(p-r)}^2$ at each iteration.

The Hansen and Johansen procedure is employed to test for the stability of the long-run equi-

librium. Figure 4 plots the recursive trace statistics normalized by the appropriate 5% critical values so that values greater than one imply statistical significance at the 5% level. There is strong evidence that the long-run equilibrium has been statistically significant since the late 1970s. Figure 5 plots the recursive LR statistics, normalized by the 5% critical value, associated with the hypothesis of a stable cointegration space, i.e. β is constant over the entire sample. There is no evidence against this restriction, thus the relationship between the oil production of Saudi Arabia and the other OPEC nations has been stable over the sample.

3.3 Dynamic Analysis

The VAR of equation (5) is very popular in the time series and macro literature because of its ability to generate inference on dynamic relationships. A VAR can be interpreted as the reduced form of a dynamic simultaneous equations system. The moving average representation (MAR) is useful for producing estimates of dynamic multipliers. These multipliers provide information about the time paths of the endogenous variables when subjected to shocks or innovations. Unfortunately the source of the innovation is not identified from the reduced form VAR parameters. Like a standard simultaneous equations model, the VAR must be subjected to identifying restrictions in order to yield interpretable dynamic responses to innovations.

Conventional structural VAR innovation identification in a p -dimensional system requires $(p(p - 1))$ identifying restrictions. In conventional applications undertaken without incorporating knowledge of cointegration rank, $p(p - 1)/2$ of these restrictions come from the assumption that the structural innovations are independent, i.e., that the structural error covariance matrix is diagonal. The remaining $p(p - 1)/2$ restrictions must come from restrictions imposed by the econometrician.¹⁶ The total number of restrictions imposed in these exercises is the same as that required for complete contemporaneous structure identification discussed in the original work of the Cowles Commission.

In a p -dimensional system with cointegration rank r , there exist $k = p - r$ stochastic trends

driving the long-run properties of all of the endogenous variables. Thus only k of the p structural innovations result in permanent movements of the endogenous variables. The remaining r innovations have only transitory dynamic effects. Identification of a structural VAR is simply an exercise in identifying the k permanent innovations and the r transitory innovations. As demonstrated in the Appendix B, the existence of cointegration implies certain restrictions on the VAR representation of the data. These cointegrating restrictions help reduce the number of ad hoc identifying restrictions that need to be imposed by the econometrician. In the analysis, no extra restrictions are required beyond the assumption that the structural errors are independent. The existence of cointegration provides all of the restrictions necessary to just-identify the structural model.

As noted previously, a direct long-run relationship is a necessary condition for a cartel market structure to exist. However, other exogenous factors could mask a non-cooperative environment. As such, the use of dynamic analysis assists to further identify the true market structure.

Figure 6 displays the dynamic impulse responses from the identified VAR.¹⁷ The panels on the left display the responses of Saudi and non-Saudi OPEC output from a shock to the permanent innovation (corresponding to hypotheses H2a-H2c in Table 1) while those on the right display the dynamic paths each series takes when subjected to a transitory shock (corresponding to Hypotheses H1a-H1c in Table 1).

Permanent innovations can be interpreted as demand shocks or productivity-cost shocks, for example a (positive) technology shock to the production functions of the OPEC nations that permanently raises the output levels of all members. Consistent with maintaining a cooperative oligopoly, both Saudi and non-Saudi OPEC output levels increase in the same proportion in the long run. However, the short-run response of Saudi output is quite interesting. Saudi output initially falls in response to a permanent shock to non-Saudi OPEC output and only gradually increases over time. In fact a new long-run equilibrium is not reached for about five years. This suggests that Saudi Arabia acts as a swing producer (consistent with Jones, 1980, and Alhajji and Huettner, 2000a and 2000b); Saudi Arabia changes its output in response to permanent shocks to smooth the

adjustment of OPEC output to a new steady state. The response of Saudi Arabia to permanent shocks in other OPEC member production is consistent with hypothesis H2b in Figure 1.

Compared to the permanent shocks, transitory innovations, which can be interpreted as cheating by one or more cartel members, invoke a different response by Saudi Arabia. Saudi Arabia increases its production in response to transitory increases in non-Saudi OPEC production, consistent with hypothesis H2c, and contrary to the response predicted by competition or non-cooperative oligopoly. The magnitude of the Saudi response is almost double that of the 'cheaters,' consistent with Saudi Arabia playing a dual role as the cartel enforcer. When Saudi Arabia responds with a large increase in output, *ceteris paribus*, this effectively punishes the 'cheaters' by attempting to reduce the market price for crude oil. The impulse response patterns are consistent with the enforcement model of Osborne (or the tit-for-tat strategy of Griffin and Neilson) but are not consistent with non-cooperative oligopoly models.

In summary, the short-run dynamics indicate that OPEC is a successful quantity cartel with Saudi Arabia acting in the dual role of cartel enforcer *and* swing producer, depending on whether output increases are caused by temporary or permanent shocks, respectively. Because short-run increases in other producer's output invoke an increase in Saudi output, whereas permanent increases in other producers' output invoke an immediate decrease in Saudi output, the cartel arrangement is the only market structure consistent with these findings (see Figure 1). These findings allow us to advance the study of market structure beyond the identification problems encountered in other studies. Specific to OPEC, the findings provide support while synthesizing the conflicting results of Griffin (1985), Griffin and Neilson (1994), and Jones (1990), although using a very different empirical technique.

4 Conclusions

This paper provides an empirical methodology to determine market structure based upon the long-run relationships and short-term transition dynamics between producer outputs. Specifically, innovations analysis within a structural VAR framework is applied to output series to test hypotheses about various market structures, including competition, non-cooperative oligopoly and cooperative oligopoly. To illustrate, the approach is applied to the often debated case of OPEC. Recent techniques developed in the structural VAR literature are used to incorporate the suggestion of Staiger and Wolak (1992) that cartel stability, and market structures in general, may depend upon intertemporal stability of market shares.

The approach indicates that Saudi Arabia behaves in a manner consistent with Osborne's (1976) quota rule and the tit-for-tat strategy postulated by Griffin and Neilson (1994) in response to cheating by cartel members. The cartel arrangements are enforced by Saudi Arabia, the largest of the OPEC members in terms of production and excess capacity, consistent with Osborne's model. However, OPEC is also accommodating to permanent changes in OPEC production levels, caused for example by permanent changes in extraction costs or permanent demand shocks, with Saudi Arabia acting as a swing-producer.

The approach taken here has two distinct implications. First, the methodology provides a possible solution to the econometric-based identification problems associated with various versions of imperfect competition. The approach herein provides testable hypotheses for which time series econometrics is an appropriate methodology. In the application to OPEC, it is possible to isolate the actual market structure that best fits OPEC production data. Second, the procedure is based on quantity alone, which is useful when all output is sold at a common price. This approach may be applicable to other markets in which the actual structure is still open to debate, and in areas such as antitrust, structure-conduct-performance studies, and other areas of industrial and micro economics.

Appendix A

A Brief Overview of OPEC

Before 1983, OPEC members used price as the signaling mechanism to deter cheating (New York Times, 1989). This method was easy for two principal reasons. First, OPEC was the predominant producer of crude oil during this time; OPEC enjoyed its maximum market share of world oil production at 55.80% in 1973 (Alhajji and Huettner, 2000a). Thus, any changes in price not demand-driven could credibly be attributed to the supply of crude oil by OPEC members. Second, the collection and reporting of member-country outputs was limited at best, whereas spot and future prices of crude oil were readily available in the late 1970s.

While price was a convenient and useful detection tool in the early stages of OPEC's existence, one of its biggest drawbacks was that not all grades of crude oil from OPEC member countries were of the same quality. Product heterogeneity has been shown to cause difficulties in maintaining a collusive structure (see Carlton and Perloff, 1994). Several other factors contemporaneously added to price becoming an ineffective tool for detection. For example, from 1973 to 1985 OPEC experienced a decline in its world market share of output from a maximum of 55.80% to a minimum of 30.00%, as several new facilities came on-line outside the control of OPEC members, e.g., in Alaska and the North Sea.¹⁸ Second, the collection and reporting of oil production data, confirmed by third-party agents, became standard practice of all OPEC countries. The loss of market share made price a noisy signal of cheating because changes in world crude prices could more readily be caused by non-OPEC countries. Further, the availability of output data made the enforcement of quantity quotas more realistic.

Some claim that OPEC is not a cartel but that, in order to maintain world prices, Saudi Arabia acts as a swing producer (Alhajji and Huettner, 2000a and 200b). From 1981 to 1985, Saudi Arabia reduced its output from 8.5 million barrels a day (mbd) to little more than 2 mbd. This reduction in output (and subsequent oil revenues) caused severe hardship on the national economy

of Saudi Arabia. At the end of 1985, Saudi Arabia increased its output by more than 200 percent, thereby abandoning the enforcement of the cartel's quota agreements (Scherer, 1996, and Griffin and Neilson, 1994). However, it is not clear whether this production increase was an abandonment of the cartel structure or merely a rational response to other market factors. Griffin and Neilson (1994) and Jones (1990) both analyze the behavior of OPEC during the mid 1980's in an attempt to explain the sudden decrease in the price of crude oil. Jones contends that OPEC follows a loose market sharing agreement whereas Griffin and Neilson find econometric evidence that Saudi Arabia abandoned the swing producer model and adopted a tit-for-tat strategy which enforced the cartel's pre-arranged market sharing agreement.

Al-Sultan (1993) presents an overview of various theoretical and empirical models with which to analyze OPEC behavior over time. He presents evidence that OPEC does not correspond with a competitive market and thus must be imperfectly competitive. However, he claims an identification problem in being unable to determine if the imperfectly-competitive structure follows a Cournot, cartel or other form of firm interaction.

Griffin (1985) focuses on OPEC in the context of a market sharing agreement and concludes that this market structure is superior to the previously mentioned alternatives. Griffin and Neilson (1994) test whether a regime change in market structures can explain the sudden decrease in world oil prices in the mid-1980s. They contend that Saudi Arabia chose to employ a swing-producer strategy as long as Saudi Arabian profits were greater than would obtain in Cournot competition. Basing their regime change upon anecdotal evidence, they find empirical support that Saudi Arabia switched from a swing-producer strategy, thereby meeting price targets, to a cartel enforcer, using a tit-for-tat strategy. Our empirical analysis encompasses the time frame of both Griffin (1985) and Griffin and Neilson (1994) and, as it turns out, supports both sets of findings albeit in a more general framework.

Some recent contributions to the literature focusing on OPEC have continued the search for appropriate market structures. Jones (1990) investigates a period of declining world oil prices in the

late 1980's and supports Griffin's (1985) findings for a period of rising world oil prices. Specifically, he concludes that price adjustments were the result of purposeful cartel decisions rather than evidence of a breakdown in cartel solidarity.

Dahl and Yücel (1991) undertake a multi-equation empirical approach to test the various market structures previously attributed to OPEC. Contrary to our results below, they find no evidence of cointegration (i.e., any long-run relationships) between any one country's output and the rest of OPEC production. They claim that this provides evidence of no effective coordination amongst OPEC members but that a small (unnamed) group of OPEC members may behave as swing producers.

Appendix B

This appendix discusses the complete structural identification of a VAR characterized by cointegration. Consider the Wold moving average representation of the system in (5).

$$\Delta X_t = C(L)(\mu + \varepsilon_t) = \delta + C(L)\varepsilon_t \quad (\text{A1})$$

and form a multivariate Beveridge-Nelson decomposition from (A1) by separating the matrix polynomial into components associated with long-run and short-run information to obtain $C(L) = C(1) + C^*(L)(1-L)$ where $C(1)$ is the sum of the moving average coefficients and $C_i^* = -\sum_{i=j+1}^{\infty} C_i$, $i = 1, 2, \dots$. The representation obtained by multiplying (A1) by $(1-L)^{-1}$ (e.g. accumulating the differences) is then

$$X_t = X_0 + C(1) \left(\mu t + \sum_{s=1}^t \varepsilon_s \right) + C^*(L)\varepsilon_t \quad (\text{A2})$$

The second term on the right side of equation (A2) is the permanent portion of the vector process. When the vector process is nonstationary but *not* characterized by cointegration, $C(1)$ is full rank and p distinct shocks leave a permanent imprint on the data. When the variables in the system are cointegrated there are a reduced number of trends which are common to each variable in X_t , thus (A2) is called the common trends representation. When cointegration rank is r the number of common trends is k such that $r + k = p$ the dimension of X_t .

When cointegration characterizes the system X_t it is possible to identify the $k < p$ permanent innovations by recognizing the reduced rank nature of the reduced form total impact matrix, $C(1)$. To illustrate, use a parsimonious notation to express $C(1)$ as the product of two $p \times k$ matrices of rank k , $C(1) = \beta_{\perp} \alpha'_{\perp}$.¹⁹ The first matrix is the factor loading that is by construction orthogonal to the cointegration space β . The second matrix is represented by α_{\perp} to correspond to the matrix that defines the k independent permanent shocks as linear combinations of the p reduced form

innovations in the system. From this perspective, identification of the permanent innovations from knowledge of $C(1)$ is the dual of establishing the identity of the cointegrating relations, β and error correction terms, α , from Π . Accordingly, this requires $k(k-1)$ restrictions. One-half of these can be obtained from innovation independence restrictions while the remaining $k(k-1)/2$ restrictions are imposed on $C(1) = \beta_{\perp} \alpha'_{\perp}$.

Establishing the identity of the permanent innovations that underlie a nonstationary vector process partially identifies a system that, following the Granger representation theorem (GRT), can be represented by k permanent and r transitory distinct innovations. Several procedures for identifying the remaining transitory innovations are available, e.g. Sims (1980), Bernanke (1986), Sims (1986). Warne (1993) adopts the *a priori* restriction that the transitory innovations lie in the space that is orthogonal to the permanent innovations. The advantage of this approach is that once the cointegration vectors are identified, the sets of permanent and transitory innovations may be identified in separate exercises. That is, imposing alternative identifying restrictions on the permanent portion of the system does not alter the identity of the transitory innovations. Warne demonstrates that transitory innovation identification is a straightforward exercise in identifying r distinct innovations requiring $r(r-1)$ restrictions. One half of these restrictions may be obtained by imposing innovation independence. The remainder can come from restricting how shocks to certain transitory innovations affect variables in the first period.²⁰

The relationship between identification of the complete p -dimensional structural VAR and the identification conditions discussed above is now easily seen. In standard structural VAR applications $p(p-1)/2$ restrictions are required in addition to the $p(p-1)/2$ innovation orthogonality constraints to obtain identification (after arbitrary normalization). In the case of cointegrated VAR systems it is possible to also utilize the $p(p-1)/2$ innovation independence restrictions. But, knowledge of cointegration rank r implies that r structural innovations leave no long-run imprint on the p variables in the system and this information is useful in establishing the identity of the innovations. These pr homogeneous restrictions deliver an additional kr independent restrictions

that can be applied toward the identification of the model. With the addition of the $k(k - 1)/2$ and $r(r - 1)/2$ restrictions required to sort out among the sets of permanent and transitory innovations respectively, the $p(p - 1)/2$ required for system identification are obtained. Knowledge of cointegration rank then reduces the number of restrictions required to identify the complete structure of the system by kr . Given that our system of variables X_t has dimension of two, i.e. it is a bivariate VAR, that can be characterized by cointegration rank $r = 1$ thus implying that $k = 1$, the above discussion implies that no restrictions, beyond structural error independence, are needed to exactly identify the econometric model. This bivariate cointegrated VAR is a special case where cointegration restrictions, which are testable, yield the necessary restrictions to achieve identification (see Crowder and Wohar, 1999, for a discussion along these lines).

Notes

¹Some representative studies include Buschena and Perloff (1991), who analyze market structure using changes in the supply of fringe firms, and Rosse and Panzar (1977), Panzar and Rosse (1987), and Shaffer (1982), who analyze market structures using revenues and input prices.

²While sufficiently large demand shocks may shift the reaction functions of Cournot competitors such that all firms increase their output, this does not change the strategic relationship between the production levels of the firms.

³Our results are also consistent with Reynolds (1999) who claims that if Saudi Arabia was a price leader all other countries could increase output without fear of retaliation from Saudi Arabia.

⁴A cartel may give one (or few) cartel member(s) the responsibility of quota-rule enforcement. If larger producers are charged with maintaining the quota-rule, the threat of retaliation to cheating is more credible, as larger producers are more likely have larger absolute excess capacity.

⁵See Bulow, Geanakoplos and Klemperer (1985) for an exposition on these stability conditions.

⁶For example, a permanent shock will shift all outputs to a new steady state equilibrium while outputs return to the original equilibrium after a transitory shock.

⁷Note that Saudi output must increase in the long run in order to maintain the equilibrium implied by hypothesis H3.

⁸The data were graciously provided by S. Gurcan Gulen.

⁹As mentioned below, this is the only combination of countries that exhibits cointegration in output levels.

¹⁰The results from estimating equation (4) without the time trend are qualitatively identical and

so are not presented.

¹¹The lag truncation parameter was set to twelve since this value minimized the Schwartz-Bayesian Criterion (SBC) and yielded white noise residuals.

¹²The normalization of one of the parameters to be unity is consistent with a linear interpretation of the long-run relationship akin to OLS. For example the equation relating y_t to x_t as in $y_t = a_0 + a_1x_t + u_t$ implies a normalized vector of $[1 - a_1]'$.

¹³The choice of 7 lags is based upon information criteria and diagnostic tests on the residuals from the unrestricted VAR model. The lag length of 7 was the smallest lag length that eliminates significant serial correlation from the system. The specifications were extended to include lag lengths up to 13 so as to include lagged information that spans one full year. Although there is weaker evidence of cointegration in longer lag specifications, the estimated cointegration vector is very similar to that obtained in the shorter lag specification. These results are available from the authors upon request.

¹⁴This is contrary to Dahl and Yücel (1991) who found no evidence of cointegration between Saudi and non-Saudi outputs over the sample 1971q1 to 1987q2. Their tests suffer from several problems. First, the sample spans are not consistent across all countries examined. Second, the largest pan of data results in 64 observations while our data span results in 314 observations. Finally, their tests for cointegration are based on the Engle-Granger procedure which has very low power and can be very sensitive to normalization.

¹⁵It is important to recognize that the cointegrating relation between two variables can be represented as $X_{1t} = \tilde{\beta}_{21}X_{2t}$. Thus the cointegration vector is $\tilde{\beta} = [1, -\tilde{\beta}_{21}]'$ so that a negative value for $\tilde{\beta}_{21}$ is consistent with a positive relationship between X_{1t} and X_{2t} .

¹⁶Early work focused on establishing a recursive pattern to the contemporaneous impact of the

structural shocks on the data. More recent efforts have employed long-run response patterns to identify structural innovations.

¹⁷The IRFs are plotted with 90% confidence bands. The confidence intervals were generated using the bootstrapping procedure suggested by Runkle (1987).

¹⁸In 1999, OPEC enjoyed a 42.30% market share of world oil production (Alhajji and Huettner, 2000a).

¹⁹From Johansen's (1991) proof of the Granger Representation Theorem, $C(1) = \beta_{\perp}(\alpha'_{\perp}\Pi_1^*(1)\beta_{\perp})^{-1}\alpha'_{\perp}$ where β_{\perp} and α_{\perp} are $p \times k$ orthogonal complements for β and α with $k = p - r$, and $\beta'_{\perp}\beta = \alpha'_{\perp}\alpha = 0$, $\Pi(L) = \Pi(1) + \Pi_1^*(L)(1 - L)$, $\Pi_1^*(L) = \Pi + 1 - \sum_{i=1}^{q-1} \Pi_1^*L^i$, and $(\alpha'_{\perp}\Pi_1^*(1)\beta_{\perp})$ is nonsingular. Note that $\Pi_1^*(1) = \Pi_1 + 2\Pi_2 + 3\Pi_3 + \dots + q\Pi_q$. To facilitate notation, our illustration does not distinguish β_{\perp} from a simple matrix transformation, $\beta_{\perp}(\alpha'_{\perp}\Pi_1^*(1)\beta_{\perp})^{-1}$ or similarly α'_{\perp} from $(\alpha'_{\perp}\Pi_1^*(1)\beta_{\perp})^{-1}\alpha'_{\perp}$.

²⁰Warne's proposal for transitory identification is the standard recursive contemporaneous ordering adopted in traditional VAR applications.

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Table 1: Market Structure Hypotheses

Hypothesis	Reject	Fail to Reject	Condition
H1a	Cooperative Oligopoly Non-Cooperative Oligopoly	Competition	No temporary response to transitory shock
H1b	Cooperative Oligopoly Competition	Non-Cooperative Oligopoly	Negative temporary response to transitory shock
H1c	Non-Cooperative Oligopoly	Cooperative Oligopoly Competition	Positive temporary response to transitory shock
H2a	Cooperative Oligopoly Non-cooperative Oligopoly	Competition	No temporary response to permanent shock
H2b	Competition	Cooperative Oligopoly Non-Cooperative Oligopoly	Negative temporary response to permanent shock
H2c	Cooperative Oligopoly	Non-Cooperative Oligopoly Competition	Positive temporary response to permanent shock

Table 2: Dickey-Fuller Test Results

Lag ^a	Saudi Production				Non-Saudi OPEC Production							
	ADF	τ_μ	Statistic ^b	Q-Stat ^c	ADF	τ_μ	Statistic ^b	Q-Stat ^c	ADF	τ_τ	Statistic ^d	Q-Stat ^c
0		-2.28	16.31	16.05	-2.33	-2.33	34.87*	34.50*	-2.52	-2.52	34.87*	34.50*
1		-2.13	10.72	10.62	-2.12	-2.12	32.55*	32.20*	-2.32	-2.32	32.55*	32.20*
2		-2.19	9.88	9.71	-2.04	-2.04	32.94*	32.95*	-2.23	-2.23	32.94*	32.95*
3		-2.07	8.59	8.55	-2.02	-2.02	32.02*	31.74*	-2.25	-2.25	32.02*	31.74*
4		-2.11	10.76	10.71	-1.85	-1.85	25.37*	24.95*	-2.13	-2.13	25.37*	24.95*
5		-2.11	8.06	8.05	-1.74	-1.74	23.73*	22.86*	-2.03	-2.03	23.73*	22.86*
6		-2.10	7.50	7.50	-1.71	-1.71	23.72*	23.09*	-2.01	-2.01	23.72*	23.09*
7		-2.17	5.53	5.52	-1.68	-1.68	25.09*	25.76*	-1.99	-1.99	25.09*	25.76*
8		-2.13	4.76	4.76	-1.62	-1.62	25.60*	24.51*	-1.98	-1.98	25.60*	24.51*
9		-2.07	4.81	4.81	-1.74	-1.74	17.37	16.33	-2.05	-2.05	17.37	16.33
10		-2.02	5.27	5.27	-1.74	-1.74	18.56**	18.01	-2.04	-2.04	18.56**	18.01
11		-2.04	5.31	5.33	-1.71	-1.71	18.52	19.19**	-2.02	-2.02	18.52	19.19**
12		-1.95	6.99	7.01	-1.89	-1.89	7.32	7.43	-2.12	-2.12	7.32	7.43

Notes: Results in table 2 are based on the ADF testing equation $\Delta X_t = \mu + \delta t + \rho X_{t-1} + \sum_{j=1}^k \gamma_j \Delta X_{t-j} + \varepsilon_t$ estimated using OLS. *a*- Lag refers to the parameter *k* in the ADF equation. *b*- ADF τ_μ is the t-statistic testing the null hypothesis that $\rho = 0$ from the ADF equation with $\delta = 0$. The 5% critical value taken from MacKinnon (1991) is -2.89. *c*- The Q-Stat is the Ljung-Box statistic for twelfth order residual serial correlation and is distributed as $\chi^2(12)$. *d*- ADF τ_τ is the t-statistic testing the null hypothesis that $\rho = 0$ from the ADF equation. The 5% critical value taken from MacKinnon (1991) is -3.45. *- denotes significance at the 5% level. **- denotes significance at the 10% level.

Figure 1: Decision Matrix for Market Structure Based on Dynamic Decomposition
(Predicated on Failure to Reject H1c from Table 1)

Firm A's Short-Term Response to Others' Permanent Shock	Firm A's Short-Term Response to Others' Transitory Shock		
	No Change in Output (H1a)	Reduce Output (H1b)	Increase Output (H1c)
No Change in Output (H2a)	Perfect Competition	Indeterminant	Perfect Competition
Reduce Output (H2b)	Indeterminant	Asymmetric Dynamic Cournot	Cartel Punisher and Stabilizer
Increase Output (H2c)	Perfect Competition	Symmetric Dynamic Cournot	Perfect Competition

(·) indicates corresponding hypothesis from Table 1

Firm A is a representative producer cointegrated with other producers (see Section 2)

Saudi vs non-Saudi OPEC Production (Output in Logs)

1965 to 1993

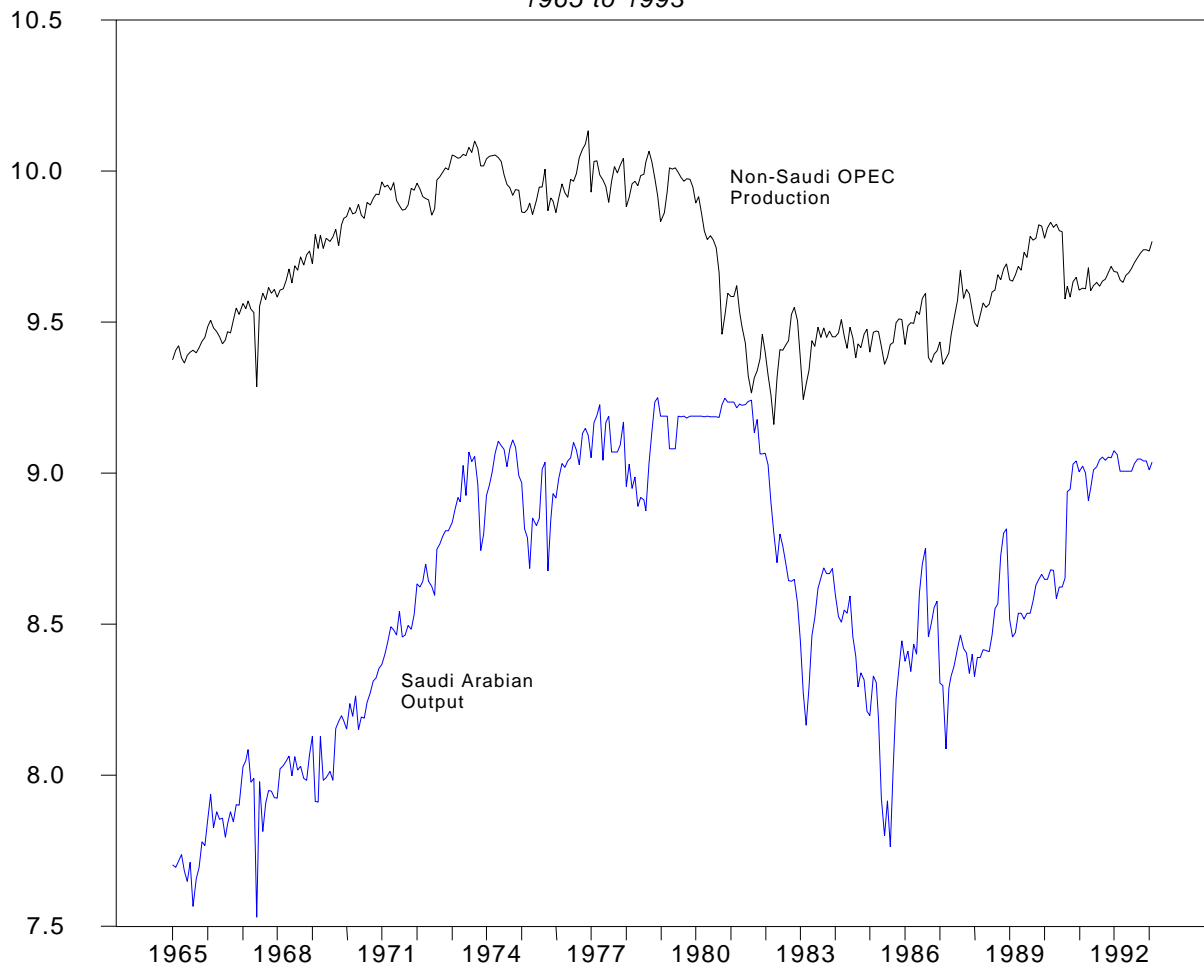
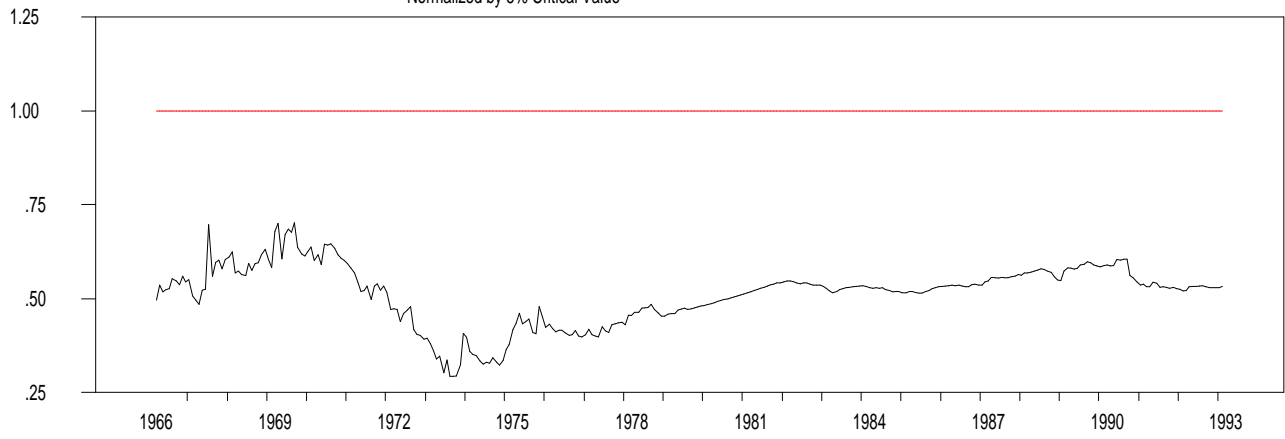


Figure 2: Plot of the Data

Zivot-Andrews Unit Root Test on Saudi Production

Normalized by 5% Critical Value



Zivot-Andrews Unit Root Test on Non-Saudi Production

Normalized by 5% Critical Value

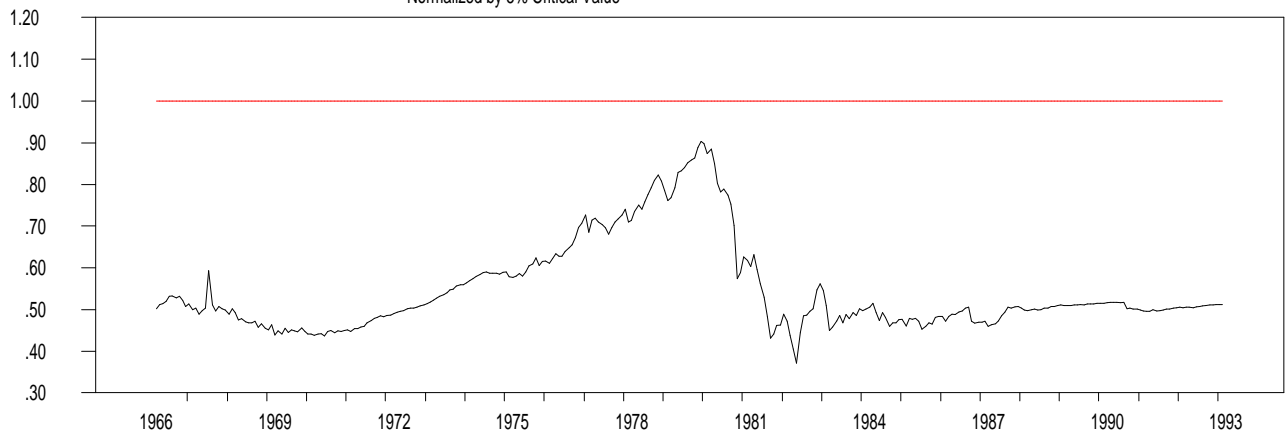
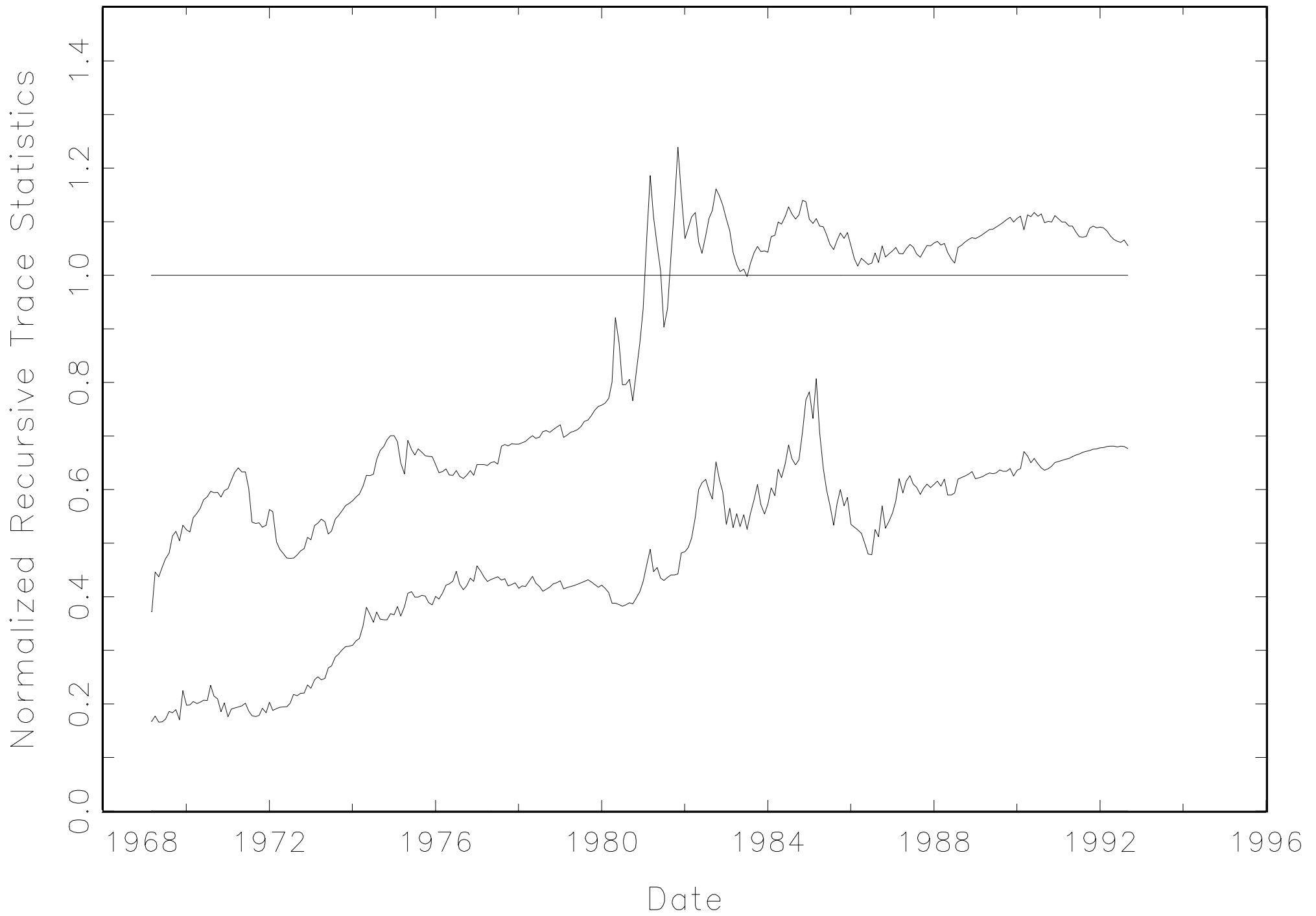
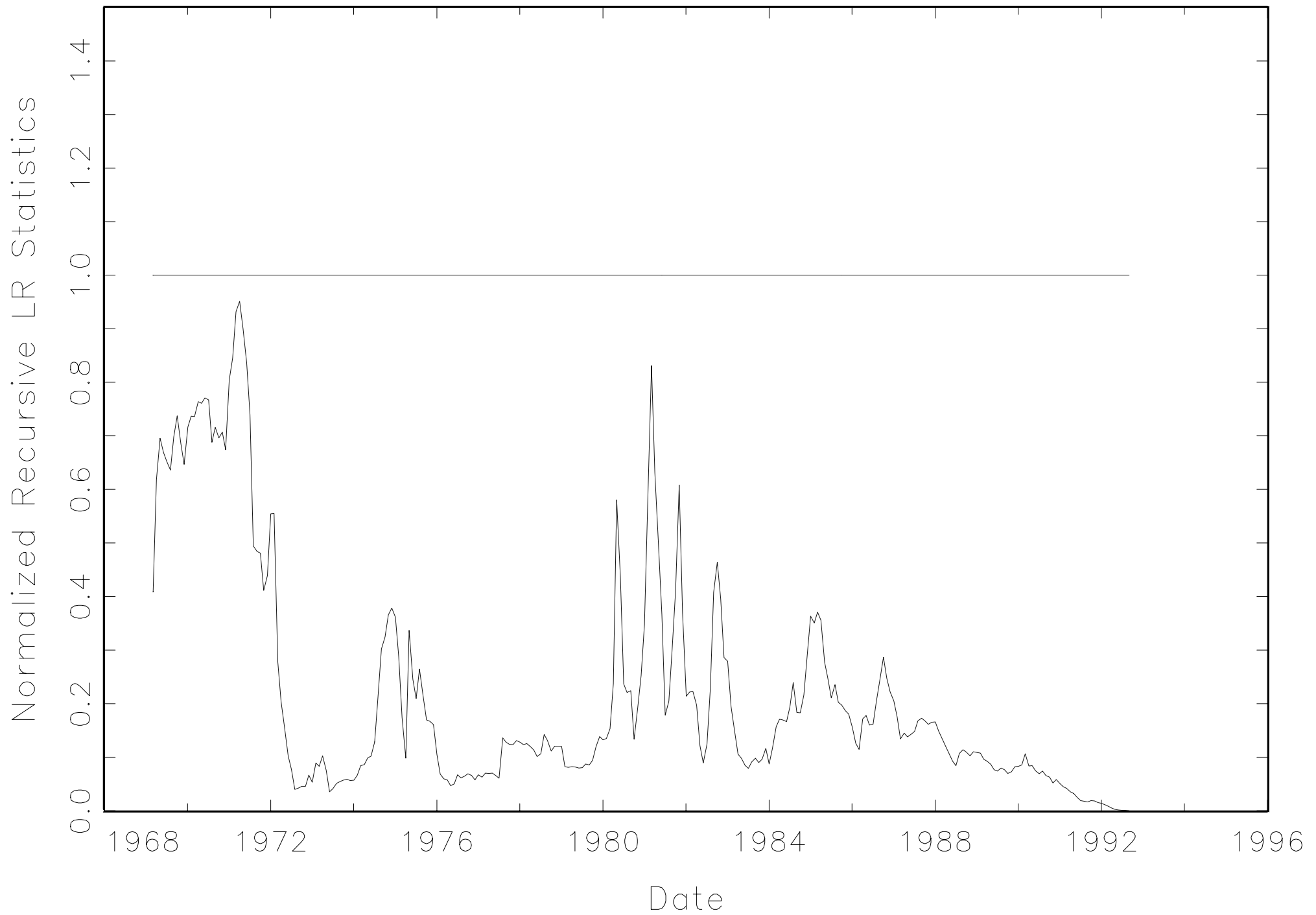


Figure 3: Zivot Andrews Unit Root Tests

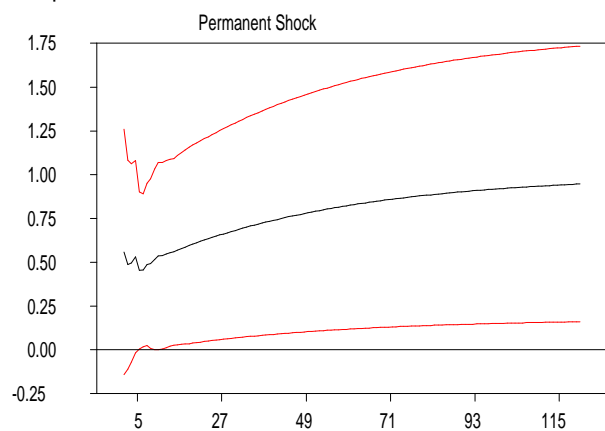
Recursive Trace Tests



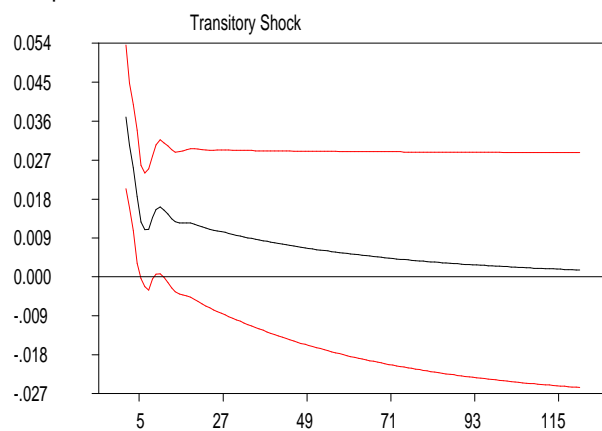
Recursive LR Tests of Constant Cointegration Space



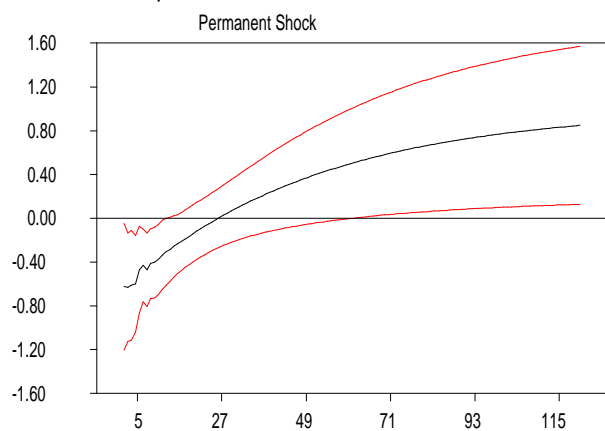
Response of Non-Saudi OPEC



Response of Non-Saudi OPEC



Response of Saudi



Response of Saudi

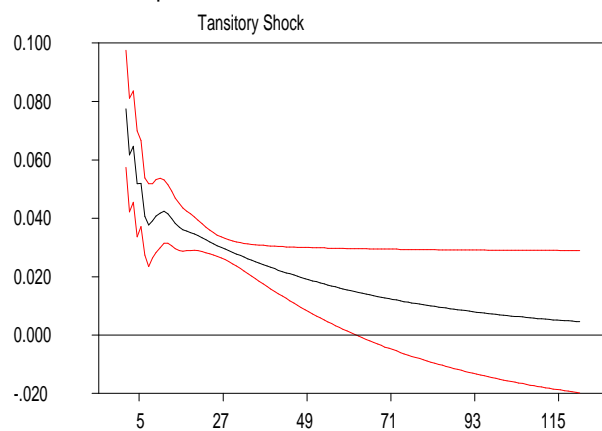


Figure 6: Impulse Response Functions