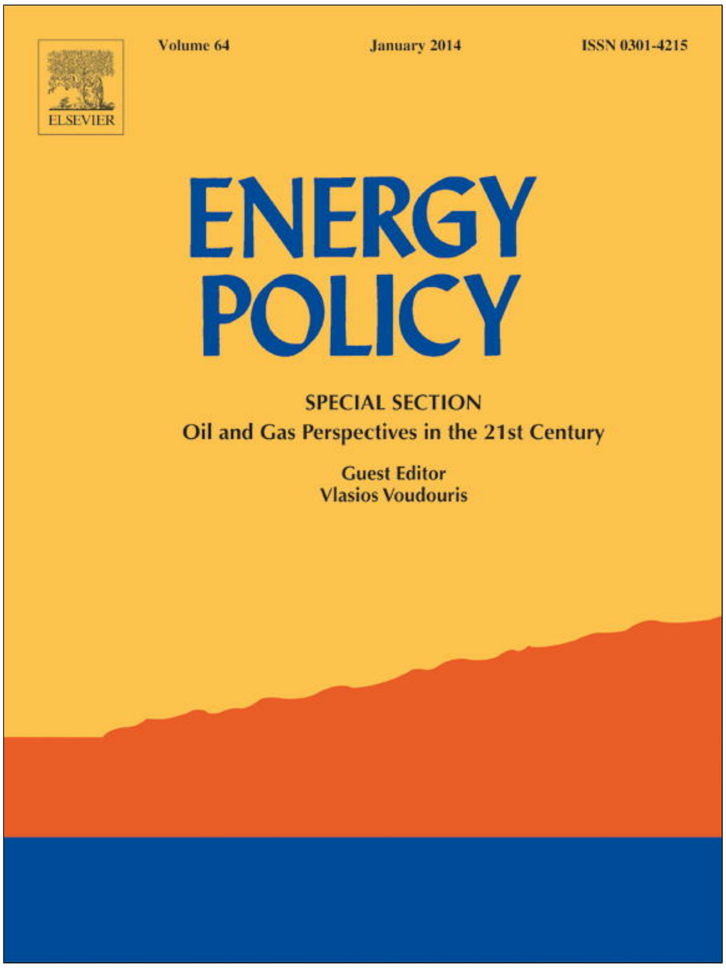
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Analysis of Saudi Arabia's behavior within OPEC and the world oil market

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ABSTRACT

We analyze oil export behavior by Saudi Arabia and the Rest of OPEC since 1973. In the literature there has been a wide range of estimates of their correlation: from positive, to zero, to negative. We find that the correlation has varied over time, from moderately high (0.7) in normal periods, to negative during each of five interruptions; the average correlation has been 0.19. Saudi Arabia's oil market behavior depends upon circumstances, but its primary goal is the stability of OPEC and the world oil market. It will coordinate export reductions with the Rest of OPEC when faced with declining demand, but it will increase exports when faced with interruptions elsewhere in OPEC. Allowing for such differences provides evidence of intelligent, context-dependent consistency. But ignoring context – by wrongly assuming the same Saudi response in Normal periods and Interruptions – can lead to a conclusion of Saudi "inconsistency" because the difference in the responses has been obscured.

1. Introduction

OPEC quadrupled crude oil prices nearly 40 years ago, and since then we have witnessed a large literature about how OPEC and its key producers have acted within the world oil market. A substantial part of this literature stems from the analysis by Griffin (1985).[1] Yet there has been surprisingly little agreement about some of the most important questions, such as the role of Saudi Arabia and whether it coordinates its production decisions with its partners in OPEC. Smith (2005, p. 75) does not find clearly discernible consistency in the actions of Saudi Arabia, while Kaufmann et al. (2008, p. 348) find no clear relationship between Saudi production and that from the Rest of OPEC.

This article re-examines these questions, with a special focus on Saudi Arabia's decisions about its levels of oil production and exports.[2] Although others have used a single model for Saudi Arabia over time, we believe that Saudi behavior has varied, depending upon the circumstances.[3] In many years Saudi Arabia has acted together with the Rest of OPEC, restricting its exports together with its OPEC partners as demand declined, and expanding its exports when demand increased. The most notable examples of proportional restriction in exports during recessions are 1974–1975, 1998, 2002, and in 2008–2009. At other times, however, the Saudis have acted independently from the Rest of OPEC, most notably at those times of supply interruption elsewhere in OPEC: 1978 in Iran, 1980–1981 in Iraq and Iran, 1990 in Kuwait and Iraq, 2003 in Iraq, 2011 in Libya. On these occasions, rather than matching the export cutbacks elsewhere in OPEC, the Saudis increased their exports to offset the interruptions.[4]

This variation in Saudi export behavior over time is evident in the correlation between the changes in Saudi oil exports and changes in exports from the Rest of OPEC. In most "normal" periods (excluding interruptions and recoveries), the correlation is relatively high, at about 0.7. But during interruptions the correlation becomes negative. Although the *average* correlation since 1973 is 0.19, this masks the wide variation over time:

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[1] Surveys of the broader literature on OPEC can be found in Gately (1984), Cremer and Salehi-Isfahani (1991), and Al-Yousef (2012).

[2] Although previous articles have analyzed OPEC oil production, we focus on OPEC oil *exports* because only OPEC exports affect the world oil market. OPEC domestic consumption has grown from less than 5% of production in the early 1970s to 25% currently. OPEC now consumes as much oil as China. Although OPEC oil production is slightly higher now than in 1973, OPEC oil exports are 20% lower. OPEC exports' share of Non-OPEC consumption has fallen from 52% in 1973 to 34% now. See Gately et al. (2012, 2013) for analyses of domestic oil consumption in Saudi Arabia and OPEC, respectively.

[3] Our view that OPEC behavior has varied over time depending upon circumstances is shared by Adelman (1982), Geroski et al. (1987) and Kaufmann et al. (2008), among others.

[4] At other times, Saudi export behavior has been designed to enforce discipline within OPEC, to encourage the honoring of production quotas and discourage over-shipment (as in 1988)—via tit-for-tat behavior that demonstrated Saudi willingness to match the behavior of its partners: over-shipping quotas when other OPEC producers do so, and honoring its quota when others do so.

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strongly positive during "normal" periods but negative during and after supply interruptions.

We analyze these different periods separately, distinguishing between normal periods and interruptions, and between increases and decreases in Saudi exports. Within this complexity, we find consistent behavior by Saudi Arabia.

The outline of the paper is as follows. In Section 2 we summarize OPEC export behavior since 1973 and the varying relationship between Saudi exports and those from the Rest of OPEC. In Section 3 we review some of the disagreements in the literature, and discuss how our analysis can help to clarify the issues. We focus especially of the asymmetric responsiveness of Saudi exports to increases and decreases in Rest-of-OPEC exports, within normal periods and during interruptions. Section 4 presents the methodology we employ, which is similar to that adopted by most authors following Griffin (1985). Section 5 presents our econometric results. Section 6 summarizes our conclusions. Data sources and details are presented in Appendix A, statistical test results in Appendix B, summary results using OPEC production (rather than exports) in Appendix C, and summary results using the DOLS method in Appendix D.

2. Background

Between 1965 and 1973 (when pricing and output decisions were controlled by the international oil companies), Saudi Arabia exports quadrupled, from 2 to 8 mbd (million barrels/day), doubling its share of OPEC oil exports to 28%. When OPEC quadrupled the price in 1973–1974 and the OPEC countries nationalized their oil reserves, it was a shock to the oil market and the world economy.[5] The price quadrupling halted the surge in demand for OPEC oil (which had been growing 10% annually for a decade), and for three years OPEC successfully managed the changes in demand that it faced. Its quarterly exports fell from 29.6 mbd in 1973q3 to 23.5 in 1975q1, but recovered quickly, to 30.5 in 1976q4. Then in late 1978 the Iranian Revolution shut down production in Iran; the Saudis increased their own exports, which partially offset this loss, but a second price shock in 1979–1980 doubled the oil price. Not long after that, Iraq invaded Iran and their war shut down a combined total of 6 mbd production. In the face of these disruptions, Saudi Arabia maintained it exports at capacity, nearly 10 mbd through 1981, which by now represented 50% of OPEC exports. Some of the background data is presented in Fig. 1.

However, in just a few years after 1981, the demand for OPEC oil collapsed, falling to only half its 1979 level. This demand collapse was largely due to the unwise decision to defend the 1979–1980 price doubling, which exacerbated the world economic recession, the shift away from oil used in electricity generation and space heating,[6] and the continuing growth of Non-OPEC supply. By 1985, Saudi Arabia had to cut its oil exports 70% from their 1981 level, to below 3 mbd (only 21% of OPEC exports). This was almost back to 1965 levels.

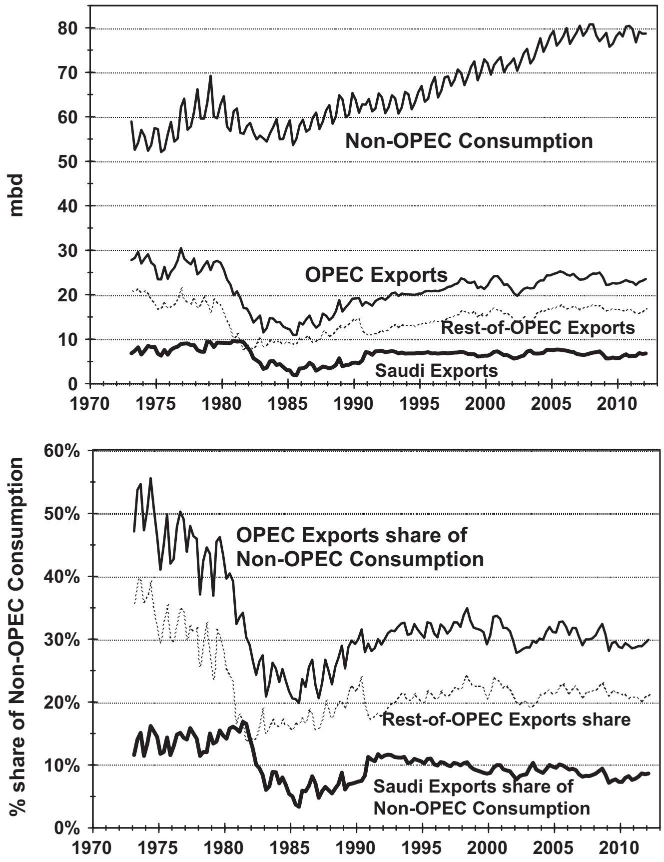

Fig. 1. OPEC oil exports (mbd) and % shares of Non-OPEC Consumption, 1973q1–2012q1.

Starting in late 1985, Saudi Arabia abandoned OPEC's price-setting, output-restricting policy, and doubled their exports within two quarters; price fell sharply, to below its 1974 level. Soon there followed *rapprochement* within OPEC, as they adopted production quotas to manage their gradual increases in exports and recovery of market share. On several occasions the Saudis encouraged discipline in honoring production quota agreements using a "tit-for-tat" strategy: match quota over-shipments by its OPEC partners and reciprocate when quotas were respected.[7]

OPEC's recovery was interrupted in August 1990 when Iraq invaded Kuwait, and exports from both countries stopped. Again, the Saudis responded, by doubling their exports within two quarters. They maintained those export levels almost unchanged for nearly a decade, while the Rest of OPEC gradually increased their exports. Prices stayed relatively low, in the $25 range.

Starting in 1998, after the Asian Financial Crisis, Saudi Arabia resumed a more active role, adjusting its export levels in response to the market. OPEC's exports continued increasing until 2005, when price began to surge as world demand grew faster than Non-OPEC and OPEC suppliers could respond. By the middle of 2008, oil prices peaked, at levels not seen since 1980, possibly exacerbated by speculative activity. This peak was soon followed by sharp declines in price, which OPEC did not attempt to prevent (unlike in the early 1980s), although Saudi Arabia and the Rest of OPEC cut their exports to lessen the extent of the price collapse. Price recovered modestly, as strong demand from the developing

[5] There were two basic explanations of these events, as discussed in Gately (1984). A majority view was that OPEC had effectively cartelized the world oil market. However, others such as MacAvoy had argued that cartelization was not the primary explanation for 1973–1974, because much higher prices were inevitable and OPEC controlled only the timing of the price increases: "the 10% annual growth rate in OPEC production from 1960 through 1973 was unsustainable, even with OPEC's large oil reserves. By mid-1973, months before the Arab–Israeli War and subsequent price quadrupling, the market was already very tight: OPEC's official prices were well below those in the spot market … As Paul MacAvoy … has argued '… there was no avoiding the substantial price increases necessary to clear the market of annual increases in oil demand." (Gately, 1984, p. 1101).

[6] See Dargay and Gately (2010).

[7] This strategy is discussed below, as well as in Geroski et al. (1987), Gately (1989), and Griffin and Neilson (1994).

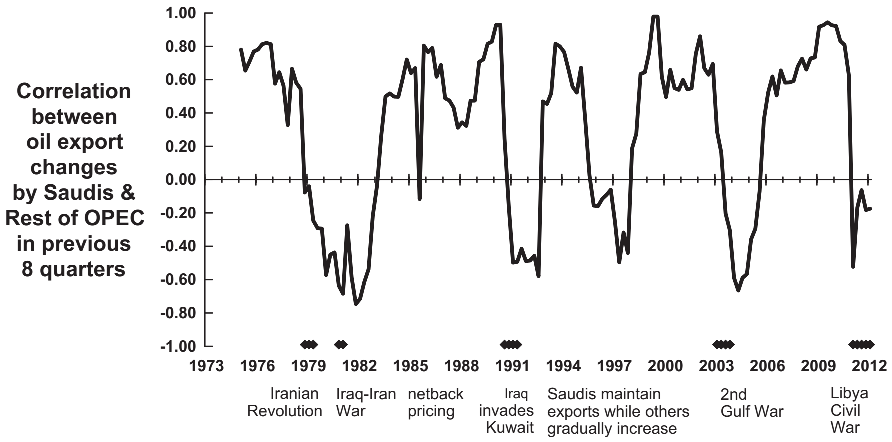

Fig. 2. Correlation between quarterly changes in oil exports by Saudi Arabia and the Rest of OPEC (each measured in mbd) over the previous 8 quarters.
Notes: Diamonds indicate quarters in which there were interruptions and subsequent recoveries.
The Iranian Revolution reduced Iranian oil exports from 6 mbd to 1 mbd in late 1978. This was partly offset by a 2 mbd increase in Saudi exports to 10 mbd.
The Iraq–Iran War in 1980 reduced each country's oil exports from about 4 mbd to about 1 mbd. The Saudis maintained full-capacity production at 10 mbd.
In August 1990, Iraq invaded Kuwait. Within 6 months, their combined oil exports of 5 mbd were completely stopped. Saudi Arabia increased their oil exports by nearly 3 mbd.
In 2003, the 2nd Gulf War reduced Iraqi exports by more than 2 mbd. This was partly offset by increases in Saudi exports.
In 2011 civil war in Libya cut production of 1.7 mbd by 90%; this was largely offset by increases in Saudi exports.

countries as well as OPEC's own demand,[8] continued to challenge world supply. Price increased again in 2011 due to exports lost during the Libyan Civil War, which were partly offset by export increases from Saudi Arabia.

There were significant differences before and after 1986 in OPEC and Saudi behavior. From 1973 to 1985, OPEC set the price and produced the oil export levels that were demanded at that price. Changes in price were relatively small except for the two price shocks (1973–1974 quadrupling and 1979–1980), but changes in exports demanded were large. This price-setting, export-restricting strategy was eventually abandoned by Saudi Arabia at the end of 1985, when they doubled export levels and let crude oil price be determined in the market by “netback pricing” of oil products.

After 1986, by contrast, OPEC selected production quota levels based upon its assessment of market demand; the market-clearing price would be determined by the resulting level of OPEC exports. There were relatively small changes in total OPEC exports, but larger changes for price, especially after 2004 when OPEC reached capacity production. Another important difference after 1986 was that price increases were quickly reversed in a few weeks if the market weakened significantly—unlike the 1979–1980 price doubling that took five years to un-do.

Saudi Arabia's export behavior has varied dramatically since 1973. Sometimes it cooperated with its OPEC partners in reducing (or expanding) its export levels, in the face of changing demand. Other times it has acted independently: *increasing* its exports on five occasions to replace supply interruptions elsewhere in OPEC; or *maintaining* its 1990 surge in exports from 1991 to 1998 while the Rest of OPEC gradually increased their market share; or *reducing* its exports unilaterally in 1981–1985 in (unwise) defense of the 1979–1980 price doubling. The critical determinant of Saudi response to reductions in Rest-of-OPEC exports is the context of those reductions: Saudi exports will be cut when those reductions result from demand declines, but Saudi exports will be increased when those reductions result from interruptions elsewhere in OPEC. The primary goal for Saudi Arabia, especially since 1986, is to maintain stability in OPEC's oil supplies regardless of geopolitical (and, to a lesser extent, oil market) conditions.

A standard measure of cooperation between Saudi Arabia and its OPEC partners is the correlation between the quarterly changes in Saudi exports and in Rest-of-OPEC exports (each measured in mbd) over the previous 8 quarters; this is graphed in Fig. 2. Cooperation between Saudi Arabia and the Rest of OPEC has been quite good in “normal” periods (that is, quarters without interruptions), with a relatively high correlation in the range of 0.6 to 0.8. However, whenever the Saudis have acted to replace supply interruptions elsewhere in OPEC (1978, 1980–81, 1990, 2003, 2011), the correlation became negative. Although the *average* correlation since 1973 equals 0.19, which suggests relatively little cooperation with the Rest of OPEC, this average is misleading.

To understand why the correlation between Saudi Arabia and the Rest of OPEC would be positive in normal periods but negative during interruptions, see Fig. 3. It compares Saudi behavior during three of the largest declines in demand (left graph) and during the four largest interruptions (right graph). In the face of demand declines (following price increases or recessions), the Saudis coordinated output cutbacks with the Rest of OPEC; their behavior was positively correlated because both were reducing output. However, in the face of interruptions elsewhere in OPEC, the Saudis *offset* those reductions; the correlation was negative: the Saudis increased output when output in the Rest of OPEC declined.

Taking account of these differences requires that the Saudi slope responses in the left and right diagrams be measured *separately*, which will make them opposite in sign (positive slope in left diagram, negative slope in right). They should not be analyzed together, because across the two diagrams the average response will tend toward towards zero. When Saudi response is wrongly assumed to be symmetric between Normal periods and Interruptions, it will be incorrectly estimated because the two separate responses have been obscured. If instead, these two types of responses were measured separately, their opposite-signed distinctiveness would not be obscured. Unfortunately, none of the existing literature allows for such distinctions, but we provide it in this paper.

Fig. 4 illustrates the variation between periods of positively and negatively correlated movement in oil exports by Saudi Arabia and the Rest of OPEC. The data are divided into six time periods, alternating between periods of moderately strong correlation (in the left column) and periods of weak or negative correlation (in the right column). All the interruptions appear in the right

[8] The changing structure of world oil demand, by region and product, is analyzed in Dargay and Gately (2010).

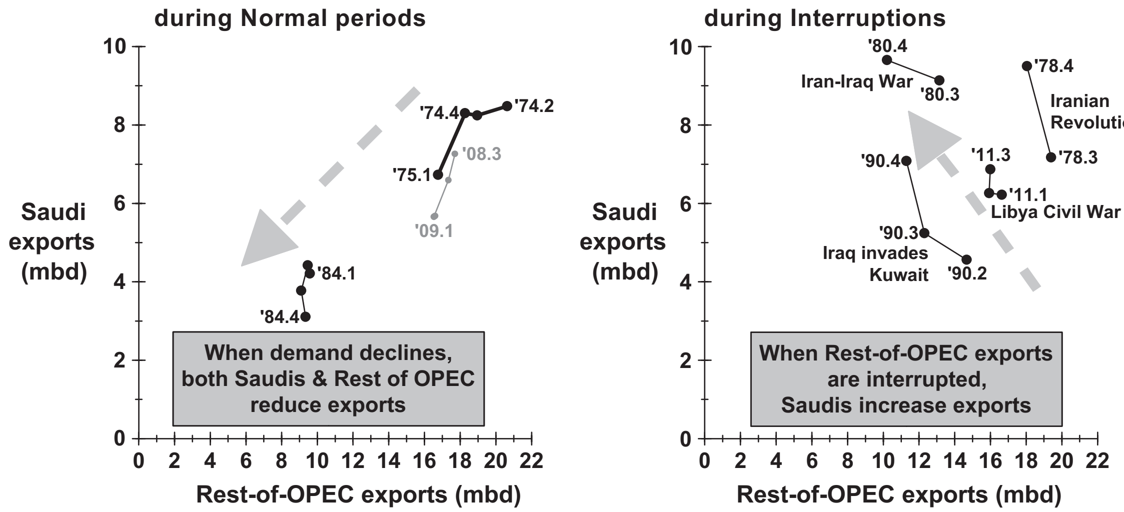

Fig. 3. Export behavior by Saudi Arabia and Rest of OPEC: coordination during Normal periods of demand cutbacks (on left), but during interruptions the Saudis offset cuts in Rest of OPEC (on right).

column (except for the 2003 War in Iraq): the 1978 Iranian Revolution, the 1980–1981 Iraq–Iran War, the 1990 Iraq invasion of Kuwait, and the 2011 civil war in Libya. The two longest periods of weak or negative correlation (upper right and middle right) each started with disruptions, which were followed by an extended period of adjustment. In 1978q3–1985q3 (upper right), Saudi exports increase in 1978q4 to offset interruptions due to the Iranian Revolution, soon followed by full-capacity Saudi exports during the 1980–1981 Iraq–Iran War interruptions. However, soon thereafter would be Saudi export cutbacks (almost unilateral) in 1981–1985, to defend the 1979–1980 price doubling—a strategy that was abandoned in 1985q4. The second long period of Saudi exports being negatively correlated with Rest-of-OPEC exports was 1990q2–1998q2 (middle right). It began with the 1990q3 Iraqi invasion of Kuwait, when the Saudis doubled their exports within two quarters, and then maintained that level of exports for most of the decade, while the Rest of OPEC gradually increased its market share.

The three graphs in the left column of Fig. 4 show extended periods of moderately strong correlation between Saudi and Rest-of-OPEC exports. Each period is ended by an interruption: respectively, the 1978q4 Iranian Revolution, the 1990q3 Iraqi invasion of Kuwait, and the 2011 civil war in Libya. Within each of the three periods, cooperation within OPEC was moderately strong; the correlation between quarterly changes in Saudi and Rest-of-OPEC exports was generally between 0.6 and 0.8. There were so notable exceptions, of course. The middle graph (1985q3–1990.2) includes the 1985–1986 price collapse and temporary shift to netback pricing by the Saudis. It also includes the Saudis' 1988 tit-for-tat strategy[9] to encourage discipline within OPEC with regard to honoring production quota agreements, whereby the Saudis would match quota over-shipments by its OPEC partners but reciprocate when quotas were respected. Between the first and fourth quarter of 1988, Saudi Arabia nearly doubled its exports, greatly exceeding its own quota; its share of OPEC exports jumped from 24% to 31%. Although the price fell by one-third, Saudi export revenue increased, because its exports increased by more than the price declined. For the Rest of OPEC, however, their export revenue fell. Having demonstrated its willingness to expand its market share so as to discipline its OPEC partners,

Saudi Arabia then reduced its exports in 1989q1 by one-third, returning its share of OPEC to 24% and its export revenue back to its level in 1988q1.

Saudi behavior is more complicated than can be captured by a single economic model. Such models were designed to explain firms' economic behavior in particular industries; geopolitical and security concerns are ignored. But Saudi Arabia is the leading producer of the world's most important product, subject to international pressures and security threats to its national sovereignty. Given the dramatic changes in geo-politics and in the market since 1973, it should not be surprising that Saudi behavior cannot be well explained by a single model. As we shall argue, it's *complicated*. Several different models would need to be adopted, depending upon the changing circumstances.

3. Literature review

The literature on OPEC behavior is huge; for general surveys, see Gately (1984) and Cremer and Salehi-Isfahani (1991). Several different models are needed to describe changes in OPEC behavior over time, depending upon market circumstances and interruptions within OPEC (as Adelman,[10] Kaufmann and others suggest). Our list of models and behaviors for Saudi Arabia needs to include:

- cooperative partner within OPEC, restricting (or expanding) exports cooperatively: pre-1978, 1986–1990 (with some tit-for-tat behavior to encourage cooperation and quota discipline), 1998–2010 (subject to capacity constraints in 2008)
- emergency replacement for export interruptions elsewhere in OPEC: 1978, 1980, 1990, 2003, 2011—but, notably, *no response*

[9] Gately (1989) argued that output-sharing cooperation within OPEC could be interpreted as a repeating prisoners' dilemma game, noting the analysis of cooperation by Axelrod(1984) in which a "tit-for-tat" strategy did best in a computer-run, two-player game: cooperate on the first move, and then do whatever the other player did on the previous move. "Practice reciprocity, for both cooperation and defection. … The players can learn that defection invites retaliation, and that cooperation can be reciprocated. Thus the threat of retaliation can restrain the centrifugal forces that encourage defection. The expectation of cooperation reciprocated can provide the centripetal force to keep the players together." (Gately, 1989, pp.113–114). See also Griffin and Neilson (1994).

[10] Adelman (1982, 1995) argues that OPEC behavior varies between dominant firm and market-sharing models, depending on market conditions.

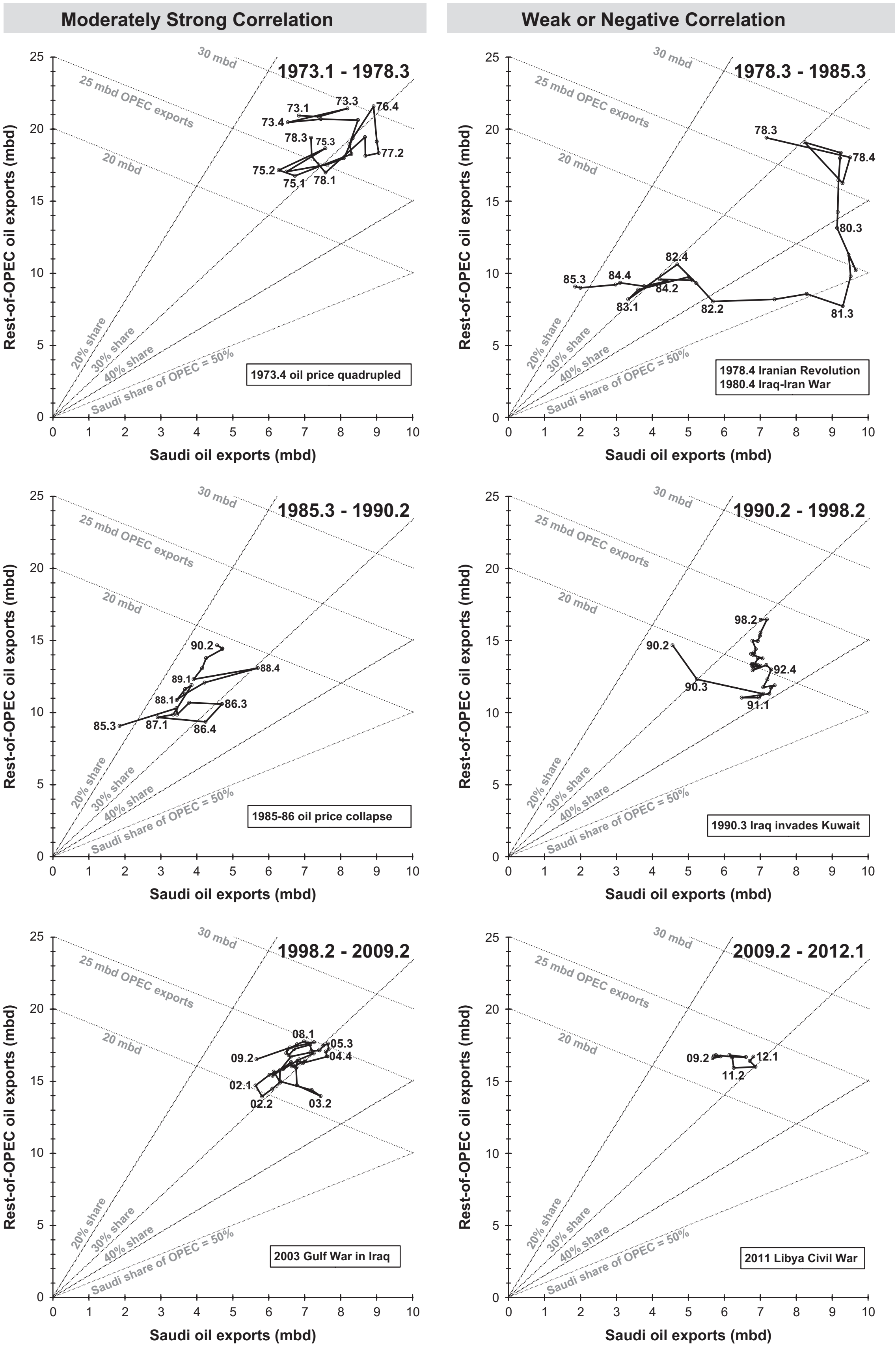

Fig. 4. Saudi and Rest-of-OPEC Oil Exports: alternating periods of moderately strong correlation and weak or negative correlation, 1973q1–2012q1.

when production in the Former Soviet Union fell in four consecutive years 1990–1993 by an average of 1 mbd.[11]

- willingness to act almost unilaterally in cutting its exports 70% from 1981 to 1985 in its unwise defense of the 1979–1980 price doubling, soon followed by abandonment of 1973–1985 price-setting, output restricting role, and shift toward gradual recovery of market share—not so much because they changed strategies but because they finally realized their mistake.[12]
- after doubling its exports in late 1990 after Kuwait was invaded by Iraq (and Saudi Arabia itself was threatened), the Saudis maintained a constant level of exports for nearly a decade, while the Rest of OPEC gradually increased their own exports and market share.

Within this large literature on the behavior of OPEC and its key producers, a seminal paper has been that of Griffin (1985). Many articles that stem from this paper are surveyed critically by Smith (2005), who cautions about drawing strong conclusions from the statistical analyses:[13]

> There is only weak evidence to indicate that Saudi Arabia has acted as a "leader" or dominant firm within the cartel, although that possibility cannot be formally rejected. If the Saudis have performed such a role, then at least one can say that it has not been executed with sufficient vigor or consistency to be clearly discernible in the data. (pp. 74–75)

We believe that this conclusion about Saudi consistency is not just overly cautious, but is actually incorrect. We believe that error is due to ignoring the *context* of Saudi response when analyzing Saudi behavior—whether the Saudis are acting cooperatively within OPEC in the face of reduced demand, or they are acting to offset Interruptions elsewhere in OPEC. Assuming *symmetric* response to different circumstances (as shown in Fig. 3) *can* lead to an incorrect conclusion that the Saudi response is inconsistent, because the Saudi responses to demand cutbacks (positive slope) and to Interruptions (negative slope) are averaged out towards zero. Taking proper account of the Saudis' different behavior between Normal periods and Interruptions allows Saudi consistency to be visible in the data, not obscured.

Smith (2005) provides his own model of producers' "compensating production changes" to evaluate OPEC behavior since 1973. The model is based upon random shocks to OPEC members' *cost* functions. This seems a very strange choice, given that the big changes in production levels were due to interruptions (1978, 1980, 1990, 2003, and 2011) or due to unwisely defending the 1979–1980 price doubling. Yet the paper has no mention of interruptions, nor are they analyzed differently from "normal" changes in production.[14] In fact, assuming symmetric response for Saudi behavior would conflict with what actually happened during interruptions. Although the Saudis normally coordinate output reductions with the Rest of OPEC when demand falls, during interruptions the Saudis *offset* output reductions rather than *match* them. To assume that Saudi response is symmetric would be to ignore context, and it can lead to an erroneous statistical conclusion: that symmetric Saudi behavior is not consistent. Thankfully for the world economy, during interruptions the Saudi response was context-dependent, not symmetric.

The paper by Kaufmann et al. (2008) is similar to ours, except that its data starts only in 1986, it analyses production rather than exports, and it examines the effect of quotas. It allows for different Saudi responses to increases and decreases in Rest-of-OPEC exports but ignores differences between Normal periods and Interruptions—largely because they exclude data from Iraq and Kuwait. We include those countries' data because they have certainly affected the production and export behavior of the Saudis. Like Smith (2005), the statistical results in Kaufmann et al. (2008) are sometimes ambiguous, and sometimes conflict with those of others:

> Saudi Arabia is the only OPEC nation analyzed here that does not display production sharing behavior. As such, this result is consistent with arguments that Saudi Arabia is a dominant firm. Indeed, this finding contradicts claims made by Griffin (1985), who argues that the positive correlation between crude oil production by Saudi Arabia and other OPEC members undermines models that posit Saudi Arabia as a dominant firm. (p. 348)

Our conclusions differ from the existing literature in several respects, especially regarding the relationship between exports from Saudi Arabia and the Rest of OPEC (and similarly for *production*). In the literature there is a wide range of estimates for the correlation, including the following:

- positive correlation: Griffin (1985, p. 958) using 1971–1983 data
- weak evidence of coordination: Dahl and Yucel (1991), using 1971–1987 data
- zero correlation: Kaufmann et al. (2008, p.348) using 1987–2003 data: "we find no relationship"
- negative correlation: Alhajji and Huettner (2000, p. 53) cited 1973–1994 data[15] to support their argument that Saudis are a dominant firm, noting that the correlation was −0.43.

Some of this disagreement follows from different time periods being considered, because the correlation has varied over time, especially when interruptions have occurred. However, even more important has been the context within which the Saudis are responding to changes in exports elsewhere in OPEC—whether the response is during Normal periods or during Interruptions. In addition, we also analyze a second type of asymmetric response of Saudi exports—between increases and decreases in Rest-of-OPEC exports. Most models ignore context completely, and assume fully symmetric response by the Saudis.

[11] Their oil exports fell from 3.92 mbd in 1989 to 1.86 in 1992.

[12] In the view of Gately (1986,1995), what OPEC did wrong in 1981-85 was that it badly misjudged the oil market elasticities and mistakenly chose an aggressive pricing strategy at a time that was very unfavorable to such strategies. Griffin and Neilson (1994) deny that this was an error on OPEC's part, but a predictable consequence. If so, then either OPEC's foresight or their optimal behavior would seem deficient, given what happened to OPEC exports and export revenue by 1985. In the view of AlMoneef (unpublished, footnote 15), "It is not clear why Saudi Arabia continued to play the virtual swing producer role within OPEC on the downside for such a long period (effectively from December 1982 till September 1985). One explanation might be its conviction that the slack oil demand and the high non-OPEC production were temporary and not structural phenomena." As noted above, OPEC exports fell dramatically after the first price shock, from 29.6 mbd in 1973q3 to 23.5 in 1975q1, but recovered quickly, to 30.5 mbd in 1976q4.

[13] Interestingly, Smith seems satisfied that the Texas Railroad Commission acted as a production cartel during the middle of the 20th century, despite lack of evidence from cointegration tests. "Based on cointegration tests, Libecap … was unable to find any evidence that Texas played the role of swing producer under the guise of the Interstate Oil Compact Commission, although the IOCC clearly acted as a well-documented and highly successful production cartel in the U.S. oil market throughout the middle third of the twentieth century." (p. 58)

[14] Our paper uses dummy variables to distinguish five periods of interrupted production in OPEC, unlike most of the literature which did not consider such interruptions as extraordinary events. Dummy variables for interruptions were used only by Hansen and Lindholt (2008) for several interruptions, and by Kaufmann et al. (2008) for 1990q3-4 only.

[15] However they also include a footnote (p.53) that the correlation during 1982-94 was 0.59, although they attribute this positive correlation to growing world demand.

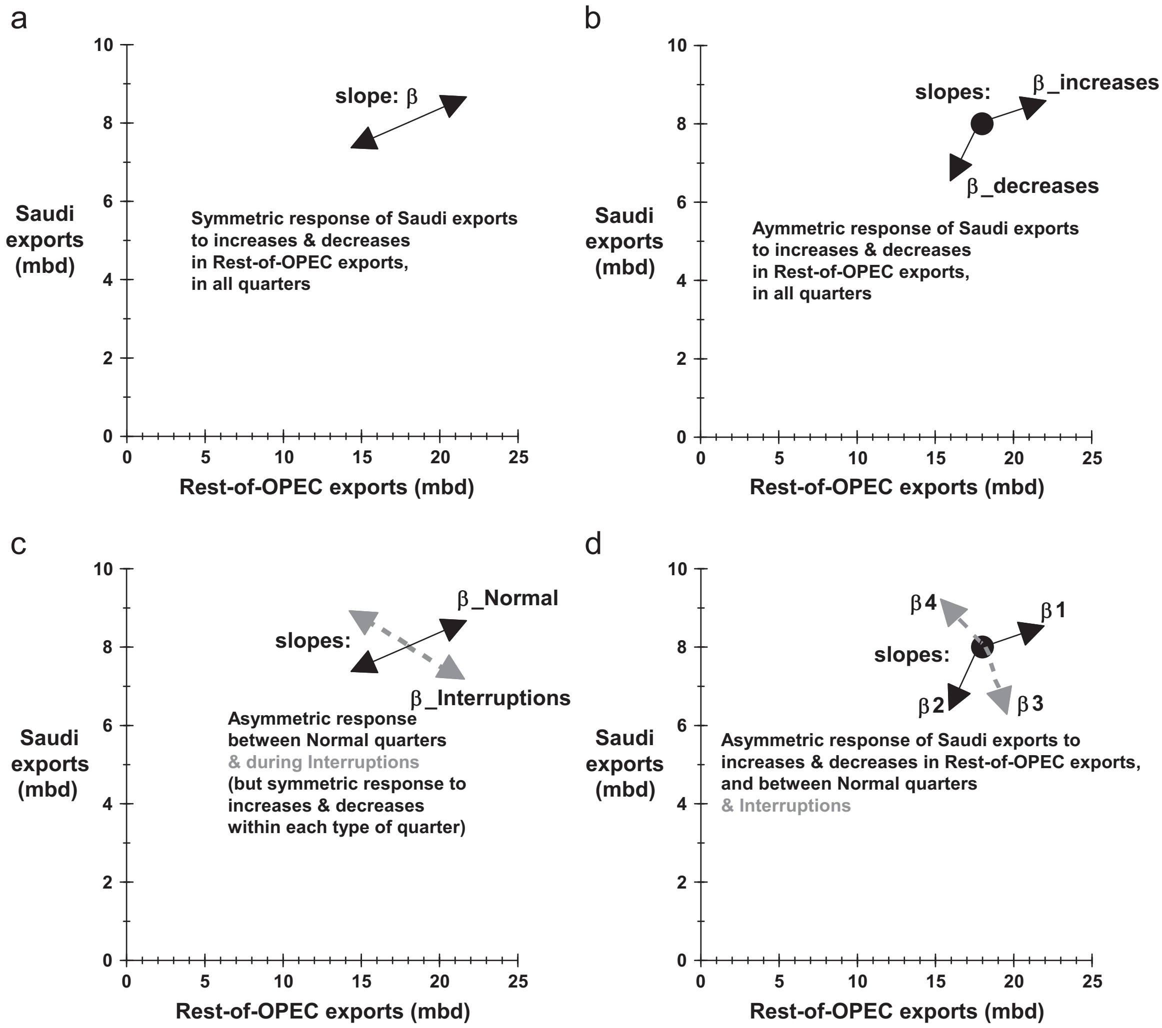

Fig. 5. Different types of Saudi export response to changes in Rest-of-OPEC exports.

The specifications that we examine are summarized in Fig. 5 (with equation numbers from Section 4.3). The standard, symmetric specification by Griffin (1985) is the upper-left graph; it is similar to that of Smith (2005). The type of asymmetry analyzed by Kaufmann et al. (2008) allows different responses for increases and decreases in Rest-of-OPEC exports, *in all quarters* (upper-right graph). A second dimension of asymmetry in Saudi response distinguishes between "normal" quarters and during interruptions—either with symmetric response to increases and decreases in Rest-of-OPEC exports (lower-left graph) or with fully asymmetric response (lower-right graph).

4. Methodology

4.1. Standard model by Griffin (1985)

Many models have been used to study the behavior of OPEC and its members regarding oil production decisions. The seminal paper of Griffin (1985) tested several alternative hypotheses about the behavior of OPEC and its members, using quarterly data for the period 1971–1983. We modify that model so that we focus on OPEC *exports* rather than OPEC production, and we analyze exports not from all OPEC members individually but only from Saudi Arabia and the Rest of OPEC. We ignore OPEC's domestic consumption of oil, which has no direct effect on the Non-OPEC ("world") oil market.[16]

The Non-OPEC ("world") demand for OPEC oil (X) is a derived demand: the difference between Non-OPEC oil demand and Non-OPEC supply, where Non-OPEC oil demand (D) is a function of real price of oil (P) and economic activity (A), and Non-OPEC supply (S) is a function of real price (P):

$$X = D(P, A) - S(P) \tag{1}$$

An individual OPEC country's export level is assumed to be some fraction of total OPEC exports (X); for Saudi Arabia this would be:

$$XS = \alpha^{*} X \tag{2}$$

To avoid the simultaneity between XS and X, Eq. (2) is modified by subtracting Saudi exports from total OPEC exports. This yields "Rest-of-OPEC" exports, $XR = X - XS$.

$$XS = \alpha' XR \tag{3}$$

where $\alpha' = (\alpha^{*})/(1-\alpha^{*})$

[16] The domestic consumption of oil within OPEC does not depend on the world oil price. OPEC members sell oil products domestically at prices below exports prices. For econometric analysis of Saudi and OPEC consumption, see Gately et al. (2012, 2013).

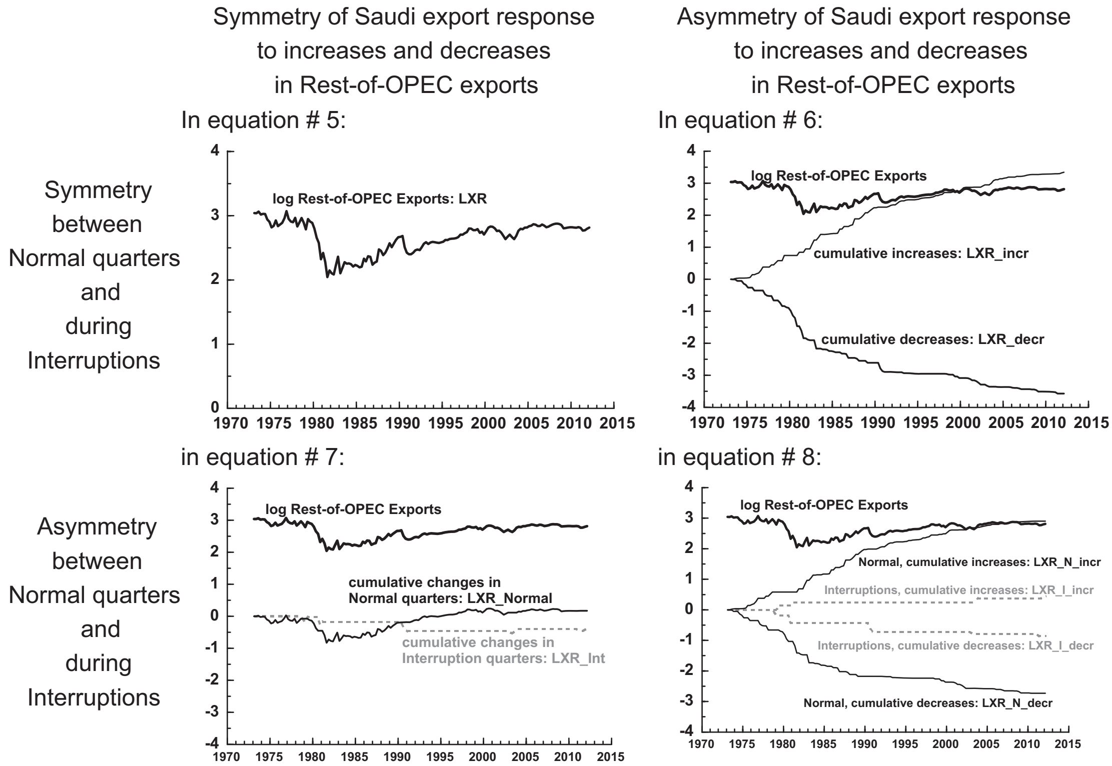

Fig. 6. Decompositions of Log of Rest-of-OPEC Exports, for use in alternative symmetry equations.

Griffin (1985) assumed that the market share coefficient α' is a function of price and utilized the following equation:

$$XS_t = \alpha' XR_t^{\beta} P_t^{\gamma} e^{\varepsilon_t} \tag{4}$$

Taking logarithms of both sides of Eq. (4), we get the equation to be estimated

$$LXS_t = \alpha + \beta LXR_t + \gamma LP_t + \varepsilon_t \tag{5}$$

where *LXS* is log of oil exports from Saudi Arabia, α is log of α', *LXR* is the log of oil exports from the Rest of OPEC, and *LP* is log of real oil prices.[17]

4.2. Alternative specifications with asymmetric response of Saudi exports

The standard specification (5) assumes symmetry in Saudi export response to Rest-of-OPEC exports, both increases and decreases, in both Normal periods and during Interruptions. We also examine three alternative specifications that allow for (but do not require) asymmetric responses. For each of these three alternatives, we utilize different decompositions of the log of Rest-of-OPEC exports, as shown in Fig. 6.

For asymmetry between increases and decreases in Rest-of-OPEC Exports, we utilize the decomposition of log of Rest-of-OPEC exports into its cumulative series of Increases and Decreases:

$$LXS_t = \alpha + \beta_{incr} LXR\_Incr_t + \beta_{decr} LXR\_Decr_t + \gamma LP_t + \varepsilon_t \tag{6}$$

where *LXR_Incr* and *LXR_Decr* represent, respectively, the cumulative increases and decreases in the log of Rest-of-OPEC exports.[18] We do a Wald test of the symmetry hypothesis $\beta_{incr} = \beta_{decr}$ in order to test whether there are different responses to increases and decreases in Rest-of-OPEC exports in all quarters, both Normal quarters and Interruptions.

For asymmetry between Normal quarters and Interruptions, we utilize the decomposition of log of Rest-of-OPEC exports into the cumulative changes during Normal quarters and Interruption quarters:

$$LXS_t = \alpha + \beta_{Normal} LXR\_Normal_t + \beta_{Interruption} LXR\_Int_t + \gamma LP_t + \varepsilon_t \tag{7}$$

where *LXR_Normal* represents the cumulative changes for all normal quarters, both increase and decreases, and *LXR_Int* represents the cumulative changes for all interruption quarters, both increases and decreases. We do a Wald test $\beta_{Normal} = \beta_{Interruption}$ in order to test whether there are different responses between Normal quarters and Interruption quarters.

Finally, in order to test for both types of asymmetry, we utilize the 4-way decomposition of log Rest-of-OPEC exports into cumulative increases and cumulative decreases, in Normal quarters and Interruptions, respectively:

$$LXS_t = \alpha + \beta_1 LXR\_N\_incr_t + \beta_2 LXR\_N\_decr_t + \beta_3 LXR\_I\_incr_t + \beta_4 LXR\_I\_decr_t + \gamma LP_t + \varepsilon_t \tag{8}$$

In this specification, we test whether there are different responses to cutbacks in Rest-of-OEPC exports between Normal quarters and Interruptions $\beta_2 = \beta_4$), as well as other types of asymmetric response.

[17] It would also be interesting to analyze the behavior of other large exporters, or even groups of OPEC members within the Gulf Cooperation Council (including Kuwait, Qatar, and UAE as well as Saudi Arabia), but we have not done that in this paper.

[18] That is, for each quarter t, $LXR\_Incr_t \equiv LXR\_Incr_{t-1} + \max(0, LXR_t - LXR_{t-1})$, where $LXR\_Incr_{t=0} = 0$;and $LXR\_Decr_t \equiv LXR\_Decr_{t-1} + \min(0, LXR_t - LXR_{t-1})$, where $LXR\_Decr_{t=0} = 0$.

4.3. Econometrics methodology

The autoregressive distributed lag (ARDL) approach to cointegration, proposed by Pesaran and Shin (1999) and Pesaran et al. (2001), has been used in this study. This approach has several advantages:

- It can be applied irrespective of whether the variables are I(0) or I(1), or a mixture of the two.[19]
- It captures both short-run and long-run dynamics when testing for the existence of cointegration.
- It offers explicit tests for the existence of a unique cointegration vector, rather than assuming that it exists.
- It is preferable in small samples.

There is a question about whether the ARDL method, described in detail below, is appropriate when price is endogenous.[20] To address this question of whether the ARDL method provides consistent results in the presence of potential simultaneity bias, we have also employed the DOLS method,[21] for Eqs. (5)–(8). Results are shown in Appendix D and discussed briefly at the end of Section 5.2.

The ARDL specifications of Eqs. (5)–(8) are given as follows:

$$\Delta LXS_t = \alpha_{10} + \sum_{i=1}^{p} \delta_{1i}\Delta LXS_{t-i} + \sum_{i=0}^{p} \gamma_{1i}\Delta LXR_{t-i} + \sum_{i=0}^{p} \lambda_{1i}\Delta LP_{t-i} + \beta_{10}LXS_{t-1} + \beta_{11}LXR_{t-1} + \beta_{12}LP_{t-1} + \varepsilon_{1t} \quad (9a)$$

$$\Delta LXS_t = \alpha_{20} + \sum_{i=1}^{p} \delta_{2i}\Delta LXS_{t-i} + \sum_{i=0}^{p} \gamma_{2i}\Delta LXR_{Incr\,t-i} + \sum_{i=0}^{p} \varphi_{1i}\Delta LXR_{Decr\ t-i} + \sum_{i=0}^{p} \lambda_{1i}\Delta LP_{t-i} + \beta_{20}LXS_{t-1} + \beta_{21}LXR_{Incr\ t-1} + \beta_{22}LXR_{Decr\ t-1} + \beta_{23}LP_{t-1} + \varepsilon_{2t} \quad (9b)$$

$$\Delta LXS_t = \alpha_{30} + \sum_{i=1}^{p} \delta_{3i}\Delta LXS_{t-i} + \sum_{i=1}^{p} \gamma_{3i}\Delta LXR_{Norm\ t-i} + \sum_{i=1}^{p} \varphi_{3i}\Delta LXR_{Int\ t-i} + \sum_{i=1}^{p} \lambda_{3i}\Delta LP_{t-i} + \beta_{30}LXS_{t-1} + \beta_{31}LXR_{Norm\ t-1} + \beta_{32}LXR_{Int\ t-1} + \beta_{33}LP_{t-1} + \varepsilon_{3t} \quad (9c)$$

$$\Delta LXS_t = \alpha_{40} + \sum_{i=1}^{p} \delta_{4i}\Delta LXS_{t-i} + \sum_{i=0}^{p} \gamma_{4i}\Delta LXR_{NI\ t-i} + \sum_{i=o}^{p} \varphi_{4i}\Delta LXR_{ND\ t-i} + \sum_{i=0}^{p} \theta_{4i}\Delta LXR_{II\ t-1} + \sum_{i=0}^{p} \lambda_{4i}\Delta LP_{t-i} + \beta_{40}LXS_{t-1} + \beta_{41}LXR_{NI\ t-1} + \beta_{42}LXR_{ND\ t-1} + \beta_{43}LXR_{II\ t-1} + \beta_{44}LXR_{ID\ t-1} + \beta_{45}LP_{t-1} + \varepsilon_{4t} \quad (9d)$$

The first step in the ARDL approach is to estimate these equations by ordinary least square (OLS) in order to test for the existence of a long-run relationship among the variables, and then conducting an F-test for joint significance of the lagged-level variables.

The null hypothesis of no cointegration in Eq. (9a) is H_0: $\beta_{10}=\beta_{11}=\beta_{12}=0$, against the alternative that H_1:$\beta_{10}\neq\beta_{11}\neq\beta_{12}\neq 0$. For Eq. (9b), H_0: $\beta_{20}=\beta_{21}=\beta_{22}=\beta_{23}=0$ against the alternative that H_1:$\beta_{20}\neq\beta_{21}\neq\beta_{22}\neq\beta_{23}\neq 0$. Similarly for Eqs. (9c) and (9d).

The cointegration bounds test provides two asymptotic critical values:

- a lower critical value assuming that the explanatory variables are stationary in levels: $I(0)$
- an upper critical value assuming that explanatory variables are non-stationary in levels but are stationary in first differences: $I(1)$.

If the F-statistic lies below the lower bound, this implies that there is no cointegration. If the F-statistic is above the upper bound, this implies that there is cointegration. If the F-statistic falls between the upper bound and lower bound, then the test would be inconclusive.

Several diagnostic and stability tests are used to check the goodness of fit of the ARDL bounds testing approach. The Breusch–Godfrey Lagrange Multiplier (LM) test examines the serial correlation of the residuals, Ramsey's RESET tests the functional form by using the square of the fitted values, the Jarque–Bera test analyzes the normality of residuals based on a test of skewness and kurtosis, and a heteroskedasticity test based on the regression of squared residuals on squared fitted values in the model. In addition, the cumulative sum of recursive residuals (CUSUM) and cumulative sum of squares of recursive residuals (CUSUMSQ) are applied to check the stability of the ARDL parameters.

If the variables are found to be cointegrated in the first stage, then in the second stage the ARDL method can be used to estimate the dynamic structure. The method of Bårdsen (1989) has been applied to find long-run coefficients for Saudi oil exports by assuming that, in the long run, all the change variables in Eqs. (9a)–(9d), respectively, are zero. These long-run equations corresponding to Eqs. (9a)–(9d), respectively, are as follows:

Complete symmetry: for increases and decreases in LXR, in Normal quarters and Interruptions:

$$LXS_t = \alpha + \beta LXR_t + \gamma LP_t \quad (10a)$$

Asymmetry for increases and decreases in LXR, but symmetry between Normal quarters and Interruptions:

$$LXS_t = \alpha + \beta_{Incr}LXR\_Incr_t + \beta_{Decr}LXR\_Decr_t + \gamma LP_t \quad (10b)$$

Symmetry for increases and decreases in LXR, asymmetry between Normal quarters and Interruptions:

$$LXS_t = \alpha + \beta_{Normal}LXR\_Normal_t + \beta_{Interruption}LXR\_Int_t + \gamma LP_t \quad (10c)$$

Complete asymmetry: for increases and decreases in LXR, in both Normal quarters and Interruptions:

$$LXS_t = \alpha + \beta_1 LXR_{N_{incr}t} + \beta_2 LXR_{N_{decr}t} + \beta_3 LXR_{I_{incr}t} + \beta_4 LXR\_I\_decr_t + \gamma LP_t \quad (10d)$$

5. Empirical results

Following standard practice in time series econometrics, the estimation process starts by testing the variables for unit roots; these results are shown in Appendix B. From these tests we conclude that all variables are not stationary at same levels; some are stationary at level and others are stationary at first differences. Hence, the presence of a stable, long-run relationship among the variables can be detected by applying the autoregressive distributed lag (ARDL) approach to cointegration proposed by Pesaran et al. (2001).

[19] However, pre-testing for the order of integration of the variables in the model is required because the procedure is not valid for I(2) series.

[20] Pesaran and Shin (1999, p. 374) have argued that "The Monte Carlo results point strongly in favor of the two-step estimation procedure, and this strategy seems to work even when the model under consideration has endogenous regressors, irrespective of whether the regressors are I(1) or I(0)". In addition, the ARDL method has been adopted in many applied papers with endogenous variables; for examples, see Feeny (2005), O'Mahony and Vecchi (2005), and Ozturk and Acaravci (2010).

[21] Developed by Stock and Watson (1993), the DOLS method can cope with the simultaneity problem as well as with stochastic trend in time series data. It has been used by Masih and Masih (1996), Narayan and Narayan (2004, 2005), and Kaufmann et al. (2008). In this method, one of the I(1) variables is regressed on other I(1) variables, the I(0) variables and lags and leads of the first difference of the I(1) variables. The presence of first difference variables and the associated lags and leads in the model obviate simultaneity bias and small sample bias among the regressors (Narayan and Narayan, 2005).

Table 1
F-statistics for cointegration.

Eq.	Assumed response of Saudi exports with respect to: Increases and decreases in Rest-of-OPEC exports	Normal quarters and Interruption quarters	Entire period: 1973q1–2012q1	Pre-1986: 1973q1–1985q3	Post-1986: 1985q4–2012q1
9a	Symmetry	Symmetry	6.5	2.87*	7.78
9b	Asymmetry	Symmetry	7.12	6.22	3.71
9c	Symmetry	Asymmetry	4.18	2.85*	16.19
9d	Asymmetry	Asymmetry	10.25	4.09	10.39

* indicates that we cannot reject the null hypothesis of no cointegration; this occurs for only two of 12 cases, the pre-1986 Eqs. 9a and 9c. In all other cases we can reject the null hypothesis of no cointegration. The calculated values of the *F*-statistics were compared with the critical values found in Pesaran et al. (2001, p. 300) and in Narayan (2005, p. 1987–1990).

5.1. Cointegration analysis

The cointegration analysis involves two stages. First, the cointegration relationship among the variables under consideration is tested by computing *F*-statistics. Second, we estimate the long-run and short-run parameters.

In the first step of the ARDL analysis, we adopt a general-to-specific modeling approach. The number of lags of difference variables is selected on the basis of Schwarz Bayesian Information Criterion (SB). We delete statistically insignificant variables from the model when justified by SB moving in the right direction.

Table 1 reports the *F*-statistics for Eqs. (9a)–(9d) respectively – for the entire period, as well as for the pre-1986 and post-1986 periods – to test the joint null hypothesis that the coefficients of lagged level variables are zero. In ten of the twelve cases we can reject the hypothesis of no cointegration. Only for two cases, pre-1986 Eqs. (9a) and (9c), we cannot reject the null hypothesis of no cointegration.

The final model was selected when the estimated equations satisfied several diagnostic tests, including a test for heteroskedasticity, the Breusch–Godfrey Lagrange multiplier test for serial correlation, the Jarque–Bera test for normality of the residuals, and the Ramsey RESET test for functional form. Also the CUSUM and CUSUMSQ statistics indicate no evidence of structural instability for the two sub-sample periods. These test results are summarized in Table B2 in Appendix B.

5.2. Estimated long-run coefficients in Saudi exports equation

Once the long-run relationship has been established, long-run coefficient estimates are obtained by normalizing the coefficients of dependent variables in each equation.[22] The estimated long-run coefficients for the Saudi oil exports are reported in Table 2, for each of the 4 specifications reflecting symmetry or asymmetry, for the entire period as well as for pre-1986 and post-1986 periods. Analogous results for oil *production* (rather than exports) are reported in Appendix C; they are qualitatively the same as all results described in this section, with one minor difference noted below.

Our preferred specification is Eq. (10d). It allows for 4-way asymmetry in the effect on Saudi exports—between increases and decreases in Rest-of-OPEC exports, in both Normal quarters and interruptions. In that specification, all four β coefficients have the expected sign: positive for Normal quarters (Saudis and Rest of OPEC increase together and decrease together), and negative for Interruptions (Saudis offset interruption cutbacks and subsequent recoveries). Three of these four coefficients (all but β_3, for recoveries from Interruptions) are significant for the entire period and for post-1986; for the pre-1986 period, only β_2 (cutbacks in Normal quarters) is significant. Price is significant only for the pre-1986 period.

The Wald test of $\beta_2=\beta_4$ allows us to reject the hypothesis that the effect on Saudi exports is the same for cutbacks in Rest-of-OPEC exports between Normal quarters and interruptions. This is not surprising, given the opposite signs for the two coefficients, both of which are significant. It confirms what we expected, given the different slopes indicated in Fig. 3. The analogous Wald test of $\beta_1=\beta_3$, for *increases* in Rest-of-OPEC exports between Normal quarters and interruptions, allows rejection for only for the post-1986 period. This is not surprising given the small number of observations for increases (recoveries) of Rest-of-OPEC exports during Interruption periods.

The equation statistics for this specification are also superior; it has the highest Adjusted R^2. As indicated in Table 1, we observe cointegration for this specification for all three periods.

The asymmetry specifications and conclusions, summarized in Fig. 7, show that both types of asymmetry must be allowed simultaneously for the interesting results to emerge. For the specification with asymmetry only between increases and decreases in Rest-of-OPEC exports (but not between Normal and Interruption quarters) – Eq. (10b) – the Wald test does not allow rejection of the symmetry hypothesis for any of the three periods. However, when both types of asymmetry are allowed, in Eq. (10d), symmetry between increases and decreases in Normal quarters ($\beta_1=\beta_2$) can be rejected, for all three periods.[23] The analogous results for production (Appendix C) are similar to these for exports, except for the post-1986 period when the results are reversed; this is the only difference for all results reported in this section of the paper.

Similarly, for the specification with asymmetry only between Normal quarters and Interruptions, Eq. (10c), the Wald test does not allow rejection of the symmetry hypothesis for the entire period or for the pre-1986 period; only for post-1986 can the hypothesis be rejected. However, when both types of asymmetry are allowed, symmetry for Rest-of-OPEC decreases between Normal and Interruption quarters ($\beta_2=\beta_4$) can be rejected for all three periods, as noted above.

Also of interest with our preferred specification (10d) is that in Normal quarters Saudi exports are 50% more responsive to decreases than to increases in Rest-of-OPEC exports (coefficients 1.51 and 0.92, respectively, for entire period)—indicating that Saudi exports bear a disproportionate share of the burden of output restriction. Finally, the price coefficient has the expected positive sign but it is significant only for the pre-1986 period.

Results from the DOLS method are shown in Appendix D. The signs and significance of DOLS coefficients (Table D1) are almost identical to those estimated with ARDL in Table 2, although the size of the DOLS coefficients are smaller. The DOLS asymmetry results (Table D2) are also similar, and even stronger. Allowing for both types of asymmetry (Eq. 8) is again the preferred specification, with even stronger asymmetry results: all of the

[22] We used the method of Bårdsen (1989), which is a procedure built into the software program Microfit 5.

[23] However, symmetry during Interruption quarters between increases and decreases ($\beta_3=\beta_4$) cannot be rejected for any of the periods. This is probably due to the small number of observations with increases (recoveries) during Interruption quarters.

Table 2
Estimated long-run coefficients in the cointegrating equation for Saudi oil exports (ARDL).

Equation:	**Entire period:1973q1–2012q1**				**Pre-1986:1973q1–1985q3**				**Post-1986:1985q4–2012q1**			
	10a	**10b**	**10c**	**10d**	**10a**	**10b**	**10c**	**10d**	**10a**	**10b**	**10c**	**10d**
Coefficients (probability-values): statistically significant at 5% level if probability-value < 0.05												
Rest-of-OPEC exports: β	0.81 (< .001)				2.75 (.028)				0.58 (< .001)			
Increases: β_increases		1.30 (< .001)				1.28 (0.479)				−0.58 (0.143)		
Decreases: β_decreases		1.29 (< .001)				1.72 (0.195)				−0.89 (0.035)		
All Normal quarters, both increases and decreases: β_Normal			1.40 (0.001)				4.73 (0.071)				0.09 (0.472)	
Normal quarters, increases: β_1				0.92 (< .001)				1.99 (0.175)				0.28 (0.028)
Normal quarters, decreases: β_2				1.51 (< .001)				2.95 (0.043)				0.64 (0.010)
All Interruption quarters, both increases and decreases: β_Interruptions			1.39 (0.032)				−4.91 (0.345)				−1.77 (< .001)	
Interruption quarters, increases: β_3				−0.30 (0.805)				−2.58 (0.457)				−0.66 (0.127)
Interruption quarters, decreases: β_4				−1.28 (0.020)				−3.78 (0.155)				−1.38 (< .001)
Price (γ)	−0.08 (0.446)	0.04 (0.796)	0.08 (0.622)	0.1(0.200)4	1.77 (0.050)	0.73 (< .001)	0.76 (< .001)	0.76 (< .001)	0.08 (0.448)	0.08 (0.551)	0.08 (0.025)	0.06 (0.288)
Constant		2.06 (< .001)	2.04 (0.003)	1.81 (< .001)	−12.2 (0.062)					0.82 (< .001)	0.82 (< .001)	1.75 (< .001)
Equation statistics[a]												
Adjusted R^2	0.85	0.86	0.87	0.88	0.91	0.9	0.91	0.91	0.83	0.85	0.9	0.92
Hypothesis tests for symmetry. Wald statistic: $\chi^2(1)$ (probability-value)												
Null hypothesis of symmetry can be rejected using 5% level if Probability-value < 0.05												
β_increases = β_decreases: symmetry for increases and decreases		0.018 (0.894)				0.56(0.454)				0.77(0.380)		
β_Normal = β_Interruptions: symmetry for Normal and Interruption quarters			0.001 (0.993)				1.65(0.199)				126. (< .001)	
$\beta_2 = \beta_4$: symmetry for decreases in Normal and Interruption quarters				21.6 (< .001)				3.4(0.065)				58.4 (< .001)
$\beta_1 = \beta_3$: symmetry for increases in Normal and Interruption quarters				1.12 (0.290)				1.40(0.237)				5.07 (0.024)
$\beta_1 = \beta_2$: symmetry in Normal quarters for increases and decreases				9.81 (0.002)				4.03(0.045)				6.04 (0.014)
$\beta_3 = \beta_4$: symmetry in Interruption quarters for increases and decreases				0.78 (0.375)				0.29(0.592)				2.42 (0.120)

[a] For all equations, F-statistic probability-value < 0.001.

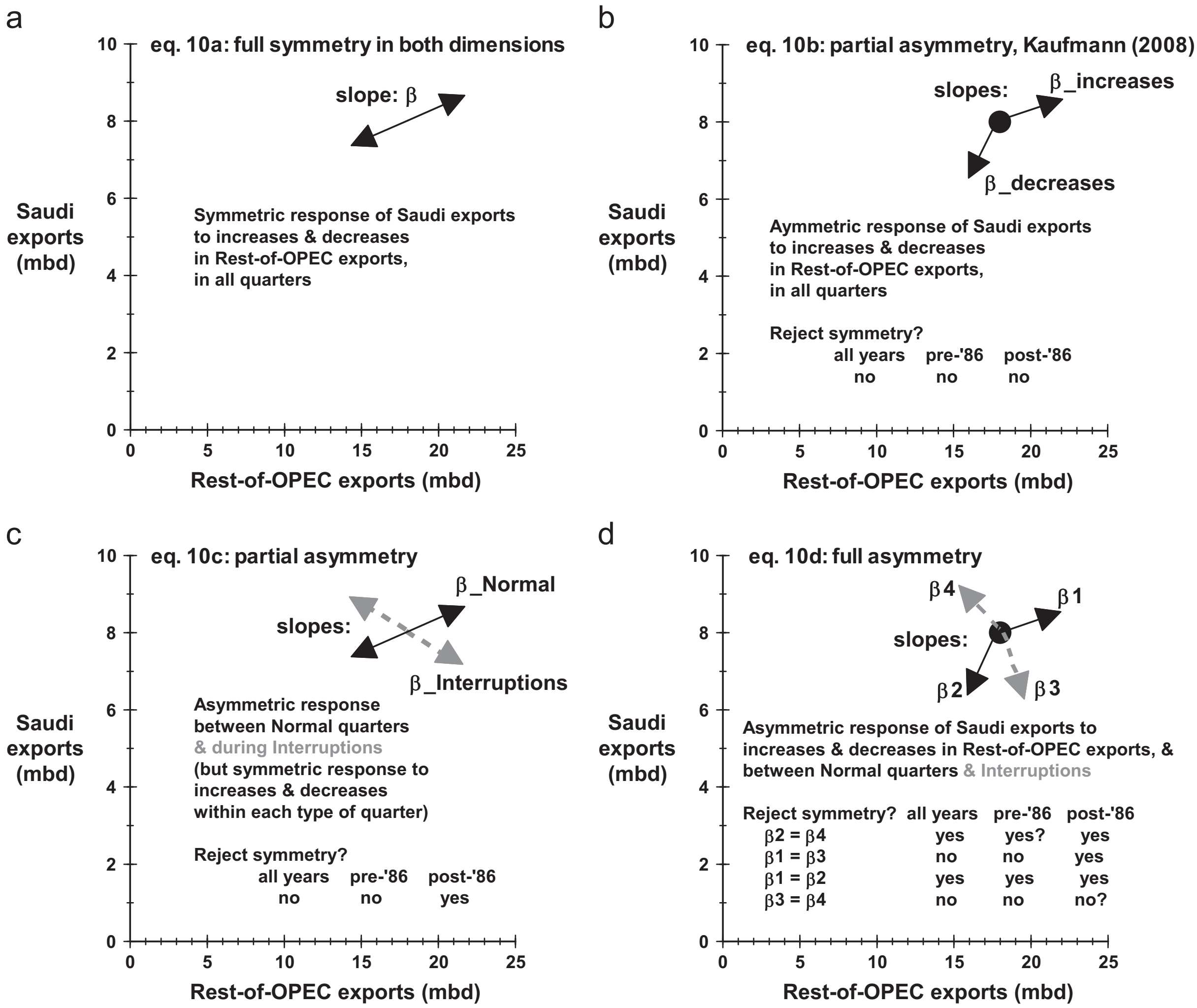

Fig. 7. Different types of Saudi export response to changes in Rest-of-OPEC exports, with Wald test results for alternative hypotheses about symmetry (ARDL).

four symmetries (except for $\beta_1=\beta_3$) can be rejected for the entire period and for both pre-1986 and post-1986.[24]

6. Conclusions

Our work builds upon Griffin (1985) and subsequent literature to analyze quarterly oil export and production behavior by Saudi Arabia and the Rest of OPEC for the period 1973q1–2012q1.

Saudi Arabia's output behavior has varied over time in a systematic way, in response to market conditions and also to interruptions within OPEC. Its behavior differed between “normal” periods and periods with interruptions. In normal periods, when faced with reduced demand, Saudi Arabia cooperated with its OPEC partners to restrict output. During interruptions, however, it would *increase* its output to offset reductions in the Rest of OPEC, *not* to match the reductions. By contrast, a single model assuming the same response by the Saudis to output reductions by the Rest of OPEC – regardless of whether those reductions were due to demand cutbacks or to supply interruptions – does not characterize history accurately. What has been consistent since 1973 has been the Saudi response to offsetting interruptions, from the 1978 Iranian Revolution to the 2011 civil war in Libya, and moderately consistent coordinated cutbacks with the Rest of OPEC when demand fell, from the 1974–1975 recession to the 2008–2009 recession.

Sometimes, as in the mid-to-late 1980's, the Saudis were especially responsive to over-shipments of quotas by its OPEC partners, and it followed a “tit-for-tat” strategy in order to encourage its partners to honor their quotas: matching over-shipments but reciprocating when quotas were honored. In addition, there were two notable examples when the Saudis acted independently from its partners for an extended period of time: (1) in 1981–1985 it cut its exports, almost unilaterally, in an unwise defense of the 1979–1980 price doubling; and (2) in the 1990’s it kept constant its exports while the Rest of OPEC increased their exports and recovered their market share.

The correlation between changes in exports by Saudi Arabia and by the Rest of OPEC reflects this variation in behavior. The *average* correlation over 1973–2012 was relatively small, at 0.19. However, this average value over 40 years masks wide variation over time. During “normal” (non-interruption) periods the correlation was about 0.7, but during and after each of five interruptions the correlation became negative. The correlation was also low during the 1985–1986 shift to netback pricing, as well as in the mid-1990s,

[24] Wald tests also allow us to reject each of the simpler symmetry hypotheses regarding Saudi response – between Normal and Interruption quarters (Eq. 7), and between increases and decreases in Rest-of-OPEC exports (Eq. 6) – for both the pre-1986 period and post-1986 period, although not for the entire period. These are also stronger asymmetry results than in Table 2 with ARDL.

when the Saudis maintained their post-1990 export surge (after the Iraqi invasion of Kuwait) while the Rest of OPEC gradually recovered.

Our preferred specification allows for the possibility of asymmetric Saudi export response, between both Normal periods and Interruptions, and between increases and decreases in Rest-of-OPEC exports. The resulting econometric results are superior to more restrictive assumptions about symmetry. We can reject the hypothesis that Saudi exports respond the same way whether in Normal periods or during Interruptions, or whether to Rest-of-OPEC export increases or decreases. The Saudis coordinate export cutbacks with the Rest of OPEC during Normal periods but they offset declines during Interruptions. In addition, during Normal periods there is much greater Saudi export response to Rest-of-OPEC export declines than to export increases. Within this complexity, we find consistency of action by Saudi Arabia, toward its primary goal: to maintain stability in OPEC's oil supplies regardless of geopolitical (and, to a lesser extent, oil market) conditions.

Saudi behavior *has* been remarkably consistent over time. But this is evident in the data only when taking account of the differences between Normal periods and during Interruptions. Otherwise, this consistency will be obscured.

Acknowledgements

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Appendix A. Data

For data purposes, we use OPEC's current membership to define OPEC back to 1973: Algeria, Angola, Ecuador, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates, and Venezuela. This simplification ignores several changes over time: Angola joined only in 2007, Ecuador suspended its membership during 1992–2007, Gabon left OPEC in 2004 and Indonesia left in 2009.

We used quarterly data from 1973Q1 to 2012Q1 for crude oil production data for Saudi Arabia and other OPEC members from U. S. Energy Information Administration, July 2012 *Monthly Energy Review*. Nominal crude oil price per barrel (US Refiners' Acquisition Cost of Imported Oil) was converted to 2005 $ using US Gross Domestic Product: Implicit Price Deflator.

Table B1
Unit-root tests of individual variables, using HEGY and ADF tests.

	HEGY unit root test			ADF unit root test			
				Without seasonal dummies		With seasonal dummies	
	$\pi_1=0$	$\pi_2=0$	$\pi_3=\pi_4=0$	Level	Difference	Level	Difference
Log price	−1.09	−5.89[c]	30.89[c]	−2.17	−9.32[c]	−2.17	−9.06[c]
Log Saudi exports	−2.54	−2.83[b]	17.58[c]	−2.52	−10.97[c]	−2.41	−12.09[c]
Log Rest-of-OPEC exports	−1.53	−5.63[c]	29.35[c]	−2.26	−13.07[c]	−2.24	−12.93[c]
Log Rest-of-OPEC exports, decomposed:							
Normal quarters	−0.92	−8.48[c]	59.09[c]	−2.19	−12.81[c]	−2.17	−12.66[c]
Interruption quarters	−1.61	−6.79[c]	15.68[c]	−1.64	−13.43[c]	−1.63	−13.30[c]
Increases	−3.75[b]	−6.29[c]	28.27[c]	−2.88[b]		−2.88[b]	
Decreases	−3.14[b]	−8.47[c]	81.16[c]	−4.07 [c]		−4.10 [c]	
Normal quarters, increases	−3.15[b]	−6.06[c]	22.45[c]	−2.81b	−10.76[c]	−2.84[a]	−10.55[c]
Normal quarters, decreases	−2.89	−4.09[c]	35.63[c]	−4.05[c]		−4.09[c]	
Interruption quarters, increases	−2.68	−6.65[c]	25.73[c]	−1.28	−11.40[c]	−1.27	−11.27[c]
Interruption quarters, decreases	−1.07	−7.20[c]	69.07[c]	−1.58	−10.28[c]	−1.57	−10.14[c]

[a] Reject the null hypothesis at 10% level of significance.
[b] Reject the null hypothesis at 5% level of significance.
[c] Reject the null hypothesis at 1% level of significance.

Table B2
Diagnostic test results (probability-values in parentheses).

Eq.	Diagnostic test	Entire period: 1973q1–2012q1	Pre-1986: 1973q1–1985q3	Post-1986 1985q4–2012q1
9a	$\chi^2_{SC}(4)$: Lagrange multiplier	11.78 (0.02)	7.07 (0.13)	10.91(0.03)
	$\chi^2_{FF}(1)$: Ramsey RESET	5.33 (0.02)	2.90 (0.09)	0.46 (0.98)
	$\chi^2_{N}(2)$: Jarque–Bera	1.61 (0.32)	3.18 (0.20)	2.98 (0.23)
	$\chi^2_{H}(1)$: Heteroskedasticity	2.23 (0.14)	1.14 (0.29)	1.67 (0.24)
9b	$\chi^2_{SC}(4)$: Lagrange multiplier	9.52 (0.07)	5.52 (0.24)	6.15 (0.19)
	$\chi^2_{FF}(1)$: Ramsey RESET	0.23 (0.64)	0.03 (0.86)	0.03 (0.86)
	$\chi^2_{N}(2)$: Jarque–Bera	2.29 (0.32)	2.61 (0.27)	1.55 (0.46)
	$\chi^2_{H}(1)$: Heteroskedasticity	0.46 (0.51)	0.17 (0.68)	0.01 (0.90)
9c	$\chi^2_{SC}(4)$: Lagrange multiplier	9.86 (0.04)	4.43 (0.35)	3.60 (0.46)
	$\chi^2_{FF}(1)$: Ramsey RESET	1.70 (0.19)	0.002 (0.90)	0.98 (0.32)
	$\chi^2_{N}(2)$: Jarque–Bera	1.53 (0.43)	1.78 (0.41)	1.69 (0.42)
	$\chi^2_{H}(1)$: Heteroskedasticity	2.92 (0.26)	0.06 (0.80)	1.96 (0.48)
9d	$\chi^2_{SC}(4)$: Lagrange multiplier	10.28 (0.04)	5.34 (0.25)	4.17 (0.38)
	$\chi^2_{FF}(1)$: Ramsey RESET	0.06 (0.80)	0.04 (0.84)	1.06 (0.30)
	$\chi^2_{N}(2)$: Jarque–Bera	2.61 (0.28)	3.19 (0.20)	3.23 (0.21)
	$\chi^2_{H}(1)$: Heteroskedasticity	2.04 (0.13)	0.44 (0.76)	1.79 (0.49)

Table C1
F-statistics for cointegration for Saudi oil production.

Eq.	Assumed response of Saudi production with respect to: Increases and decreases in Rest-of-OPEC production	Normal quarters and Interruption quarters	Entire period: 1973q1–2012q1	Pre-1986: 1973q1–1985q3	Post-1986: 1985q4–2012q1
9a	Symmetry	Symmetry	4.38	3.37*	7.05
9b	Asymmetry	Symmetry	5.60	5.00	3.75
9c	Symmetry	Asymmetry	4.78	2.94*	15.04
9d	Asymmetry	Asymmetry	7.28	4.76	17.76

* indicates that we cannot reject the null hypothesis of no cointegration; this occurs for only two of 12 cases, the pre-1986 Eqs. 9a and 9c. In all other cases we can reject the null hypothesis of no cointegration.

Table C2
Estimated long-run coefficients in the cointegrating equation for Saudi oil production.

Eq.	1973q1–2012q1				1973q1–1985q3				1985q4–2012q1			
	10a	**10b**	**10c**	**10d**	**10a**	**10b**	**10c**	**10d**	**10a**	**10b**	**10c**	**10d**
Coefficients (probability-values): statistically significant at 5% level if probability-value <0.05												
Rest-of-OPEC production: β	1.14 (<.001)				2.93 (0.041)				0.56 (<.001)			
Increases: β_increases		1.30 (<.001)				1.17 (0.400)				−0.110.0572)		
Decreases: β_decreases		1.29 (<.001)				1.62 (0.120)				−0.86 (0.001)		
All Normal quarters, both increases and decreases: β_Normal			1.38 (0.001)				4.52 (0.047)				0.29 (0.005)	
Normal quarters, increases: β_1				0.93 (<.001)				1.87 (0.120)				0.26 (0.009)
Normal quarters, decreases: β_2				1.54 (<.001)				2.82 (0.023)				0.43 (0.052)
All Interruption quarters, both increases and decreases: β_Interruptions			1.40 (0.064)				−3.98 (0.368				−1.86 (<.001)	
Interruption quarters, increases: β_3				−0.43 (0.716)				−2.79 (0.347)				−0.39 (0.252)
Interruption quarters, decreases: β_4				−1.42 (0.013)				−3.67 (0.117)				−1.68 (<.001)
Price (γ)	0.07 (0.516)	0.05 (0.656)	0.09 (0.536)	0.16 (0.09)	1.24 (0.079)	0.71 (<.001)	0.73 (<.001)	0.74 (<.001)	0.14 (0.226)	0.02 (0.838)	0.15 (<.001)	0.04 (0.284)
Constant	−1.50 (0.051)	2.04 (<.001)	2.01 (0.001)	1.78 (<.001)	−11.0 (0.087)						0.90 (<.001)	1.37 (<.001)
Equation statistics[a]												
Adjusted R^2	0.88	0.89	0.90	0.90	0.89	0.89	0.89	0.90	0.90	0.90	0.94	0.96
Hypothesis tests for symmetry. Wald statistic: $\chi^2(1)$ (probability-value) Null hypothesis of symmetry can be rejected using 5% level if Probability-value <0.05												
β_increases=β_decreases: symmetry for increases and decreases		0.003 (0.957)				0.978 (0.323)				19.1(<.001)		
β_Normal=β_Interruptions: symmetry for Normal and Interruption quarters			0.03 (0.957)				1.78 (0.182)				164.9 (<.001)	
$\beta_2=\beta_4$: symmetry for decreases in Normal and Interruption quarters				22.3 (<.001)				4.2 (0.039)				82.23 (<.001)
$\beta_1=\beta_3$: symmetry for increases in Normal and Interruption quarters				1.47 (0.225)				2.03 (0.154)				3.72 (0.054)
$\beta_1=\beta_2$: symmetry in Normal quarters for increases and decreases				9.54 (0.002)				5.01 (0.025)				1.36 (0.243)
$\beta_3=\beta_4$: symmetry in Interruption quarters for increases and decreases				0.89 (0.344)				0.21 (0.645)				11.92 (0.001)

[a] For all equations, *F*-statistic probability-value <0.001.

Annual consumption data for OPEC countries for 1973–2008 are taken from International Energy Agency, *Energy Balances of Non-OECD Countries* (Paris, 2010), with 2009–2010 estimates of oil consumption from JodiDATA: Joint Organizations Data Initiative, www.JodiData.org Because *quarterly* data on oil consumption are not available, we estimated quarterly consumption data by assuming constant linear change between annual values, from quarter to quarter. We then estimated quarterly exports as the difference between quarterly production and estimated quarterly domestic consumption.

We estimate the special impact on Saudi exports of interruptions in Rest-of-OPEC exports. Our criterion for defining the period of an interruption, for the following five periods, was the first "abnormal" production quarter until the first "new normal" quarter. Implementing this definition required some judgment of what constituted a recovery to "new normal".

Table D1
Estimated long-run coefficients in the cointegrating equation.

Eq.	Entire period: 1973q1–2012q1				Pre-1986: 1973q1–1985q3				Post-1986: 1985q4–2012q1			
	5	6	7	8	5	6	7	8	5	6	7	8
Coefficients (probability-values): statistically significant at 5% level if probability-value < 0.05												
Rest-of-OPEC exports: β	0.15 (<.001)				0.36 (<.001)				0.13 (<.001)			
Increases: β_increases		0.19 (.002)				0.06 (0.73)				−0.07 (0.29)		
Decreases: β_decreases		0.20 (.001)				0.23 (0.02)				−0.23 (.002)		
All Normal quarters, both increases and decreases: β_Normal			0.12 (0.01)				0.61 (<.001)				0.08 (0.18)	
Normal quarters, increases: β_1				0.30 (<.001)				0.16 (0.49)				0.38 (0.01)
Normal quarters, decreases: β_2				0.55 (<.001)				0.56 (0.02)				0.86 (<.001)
All Interruption quarters, both increases and decreases: β_Interruptions			0.12 (0.04)				−0.67 (0.03)				−0.59 (.002)	
Interruption quarters, increases: β_3				0.41 (0.25)				−11.6 (<.001)				0.25 (0.57)
Interruption quarters, decreases: β_4				−0.33 (0.08)				−5.69 (<.001)				−0.69 (<.001)
Price (γ)	−0.03 (0.15)	−0.004 (0.78)	−0.11 (0.47)	−0.013 (0.71)	0.16 (<.001)	0.34 (<.001)	0.13 (0.05)	1.68 (<.001)	−0.02 (0.22)	−0.06 (0.08)	0.03 (0.07)	0.05 (.20)
Constant		0.38 (.003)	0.29 (0.008)	0.88 (<.001)	−1.01 (<.001)	−0.05 (0.01)		−3.77 (<.001)			0.3 (0.04)	1.43 (<.001)
Equation statistics[a]												
Adjusted R^2	0.87	0.87	0.90	0.89	0.89	0.89	0.90	0.87	0.85	0.85	0.91	0.89
Hypothesis tests for symmetry. Wald statistic: $\chi^2(1)$ (probability-value)												
Null hypothesis of symmetry can be rejected using 5% level if probability-value < 0.05												
β_increases = β_decreases: symmetry for increases and decreases		0.44 (0.51)				4.66 (0.03)				5.93 (0.01)		
β_Normal = β_Interruptions: symmetry for Normal and Interruption quarters			0.05 (0.81)				10.36 (0.001)				11.41 (<.001)	
$\beta_2=\beta_4$: symmetry for decreases in Normal and Interruption quarters				15.87 (<.001)				22.72 (<.001)				33.48 (<.001)
$\beta_1=\beta_3$: symmetry for increases in Normal and Interruption quarters				0.11 (0.74)				26.06 (<.001)				0.11 (0.74)
$\beta_1=\beta_2$: symmetry in Normal quarters for increases and decreases				16.15 (<.001)				13.32 (<.001)				14.23 (<.001)
$\beta_3=\beta_4$: symmetry in Interruption quarters for increases and decreases				6.05 (0.01)				25.99 (<.001)				5.25 (0.02)

[a] For all equations, F-statistic probability-value < 0.001.

Iranian revolution three quarters, starting in 1978q4
Iraq–Iran War two quarters, starting in 1980q4
Iraq invasion of Kuwait four quarters, starting in 1990q3
Second Gulf War four quarters, starting in 2003q1
Libya Civil War five quarters, starting in 2011q1

The ending of some interruptions were more difficult to define, especially the Iraq–Iran War and the Iraq invasion of Kuwait. The Iraq–Iran War lasted for most of the 1980's, although the initial reductions in production happened in the first two quarters. An additional complication was that the start of the war coincided with massive reduction in demand for OPEC oil after the 1979–1980 price doubling; this necessitated cutbacks in OPEC production in order to defend the price doubling. Similarly, the ending date for the Iraq invasion of Kuwait was difficult to define. The invasion and subsequent war almost eliminated production in both countries at the end of 1990. Despite a quick end to the war, it took much longer to recover from oil field destruction in Kuwait, which was still increasing its production through 1992. Nor did Iraq production recover very quickly; its production by 1997 was still only one-third of its 1989 production, a level which it is only now approaching once again.

Appendix B. Unit root test results and diagnostic test results

Since we are using quarterly data, we employ the seasonal unit root test proposed by Hylleberg et al. (1990), known as HEGY.[25] Ghysels et al. (1994) conclude that this test is the most useful among the alternatives. We also utilize the Augmented Dickey-Fuller unit-root test. The results of both tests are reported in Table B1.[26] The HEGY procedure for seasonal unit root test is as follows:

$$y_{4t} = \mu_t + \pi_1 y_{1,t-1} + \pi_2 y_{2,t-1} + \pi_3 y_{3,t-2} + \pi_4 y_{3,t-1} + \sum_{i=1}^{p} \varphi_i y_{4t-i} + \varepsilon_t$$

where $\mu_t = DT + DS = \delta + \beta t + \Sigma \alpha_s D_{s,t}$.

Lags of y_{4t} are included to ensure that the residuals are white noise.

$$y_{1t} \equiv (1 + L + L^2 + L^3) y_t = y_t + y_{t-1} + y_{t-2} + y_{t-3}$$

[25] As noted in Appendix A, we estimated quarterly data on consumption by assuming simple linear changes in annual data; hence we do not have standard "seasonality" in this quarterly data.

[26] We did not take account of the effect of structural breaks upon the unit root tests. For a discussion of this issue, see Perron (2006).

Table D2
Tests of symmetry hypotheses: comparisons from ARDL and DOLS methods.

Reject symmetry hypothesis?	Method	Eq.	Time period		
			All years	Pre-'86	Post-'86
β_increases=β_decreases	ARDL	10b	No	No	No
	DOLS	6	No	Yes	Yes
β_Normal=β_Interruptions	ARDL	10c	No	No	Yes
	DOLS	7	No	Yes	Yes
$\beta_2=\beta_4$ Decreases in Normal and Interruption quarters	ARDL	10d	Yes	Yes?	Yes
	DOLS	8	Yes	Yes	Yes
$\beta_1=\beta_3$ Increases in Normal and Interruption quarters	ARDL	10d	No	No	Yes
	DOLS	8	No	Yes	No
$\beta_1=\beta_2$ Increases and decreases in Normal quarters	ARDL	10d	Yes	Yes	Yes
	DOLS	8	Yes	Yes	Yes
$\beta_3=\beta_4$ Increases and decreases in Interruption quarters	ARDL	10d	No	No	No?
	DOLS	8	Yes	Yes	Yes

$$y_{2t} \equiv -(1-L+L^2-L^3)y_t = -(y_t - y_{t-1} + y_{t-2} - y_{t-3})$$

$$y_{3t} \equiv (1-L^2)y_t = y_t - y_{t-2}$$

$$y_{4t} \equiv (1-L^4)y_t = y_t - y_{t-4}$$

We test the following hypotheses:

$H_A : \pi_1 = 0 =>$ nonseasonal unit root.
$H_B : \pi_2 = 0 =>$ biannual seasonal unit root.
$H_C : \pi_3 = \pi_4 = 0 =>$ annual unit root.

From HEGY unit root tests, all the three null hypothesis $\pi_1=0$, $\pi_2=0$ and $\pi_3=\pi_4=0$ are rejected for XR_incr, XR_decr, and XR_Ni, which implies these variables, are stationary at level and there is no evidence of nonseasonal unit root, biannual unit root and annual unit root. For all remaining variables, the null hypothesis $\pi_1=0$ cannot be rejected, which implies a non-seasonal unit root exist at zero frequency; in other words, there exists a unit-root in the long -run for these variables. Similarly, the hypothesis $\pi_2=0$ and $\pi_3=\pi_4=0$ are rejected for all other variables. Therefore, we can conclude that there is no biannual and annual unit root in all these variables. The results of the ADF test support the findings of the HEGY test: ADF tests do not reject the null hypothesis of unit root in levels for all variables except XR_incr, XR_decr, and XR_Ni.

Thus from Table B1 we conclude that all variables are not stationary at same levels; some are stationary at level and others are stationary at first differences. Hence, the presence of a stable, long-run relationship among the variables can be detected by applying the autoregressive distributed lag (ARDL) approach to cointegration proposed by Pesaran et al. (2001).

Also, as noted in the text, several diagnostic tests were done for equations (9a) … (9d):

- $\chi^2_{SC}(4)$ Lagrange multiplier test of the residuals serial correlation.
- $\chi^2_{FF}(1)$ Ramsey's RESET test using the square of the fitted values for functional form.
- $\chi^2_{N}(2)$ Jarque–Bera test of the normality of the residuals based on an analysis of skewness and kurtosis.
- $\chi^2_{H}(1)$ Heteroskedasticity test, based on the regression of squared residuals on squared fitted values.

The results are shown in Table B2.

Appendix C. Econometric results for production

This appendix presents the analogous ARDL results for oil *production* rather than exports. Shown below are Tables C1 and C2, which are analogous to Tables 1 and 2 respectively. The results are qualitatively the same as all results for exports, with one minor difference noted in Section 5.2 of the text.

Appendix D. DOLS econometric results for exports

This appendix presents econometric results for exports in Table D1, using an alternative econometric method DOLS, which differs from the ARDL method used in Table 2.

Table D2 compares the asymmetry results from the ARDL and DOLS methods, in Tables 2 and D1, respectively. As noted in Section 5.2, the DOLS asymmetry results are also similar to the ARDL results, and even stronger.

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