Title
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ARBITRAGE AND THE LAW OF ONE PRICE: SETTING THE RECORD STRAIGHT

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Abstract

Using retail commodity prices, most research finds positive Border Effects and rejects effective arbitrage and the Law of One Price. On the other hand, using auction prices, the finance literature and a few articles using commodities support effective arbitrage and the LOP. Using longer intervals and a wider variety of commodity auction prices than ever before, I find strong support for effective arbitrage and the LOP. In addition, for the first time, I use auction prices to look for Border Effects. Both half lives and standard deviations reject positive Border Effects.

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1. Introduction.

Arbitrage and the Law of One Price (LOP) are important. The failure to respond to risk-free profit opportunities would reject basic assumptions like profit and wealth maximization. But the claims about arbitrage and the LOP are mixed.

The consensus is that arbitrage is effective in *financial* markets and, as a result, that the LOP holds in financial markets. For example Armitrage et al (2012, 3080) say that: "Evidence in financial markets of an opportunity for pure arbitrage, and therefore a violation of the Law of One Price, is considered an anomaly…". While Akram et al (2008, 237) say the following:

> Arbitrage is one of the fundamental pillars of financial economics. It seems generally accepted that financial markets do not offer risk-free arbitrage opportunities, at least when allowance is made for transaction costs.

But claims are mixed in commodity markets. A few articles support effective arbitrage and the LOP. But the consensus is that arbitrage and the LOP fail in commodity markets. Lee (2008, 1029) describes that consensus as follows:

> The Law of One Price states that international relative price differentials should be arbitraged away so that identical goods in different countries should sell for the same price when expressed in a common currency. Yet the evidence from the empirical literature shows that not only are relative prices quite different across countries, but also such deviations are highly volatile and persistent.

The mixed claims in commodity markets are partially the result of differences regarding the meaning of "arbitrage" and the "Law of One Price". The literature that Lee (2008) refers to uses markets where contracts cannot eliminate uncertainty regarding selling prices.

Michael et al (1994), Pippenger and Phillips (2008a) and the related research that supports effective arbitrage and the LOP uses commodity auction markets similar to those in the financial research where contracts can eliminate price uncertainty.

Another part of the problem with the research is its historical link to the pure theory of trade. That link often leads researchers to think in terms of "traded" versus "non-traded" goods.[1] But that distinction is not appropriate for research on commodity arbitrage and the LOP. For that research the appropriate distinction is between retail, wholesale and auction markets. Arbitrage obviously is not possible if a good is not traded. But arbitrage is also not possible in many goods that are traded. Kleenex is a traded good, but arbitrage as it is defined in dictionaries and encyclopedias and used here, is still not possible in Kleenex.

2. Literature Review.

Subsection 2.1 reviews how dictionaries and encyclopedias devoted to economics define "arbitrage" and the "Law of One Price". Subsection 2.2 reviews the research that uses retail prices to test the LOP. Section 2.3 reviews the literature on Border Effects. Section 2.4 reviews the literature using commodity auction prices.

2.1. Definitions.

Dictionaries and encyclopedias specializing in economics clearly define arbitrage as a "risk-free" transaction.[2] For example, *The New Palgrave Dictionary of Economics* (2008, 188) begins the discussion of arbitrage as follows: "An arbitrage opportunity is an investment strategy that guarantees a positive payoff in some contingency with no possibility of a negative payoff….". *Wikipedia* (25 May 2010) says the following: "When used by academics, an arbitrage is a transaction that involves no negative cash flow at any probabilistic or temporal state and a positive cash flow in at least one state; in simple terms, it is a risk-free profit."

The following quote from *The Penguin Dictionary of Economics* (1998, 241) is a fairly typical definition of the Law of One Price:

[1] For a more extensive discussion of this problem in commodity research see Bernard et al (2010).
[2] In this context "risk-free" refers to certainty regarding prices. As in all transactions, there is always the risk in arbitrage that a contract might not be fulfilled.

> The law, articulated by Jevons, stating that 'In the same open market, at any moment, there cannot be two prices for the same kind of article.' The reason is that, if they did exist, arbitrage should occur until the prices converge.

The New Palgrave Dictionary of Economics (2008) does not have a separate heading for the LOP. The law is discussed on page 189 under the heading of Arbitrage. "The assertion that two perfect substitutes (for example, two shares of stock in the same company) must trade at the same price is an implication of no arbitrage that goes under the name of the law of one price."

The auction markets used in the financial literature and by Michael et al (1994), Pippenger and Phillips (2008a) and related research in commodity markets are consistent with these definitions of arbitrage and the LOP because commodity auction markets typically include both spot and futures markets. That is not true of the research referred to by Lee (2008).

2.2. Retail and wholesale.

One cannot test the LOP as it is defined in dictionaries and encyclopedias in retail and most wholesale markets because arbitrage as defined in those publications is not possible in retail and most wholesale markets. If one grocery store sells seedless red grapes at $0.99 per pound and a store across the street sells them for $2.00 a pound, one cannot buy them at $0.99 and sell them for $2.00.

Arbitrage also is not possible in most wholesale markets. Brand names and marketing contracts usually prevent arbitrage by preventing active wholesale markets. For example there is no active forward market for Kleenex in either the U.S. or Japan. But there are exceptions like wholesale markets for fresh fish and fresh flowers. It is possible to buy live lobsters at the wholesale market in Boston on Monday and simultaneously sell them in LA later that week. But that is not true for frozen lobster where there are brand names and no active wholesale markets.

Several articles study international price convergence in retail markets and claim that they are testing the LOP. None find strong support for the LOP. Recent examples using individual prices rather than indexes include Asplund and Friberg (2001), Haskel and Wolf (2001), Lutz (2004), Goldberg and Verboven (2005) and Crucini and Shintani (2008).[3] The most influential is probably Asplund and Friberg (2001) who use prices for identical goods in duty free stores on Scandinavian ferries. Goldberg and Verboven (2005, 50) describe their results as follows: they "find that the LOOP does not even hold for identical goods sold at the same location as long as these goods are denominated in different currencies….."

But arbitrage is not possible on those Scandinavian ferries or similar ferries around the world. No one on a Scandinavian ferry can buy a particular brand of vodka using Swedish kronor and then turn around and sell it back to the duty free store for Finnish markka.

The same problem applies to all supposed tests of the LOP using retail prices. Retail stores sell at retail prices. They do not buy at retail, they buy at wholesale. Put bluntly, at the retail level all goods are "non-traded" because no one, not even duty free stores on Scandinavian ferries, both buys and sells at retail.[4]

But non-traded does not mean the absence of *economic* links between international retail markets. One link works from the domestic retail market through the domestic wholesale market to the foreign wholesale market and then through that market to the foreign retail market. Another link operates from the domestic retail market through domestic production to domestic auction markets then through those markets to foreign auction markets, foreign production and finally foreign retail markets. These indirect links between international retail markets are not

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[3] Crucini and Shintani (2008) do not claim that the LOP fails even though they find half lives of 19 months.

[4] "No one" is a bit strong. I saw a small grocery store in a remote area selling Kirkland products that they almost certainly bought at CostCo. But even that store did not both sell and buy the goods on its shelves.

very strong in the short run, but they presumably provide the long-run link that we see in tests of Purchasing Power Parity using retail price indexes.[5]

2.3. Border Effects.

Several articles estimate Border Effects using retail indexes or prices. They include Engel and Rogers (1996), Parsley and Wei (2001), Morshed (2003), Borraz (2006), Ceglowski (2006), Cheung and Lai (2006), and Horvath et al (2008).[6] They appeal to either arbitrage or the LOP, or both, and reject them.[7]

Parsley and Wei (2001, 92) for example say the following:

> In Fig. 2, we repeat the exercise for 1990. The comparison with Fig. 1 is striking. The between-country distribution has diverged from the two within country distributions. Japanese prices expressed in US dollars have risen even more relative to US prices. The violation of the law of one price became even more severe.

Given the weak links between international retail markets discussed above, we should expect wide borders at the retail level. However those wide borders do not reject the LOP and effective arbitrage because arbitrage is not possible between retail markets. But one can look for evidence of effective commodity arbitrage and the LOP in auction markets.

2.4. Auction markets.

Several articles use prices from auction markets like mine to evaluate commodity arbitrage and the LOP. They include Protopapadakis and Stoll (1983) and (1986), Goodwin et al (1990), Goodwin (1992), Michael et al (1994) and Pippenger and Phillips (2008a) and (2008b). With the exception of Protopapadakis and Stoll (1983) and (1986) they all use monthly grain prices.[8] This research generally supports effective arbitrage and the LOP.

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[5] See Taylor (2006) for a recent review of PPP.
[6] Dissenting articles include Morshed (2007) and Gorodnichenko and Tesar (2009).
[7] Using individual retail prices, Crucini and Shintani (2008) do not find a border effect.
[8] Note that the monthly prices are usually averages of daily closing prices and that averaging introduces spurious autocorrelations into series that otherwise would be martingales. See Working (1960).

3. New evidence.

Commodity arbitrage normally involves three "simultaneous" actions: (1) buying a commodity spot or with a nearby futures contract in one location, (2) arranging for the shipping of the commodity to a second location and (3) selling the commodity in that second location when it is due to arrive. The first and third actions normally require active auction markets. The second requires active markets where arbitragers can find the necessary transportation as needed.

Although wholesale transactions, particularly international transactions, routinely involve forward contracts, the relevant forward *markets* do not normally exist at the wholesale level. They normally exist only in auction markets where transactions are relatively large, products are "homogeneous" and, as a result, transaction costs per dollar are relatively low. Since true commodity arbitrage requires these forward markets and the only place they normally exist is in auction markets, it follows that we should use auction prices to test the Law of One Price.

Forward contracts pose practical problems for testing commodity LOP because forward prices are not easily obtainable. I have neither the time nor the resources to obtain them. So, like most previous work using auction prices, I am forced to use spot prices. Fortunately, as Fama and French (1987) and Kearns (2007) have shown, while forward exchange rates are biased estimates of future spot exchange rates, in commodity markets forward prices appear to be unbiased estimates of future commodity prices.

3.1. Data

My prices cover a wider range of products over longer intervals than previous research. In addition, this is the first time that auction prices have been used to evaluate Border Effects.

TABLE 1
PRODUCTS, INTERVALS, AND SOURCES

Variety	Acronym/Ports	Period and Source	
No. 2 Dark Northern Spring Wheat, 14% Protein	DNS		
	Japan, Pacific and Gulf	1975:09 to 1981:10	*World Wheat Statistics*
	Gulf	1974:01 to 2001:12	*World Wheat* (or *Grain*) *Statistics*
	Rotterdam	1974:01 to 1990:12	*World Wheat* (or *Grain*) *Statistics*
	Rotterdam	1989:06 to 1995:10	U.S. Department of Agriculture *Wheat Situation & Outlook Report*
	Rotterdam	1994:07 to 2001:12	*World Grain Statistics*
No. 2 Western White Wheat	WW Japan and Pacific	1975:09 to 1981:10	*World Wheat Statistics*
No. 2 Hard Winter Wheat, 13% Protein	HW13 Japan and Gulf	1976:01 to 1981:07	*World Wheat Statistics*
Hard Winter Wheat, Ordinary	HWO Gulf and Pacific	1974:01 to 1999:02	*World Wheat (or Grain) Statistics*
No. 2 Western White Wheat	WW Japan and Pacific	1975:09 to 1981:10	*World Wheat Statistics*
No. 2 Yellow Corn	YC Rotterdam and Gulf	1987:01-1998:06	UN Conference on Trade and Development, *Handbook of Statistics*
Shipping rates	Gulf-Rotterdam, Gulf-Japan, Pacific-Japan	1974:01 to 2001:12	*World Wheat (or Grain) Statistics*
No. 2 Diesel Fuel	Gulf, New York, Los Angeles, Rotterdam and Singapore	1993:10 or 1995:05 to 2007:02 or 2007:10	WWW.ECONSTATS.COM EAI Daily Energy Spot Prices
Fuel Oil	Gulf, New York, Los Angeles, Rotterdam and Singapore	1995:05 to 2007:10	WWW.ECONSTATS.COM EAI Daily Energy Spot Prices
Gasoline, Regular	Gulf, New York, Los Angeles, Rotterdam and Singapore	1992:07to 2007:10	WWW.ECONSTATS.COM EAI Daily Energy Spot Prices
Jet Fuel	Gulf, New York, Los Angeles, Rotterdam and Singapore	1990:09 to 2007:10	WWW.ECONSTATS.COM EAI Daily Energy Spot Prices
Rubber	Malay and U.K.	1974:01 to 1979:12*	Protopapadakis and Stoll (1986) ♦**
Silver	U.S. and U.K.	1972:07 to 1980:05*	Protopapadakis and Stoll (1986)†
Tin	U.S. and U.K.	1974:01 to 1980:07*	Protopapadakis and Stoll (1986) ♦**

* Weekly. Original Sources: ** Financial Times of London (U.K.). ♦ Journal of Commerce (N.Y.). † Samuel Montague.

3.1.1. Grains. Goodwin et al (1990), Michael et al (1994) and Pippenger and Phillips (2008a) and (2008b) use shorter versions of my grain prices and freight rates to test the LOP. But only Pippenger and Phillips (2008b) estimate half lives.

Table 1 describes the sources for my grain prices. Between the U.S. and Rotterdam the data cover over 25 years. Earlier research covers only 10 to l1 years. Freight rates for wheat vary with the size of the ship and at times more than one rate is published. Mine are the same as in Michael et al (1994). Unlike prices, freight rates are not spot. Footnotes in *World Wheat Statistics* describe the freight rates as follows: “Estimated mid-month rates based on current chartering practices for vessels to load six weeks ahead.” Freight rates are forward, not spot, prices. These forward rates imply that there is an active forward market for shipping grain.

Goodwin et al (1990) use similar corn prices between the U.S. and Rotterdam. Their data cover only six years while mine cover over 11 years.

The grain prices used here have several advantages: (1) "identical" products, (2) all prices in dollars, (3) freight rates are available for wheat, (4) for Rotterdam wheat prices cover an unusually large number of years, about 25. (5) export prices are free on board (FOB) and import prices include certificates, insurance and freight (CIF), (For Japan, prices do not include insurance.) and (6) most important of all, arbitrage should be possible in all these markets.

The first part of Table 1 describes the types of grains, data sources, ports and the acronyms used later to identify the different grains. A ‘J’, ‘P’, ‘G’ or ‘R’ attached to an acronym indicates the port. For example, DNSR is Dark Northern Spring wheat at Rotterdam.

Wheat is a 'heavy' grain. For wheat, one metric ton equals 36.7437 bushels. For corn, one metric ton equals 39.3682 bushels. Since a metric ton of corn takes up more space than a metric ton of wheat, I would expect freight rates for corn to be slightly higher than for wheat. Unfortunately I do not have separate freight rates for corn. I apply the freight rates for wheat to corn. Since the difference should be small and the two freight rates should move together, applying freight rates for wheat to corn should not be a serious problem.

For trade with Japan, I use the same intervals used earlier by Michael et al (1994) and Pippenger and Phillips (2008a) and (2008b). For a visual inspection of that data, see Michael et al (1994). I do not extend the Japanese data for two reasons: (1) starting in 1982 several months of Japanese prices are missing and (2) in the 1990s Japan erected non-tariff barriers to wheat imports that created artificial price differentials.[9]

I use corn prices between Gulf ports and Rotterdam as soon as they are available from UNCTAD's *Handbook of Statistics*. They end in mid 1998 because about then Europe began to impose restrictions on importing genetically modified foods and most corn grown in the United States is genetically modified.

Some grain prices are missing. Except for DNSR during the early 1990s, there are never more than two missing months in a row. When only one month is missing, it is replaced with the previous month. When two months in a row are missing, the first month is replaced with the preceding month and the second month is replaced with the following month.[10]

In the early 1990s, about 18 months of data are missing for DNSR and then a few months later about another six months are missing. As Table 1 indicates, there is a second source for the missing data, but where they overlap the two sources do not always agree. It is possible to use the USDA data to fill in the missing data from World Grain Statistics, but the replacement produces unusual error terms that require long lags in tests for unit roots and cointegration. Those long lags reduce the significance of the tests. As an alternative, where there are USDA prices for DNSR, I report separate results using those prices for Rotterdam with freight rates and Gulf prices from World Grain Statistics.

3.1.2. Rubber, Metals and Petroleum Prices. The latter half of Table 1 describes the other prices, relevant ports, intervals and sources. Rubber and metal prices are for Wednesday of

[9] For a discussion of Japanese protectionist policies in the wheat market see Fukuda et al (2004).
[10] Using more sophisticated techniques tends to introduce spurious serial correlation.

each week. The prices for rubber and metals were supplied by Protopapadakis and Stoll. They describe them in more detail.

Rubber prices may not be for identical products. For each Wednesday, the *Journal of Commerce* quotes a single price for rubber in London. In another section it quotes U.S. prices for several different grades that on a given day can range in price from 26.25 to 42.75 cents per pound. As a result, there is a strong possibility that the rubber prices are not for identical products.

All petroleum prices, both at U.S. and foreign ports, are monthly averages of closing daily prices. For foreign ports, the foreign currency price is converted into U.S. dollars using the closing dollar price of the foreign currency for that day. Since prices in these markets are also approximately martingales, the monthly petroleum prices are essentially an average of each day's last transaction. To the best of my knowledge, this is the first time that petroleum prices like these have been used to test the LOP.

3.2. Test Equations.

I have freight rates for wheat. I also know the direction of trade for grains because the United States is a major grain exporter. U.S. prices are FOB and foreign prices are CIF. As a result, for grains I can account for most of the relevant shipping costs by computing the price differentials as the foreign forward CIF price minus the spot U.S. FOB price plus the freight rate. That approach produces the following *ideal* test equation for grain prices.

$$\mathrm{Ln}(P^{F}_{t+1}) - \mathrm{Ln}(p^{D}_{t} + f_{t}) = u_{t} \quad (1)$$

Where $Ln(P^{F}_{t+1})$ is the log of the dollar price of grain at time t in a foreign port one month forward. $Ln(p^{D}_{t} + f_{t})$ is the log of the spot price in the appropriate U.S. port plus the freight rate for loading at time t.

But I am missing two critical parts of that ideal test equation: First I do not have f_t, the freight rate for loading at time t. Second I do not have P^F_{t+1}, the forward price for $t+1$.

But I do have f_t, the price for loading in six weeks. So I can either use f_t or f_{t-1} as a proxy for f_t. f_t is the forward price for loading in six weeks. f_{t-1} is the price for loading in a little less than two weeks. I use f_{t-1}.

Although I do not have the forward price P^F_{t+1}, forward commodity prices appear to be unbiased estimates of future spot commodity prices. As a result, I can use the future spot price p^F_{t+1} as an unbiased estimate of P^F_{t+1}.

Replacing f_t with f_{t-1} and P^F_{t+1} with p^F_{t+1} produces eq. (2).

$$\mathrm{Ln}(p^F_{t+1}) - \mathrm{Ln}(p^D_t + f_{t-1}) = u_t + \varepsilon_t \tag{2}$$

Where ε_t is the additional error due to using f_{t-1} as a proxy for f_t and p^F_{t+1} as a proxy for P^F_{t+1}.

I do not have freight rates for the other products and I do not know the direction of trade for those products. For those products I follow the LOP and Borders literature and use eq. (3).

$$\mathrm{Ln}(p^F_t) - \mathrm{Ln}(p^D_t) = z_t \tag{3}$$

I also estimate eq. (3) with grain prices. Those estimates provide consistent results for all products and also provide some insight regarding the importance of time and transportation costs.

Like most auction prices, my prices appear to be approximately martingales and therefore have unit roots. Pippenger and Phillips (2008b) show that $Ln(p^F_{t+1})$ and $Ln(p^D_t + f_{t-1})$ are cointegrated and that the differentials $Ln(p^F_{t+1}) - Ln(p^D_t + f_{t-1})$ are stationary. To save space I do not replicate their results. I show that for the other commodities $Ln(p^F_t)$ and $Ln(p^D_t)$ are cointegrated and that the $Ln(p_t^F) - Ln(p_t^D)$ are stationary. I also estimate half lives for $Ln(p_t^F) - Ln(p_t^D)$ and, where possible, for $Ln(p_{t+1}^F) - Ln(p_t^D + f_{t-1})$.

3.3. Cointegration.

Tables 2 and 3 report tests for linear cointegration between $Ln(p_t^F)$ and $Ln(p_t^D)$. These and all later tables use EViews. There are two tests for cointegration: the Johansen trace statistic and the augmented Dicky-Fuller (ADF) test.[11] When needed, the ADF statistic is corrected for conditional heteroscedasticity. That correction is not available for the Johansen test. All tables consider lags up to one year. The Akaike Information Criteria from the ADF test is used to choose the lag length for both tests. Significance levels for the ADF tests are taken from Engel and Granger (1987). Significance levels for Johansen tests are from EViews.

In most cases, lag lengths are the same with or without GARCH. When lags differ for ADF and Johansen tests, it is because the ADF test is corrected for conditional heteroscedasticity and that correction affects the lag length for the ADF test.

All tables include a variety of tests for errors from ADF tests. Similar tests are not available for Johansen statistics or later the Phillips-Perron version of ADF tests. For the LM, Arch and both Q tests I report the result for the lag with the lowest probability. If it is not significant, no lag is significant. There is also a Jarque-Bera test for normality. Like most auction prices, my prices are often leptokurtic.

[11] Phillips-Perron tests were also used and produce results similar to ADF tests. They have been omitted to save space.

Table 2

Cointegration Tests: Grain Prices with no Freight Rates and Export Price not Lagged

Product/Ports Test	DNS Gulf-Rott 74:1-90:12	DNS Gulf-Rott 89:6-94:10	DNS Gulf-Rott 94:7-01:12	Corn Gulf-Rott 87:4-98:6	DNS Gulf-Japan 75:9-81:10
ADF (Lag)	-6.154 (0)	-5.305 (12)	-3.880 (6)	-3.457 (3)	-4.529 (3)
Significance	**	**	**	*	**
Garch	0,0	1,1	2,1	0,0	0,0
Johansen (Lag)	212.39 (0)	27.714 (2)	16.659 (6)	24.206 (3)	24.098 (3)
Significance	**	**		*	*
Q Stat. (Lag)	15.219 (12)	6.676 (4)	0.434 (1)	0.010 (1)	3.169 (8)
[Probability]	[0.230]	[0.154]	[0.510]	[0.920]	[0.923]
LM Stat. (Lag)	19.012 (12)	NA	NA	0.395 (1)	7.734 (7)
[Probability]	[0.088]	NA	NA	[0.529]	[0.391]
Arch (Lag)	6.959 (3)	6.653 (9)	4.764 (7)	0.152 (1)	8.631 (4)
[Probability]	[0.073]	[0.673]	[0.689]	[0.697]	[0.071]
Jarque-Bera	15.114	0.690	2.208	775.760	0.773
[Probability]	[0.000]	[0.708]	[0.332]	[0.000]	[0.680]
Residuals^2					
Q Stat. (Lag)	2.581 (1)	6.296 (9)	10.922 (12)	0.156 (1)	9.992 (4)
[Probability]	[0.108]	[0.710]	[0.536]	[0.693]	[0.041]

* Significant at 5 percent. ** Significant at 1 percent. Critical values 3.17 and 3.77 are from Engel and Granger (1978).

Table 2

Continued

Product/Ports Test	HW13 Gulf-Japan 75:9-81:10	DNS Gulf-PP 74:1-99:4	HWO Gulf-PP 74:1-86:4	DNS PP-Japan 75:9-81:10	WW PP-Japan 75:9-81:10
ADF (Lag)	-4.019 (0)	-2.407 (10)	-3.152 (0)	-2.867 (12)	-2.690 (7)
Significance	**				
Garch	0,0	0,0	1,0	0,0	0,0
Johansen (Lag)	57.178 (0)	20.288 (10)	194.86 (0)	20.311 (12)	14.895 (7)
Significance	**	*	**	*	
Q Stat. (Lag)	10.486 (7)	0.331 (2)	4.537 (4)	0.265 (1)	0.024 (1)
[Probability]	[0.163]	[0.847]	[0.338]	[0.607]	[0.877]
LM Stat. (Lag)	9.998 (6)	8.898 (4)	NA	2.114 (1)	12.244 (12)
[Probability]	[0.125]	[0.064]	NA	[0.146]	[0.426]
Arch (Lag)	0.969 (1)	14.941 (8)	1.563 (2)	0.966 (1)	6.617 (5)
[Probability]	[0.325]	[0.060]	[0.458]	[0.326]	[0.251]
Jarque-Bera	12.835	67.524	173.74	17.917	2.087
[Probability]	[0.002]	[0.000]	[0.000]	[0.000]	[0.352]
Residuals^2					
Q Stat. (Lag)	11.089 (7)	16.136 (8)	1.164 (2)	1.028 (1)	11.036 (9)
[Probability]	[0.135]	[0.040]	[0.559]	[0.311]	[0.273]

Table 2 reports the results of estimating eq. (3) for all grains. No Q statistic, LM statistic, Arch statistic or Q statistic for squared residuals is significant. Jarque-Bera tests often indicate fat tails.

For most prices in Table 2, at least one test rejects the null of no cointegration at the 1 percent level. There is, however, one case where neither test rejects the null at 5 percent: WW between Pacific ports and Japan. But all that is needed to reject the null for that pair is to lag the export price by one month. With that lag, both tests reject the null at the 1 percent level. The failure to reject the null for this pair of prices appears to be the result of the low power of the tests and the importance of time in commodity arbitrage.

Table 3
Cointegration Tests for Price Differentials: Petroleum Products, Rubber and Metals

Product/Ports Test	Diesel Gulf-LA 95:5-07:10	Diesel Gulf-NY 95:5-07:10	Diesel Gulf-Rott 95:5-07:10	Diesel Gulf-Sing 95:5-07:10	Diesel LA-NY 95:5-07:10	Diesel LA-Rott 95:5-07:10
ADF (Lag)	-14.065 (1)	-11.221 (0)	-9.273 (0)	-6.322 (0)	-4.052 (11)	-4.710 (7)
Significance	**	**	**	**	**	*
Garch	2,2	0,0	0,0	0,0	0,0	1,1
Johansen (Lag)	46.764 (1)	94.105 (0)	71.304 (0)	38.065 (0)	23.979 (11)	15.823 (7)
Significance	**	**	**	**	*	
Q Stat. (Lag)	7.523 (7)	0.722 (2)	9.616 (10)	12.387 (10)	0.100 (1)	0.086 (1)
[Probability]	[0.377]	[0.697]	[0.475]	[0.260]	[0.751]	[0.770]
LM Stat. (Lag)	NA	0.624 (1)	9.834 (10)	7.940 (4)	4.281 (3)	NA
[Probability]	NA	[0.429]	[0.455]	[0.094]	[0.233]	NA
Arch (Lag)	2.854 (3)	0.032 (1)	0.080 (1)	2.735 (1)	4.289 (2)	3.569 (2)
[Probability]	[0.415]	[0.859]	[0.778]	[0.098]	[0.117]	[0.168]
Jarque-Bera	16.254	1203.466	784.044	110.481	5.623	23.405
[Probability]	[0.000]	[0.000]	[0.000]	[0.000]	[0.060]	[0.000]
Residuals^2						
Q Stat. (Lag)	2.830 (3)	0.033 (1)	0.082 (1)	2.805 (1)	4.445 (2)	3.747 (2)
[Probability]	[0.419]	[0.857]	[0.775]	[0.094]	[0.108]	[0.154]

* Significant at 5 percent. ** Significant at 1 percent. Critical values 3.17 and 3.77 are from Engel and Granger (1978).

Table 3
Continued

Product/Ports Test	Diesel LA-Sing 95:5-07:10	Diesel NY-Rott 95:5-07:10	Diesel NY-Sing 95:5-07:10	Diesel Rott-Sing 95:5-07:10	Fuel Oil♦ Gulf-LA 93:10-07:2	Fuel Oil Gulf-NY 93:10-07:2
ADF (Lag)	-4.387 (4)	-5.885 (1)	-3.903 (12)	-4.999 (5)	-3.490 (5)	-3.799 (4)
Significance	**	**	**	**	*	**
Garch	1,1	1,1	1,1	2,1	3,3	0,0
Johansen (Lag)	14.582 (4)	42.019 (1)	31.402 (1)	44.326 (0)	18.255 (3)	19.392 (4)
Significance		**	**	**		
Q Stat. (Lag)	9.532 (12)	14.744 (11)	0.454 (2)	0.009 (1)	12.480 (12)	8.910 (12)
[Probability]	[0.657]	[0.195]	[0.797]	[0.922]	[0.408]	[0.711]
LM Stat. (Lag)	NA	NA	NA	NA	NA	11.986 (12)
[Probability]	NA	NA	NA	NA	NA	[0.447]
Arch (Lag)	4.887 (2)	0.609 (2)	1.064 (1)	0.647 (2)	12.995 (10)	0.801 (1)
[Probability]	[0.087]	[0.737]	[0.302]	[0.724]	[0.224]	[0.371]
Jarque-Bera	1.761	14.445	8.283	1.082	0.839	2.536
[Probability]	[0.415]	[0.001]	[0.016]	[0.582]	[0.657]	[0.281]
Residuals^2						
Q Stat. (Lag)	5.077 (2)	0.636 (2)	1.092 (1)	0.664 (2)	11.295 (10)	0.820 (1)
[Probability]	[0.079]	[0.728]	[0.380]	[0.718]	[0.186]	[0.365]

♦ Schwarz Criterion

Table 3
Continued

Product/Ports Test	Fuel Oil Gulf-Rott 95:5-07.10	Fuel Oil Gulf-Sing 95:5-07:10	Fuel Oil LA-NY 93:10-07:2	Fuel Oil LA-Rott 93:10-07:02	Fuel Oil LA-Sing 93:10-07:02	Fuel Oil NY-Rott 93:10-07:02
ADF (Lag)	-6.111 (0)	-5.662 (1)	-3.770 (12)	-6.956 (0)	-3.284 (11)	-5.102 (3)
Significance	**	**	**	**	*	**
Garch	0,0	0,0	0,0	0,0	3,1	1,1
Johansen (Lag)	37.362 (0)	36.689 (1)	35.170 (12)	46.562 (0)	13.705 (11)	34.031 (3)
Significance	**	**	**	**		**
Q Stat. (Lag)	0.613 (1)	8.256 (7)	0.028 (1)	5.653 (6)	0.827 (1)	11.897 (12)
[Probability]	[0.434]	[0.515]	[0.867]	[0.470]	[0.363]	[0.454]
LM Stat. (Lag)	1.593 (1)	2.099 (1)	7.335 (5)	1.398 (1)	NA	NA
[Probability]	[0.207]	[0.147]	[0.197]	[0.237]	NA	NA
Arch (Lag)	16.886 (12)	0.424 (1)	2.458 (1)	4.062 (4)	17.357 (12)	14.109 (12)
[Probability]	[0.154]	[0.515]	[0.117]	[0.398]	[0.130]	[0.294]
Jarque-Bera	0.918	8.758	7.247	1.675	0.108	1.043
[Probability]	[0.632]	[0.012]	[0.027]	[0.433]	[0.947]	[0.594]
Residuals^2						
Q Stat. (Lag)	17.213 (10)	0.435 (1)	2.525 (1)	4.043 (4)	16.452 (12)	15.620 (11)
[Probability]	[0.070]	[0.510]	[0.112]	[0.400]	[0.171]	[0.156]

Table 3
Continued

Product/Ports Test	Fuel Oil NY-Sing 93:10-07:02	Fuel Oil Rott-Sing 93:10-07:02	Gas Reg Gulf-LA 92:07-07:10	Gas Reg Gulf-NY 92:07-07:10	Gas Reg Gulf-Rott 92:07-07:10	Gas Reg Gulf-Sing 92:07-07:10
ADF (Lag)	-4.617 (7)	-6.218 (0)	-5.262 (3)	-1.187 (11)	-6.218 (4)	-3.956 (2)
Significance	**	**	**		**	**
Garch	2,1	0,0	1,1	1,0	2,2	1,1
Johansen (Lag)	25.881 (7)	45.849 (0)	26.706 (3)	98.923 (0)	39.178 (4)	25.107 (2)
Significance	**	**	**	**	**	**
Q Statistic (Lag)	1.203 (3)	8.030 (9)	4.248 (5)	0.981 (3)	11.868 (12)	0.241 (1)
[Probability]	[0.752]	[0.531]	[0.514]	[0.806]	[0.456]	[0.624]
LM Statistic (Lag)	NA	0.574 (1)	NA	NA	NA	NA
[Probability]	NA	[0.449]	NA	NA	NA	NA
Arch (Lag)	4.304 (4)	0.590 (1)	10.064 (6)	1.353 (3)	0.264 (1)	0.751 (1)
[Probability]	[0.366]	[0.442[	[0.122]	[0.717]	[0.607]	[0.386]
Jarque-Bera	1.918	5.506	27.079	26.330	0.818	0.740
[Probability]	[0.383]	[0.064]	[0.000]	[0.000]	[0.664]	[0.691]
Squared Residuals						
Q Statistic (Lag)	4.605 (4)	0.603 (1)	11.100 (6)	1.412 (3)	0.269 (1)	0.766 (1)
[Probability]	[0.330]	[0.438]	[0.085]	[0.703]	[0.604]	[0.381]

Table 3
Continued

Product/Ports Test	Gas Reg LA-NY 92:07-07:10	Gas Reg LA-Rott 92:07-07:10	Gas Reg LA-Sing 92:07-07:10	Gas-Reg NY-Rott 92:07-07:10	Gas Reg NY-Sing 92:07-07:10	Gas Reg Rott-Sing 92:07-07:10
ADF (Lag)	-5.559 (4)	-5.253 (4)	-3.476 (3)	-5.655 (2)	-3.640 (3)	-4.627 (2)
Significance	**	**	*	**	**	**
Garch	1,1	1,1	1,0	0,0	0,0	2,2
Johansen (Lag)	33.013 (4)	31.022 (4)	15.955 (3)	33.669 (2)	14.610 (3)	20.552 (2)
Significance	**	**		**		*
Q Statistic (Lag)	5.413 (7)	0.122 (1)	11.309 (12)	3.428 (6)	5.489 (7)	13.700 (12)
[Probability]	[0.610]	[0.738]	[0.503]	[0.754]	[0.601]	[0.320]
LM Statistic (Lag)	NA	NA	NA	9.005 (6)	11.741 (6)	NA
[Probability]	NA	NA	NA	[0.173]	[0.068]	NA
Arch (Lag)	12.015 (12)	11.197 (11)	4.523 (3)	5.643 (4)	0.459 (1)	10.593 (8)
[Probability]	[0.444]	[0.427]	[0.209]	[0.227]	[0.498]	[0.226]
Jarque-Bera	12.753	45.804	35.974	215.880	138.815	1.102
[Probability]	[0.002]	[0.000]	[0.000]	[0.000]	[0.000]	[0.576]
Squared Residuals						
Q Statistic (Lag)	10.709 (11)	11.405 (11)	4.836 (3)	5.982 (4)	0.469 (1)	12.839 (8)
[Probability]	[0.468]	[0.410]	[0.184]	[0.200]	[0.493]	[0.118]

Table 3
Continued

Product/Ports Test	Jet Fuel♦ Gulf-LA 90:09-07:10	Jet Fuel Gulf-NY 90:09-07:10	Jet Fuel Gulf-Rott 90:09-07:10	Jet Fuel Gulf-Sing 90:09-07:10	Jet Fuel LA-NY 90:09-07:10	Jet Fuel LA-Rott 90:09-07:10
ADF (Lag)	-10.443 (0)	-3.808 (9)	-6.307 (4)	-3.19 (6)	-4.129 (11)	-4.007 (8)
Significance	**	**	**	*	**	**
Garch	NA	1,1	1,1	1,1	1,1	1,1
Johansen (Lag)	89.076 (0)	33.094 (9)	45.439 (4)	19.578 (5)	27.832 (11)	15.718 (8)
Significance	**	**	**		**	
Q Statistic (Lag)	9.350 (8)	0.529 (1)	2.185	0.165 (1)	0.081 (1)	11.784 (10)
[Probability]	[0.425]	[0.467]	[0.535]	[0.685]	[0.776]	[0.300]
LM Statistic (Lag)	5.538 (4)	NA	NA	NA	NA	NA
[Probability]	[0.236]	NA	NA	NA	NA	NA
Arch (Lag)	4.977 (2)	0.132 (1)	0.092 (1)	4.808 (5)	0.236 (10	0.022 (1)
[Probability]	[0.083]	[0.716]	[0.762]	[0.440]	[0.627]	[0.882]
Jarque-Bera	22.939	752.740	179.996	3.522	8.713	14.139
[Probability]	[0.000]	[0.000]	[0.000]	[0.172]	[0.013]	[0.001]
Squared Residuals						
Q Statistic (Lag)	5.265 (2)	0.135 (1)	0.093 (1)	4.957 (5)	0.241	0.022 (1)
[Probability]	[0.072]	[0.714]	[0.760]	[0.421]	[0.724]	[0.881]

♦ Schwarz criterion.

Table 3
Continued

Product/Ports Test	Jet Fuel LA-Sing 90:09-07:10	Jet Fuel NY Rott 90:9-7:10	Jet Fuel NY-Sing 90:9-07:10	Jet Fuel Rott-Sing 90:9-07:10	Rubber† Malay-U.K. 1-2-74 to 12-26-79	Silver† U.S.-U.K 7-5-72 to 5-28-80	Tin† U.S-U.K 1-2-74 to 7-30-80
ADF (Lag)	-2.186 (10)	-6.319 (5)	-4.342 (5)	-3.852 (2)	-3.789 (0)	-7.995 (3)	-3.781 (1)
Significance		**	**	**	**	**	**
Garch	1,1	0,0	0,0	1,1	2,2	2,2	1,1
Johansen (Lag)	7.322 (10)	40.328 (5)	20.248 (5)	16.461 (2)	15.855 (0)	90.100 (3)	30.895 (1)
Significance		**	*			**	**
Q Statistic (Lag)	0.419 (1)	0.028 (1)	3.479 (8)	0.353 (1)	40.794 (38)	1.237 (2)	1.970 (1)
[Probability]	[0.517]	[0.866]	[0.901]	[0.553]	[0.349]	[0.539]	[0.160]
LM Statistic (Lag)	NA	0.977 (1)	11.695 (11)	NA	NA	NA	NA
[Probability]	NA	[0.323]	[0.387]	NA	NA	NA	NA
Arch (Lag)	1.172 (2)	0.773 (1)	2.316 (2)	0.591 (1)	13.723 (10)	33.459 (31)	3.071 (1)
[Probability]	[0.556]	[0.379]	[0.314]	[0.898]	[0.186]	[0.349]	[0.080]
Jarque-Bera	12.190	231.363	51.778	16.095	8.152	157.383	290.395
[Probability]	[0.002]	[0.000]	[0.000]	[0.000]	[0.017]	[0.000]	[0.000]
Squared Residuals							
Q Statistic (Lag)	1.196 (2)	0.787 (1)	2.435 (2)	0.127 (1)	15.292 (12)	27.601 (31)	3.106 (1)
[Probability]	[0.550]	[0.375]	[0.296]	[0.722]	[0.226]	[0.642]	[0.078]

† Weekly.

Table 3 reports the results from estimating eq. (3) using petroleum products, rubber and metals. In most cases both tests reject the null at 1 percent. But there are twp pair where neither test rejects the null. But if one uses the more conservative Schwarz Information Criteria to select the lag length for them, at least one test rejects the null at the 5 percent level.[12]

Tables 2 and 3 suggest that the thresholds found in the PPP and LOP literature are probably not the result of transportation costs.[13] They are probably the result of using prices that are not for identical commodities and/or not from auction markets.[14] With auction prices and identical products, thresholds are not needed to find strong evidence of cointegration even when transportation costs are omitted.

Rejecting the null of no cointegration is only the first step in estimating half lives. Price differentials also must be stationary.

3.4. Stationarity.

Using the same data as Tables 2 and 3, Tables 4 and 5 report unit root tests for the simple differentials $Ln(p_t^F) - Ln(p_t^D)$. Phillips-Perron tests (PP) for unit roots replace Johansen tests for cointegration. EViews does not support a correction for conditional heteroscedasticity for PP. When probabilities are from EViews, Tables 4 and 5 report those probabilities between brackets. If they are not available, tables report significance levels from EViews using '*' and '**'.

[12] The Schwarz Information Criteria penalizes lags more heavily. Since petroleum products can move in either direction, there is no reason to believe that lags would affect the result.
[13] The threshold literature includes Michael et al (1997), Obstfeld and Taylor (1997), Lo and Zivot (2001), Taylor et al (2001), Sarno et al (2004) and Kiliç, (2009).
[14] Lo and Zivot (2001) also conclude that the thresholds are not the result of transaction costs.

Table 4
Unit Root Tests: Grain Price Differentials with no Freight Rates and Export Price not Lagged

Product/Ports Test	DNS Gulf-Rott 74:1-90:12	DNS Gulf-Rott 89:6-94:10	DNS Gulf-Rott 94:7-01:12	Corn Gulf-Rott 87:4-98:6	DNS Gulf-Japan 75:9-81:10
ADF (Lag)	-1.049 (12)	-2.962 (5)	-5.740 (12)	-4.844 (1)	-3.088 (1)
[Probability] Significance		 *	 **	[0.000]	[0.032]
Garch	1,1	1,1	2,1	0,0	0,0
PP (Lag)	-6.252 (12)	-4.705 (5)	-5.094 (12)	-5.829 (1)	-2.694 (1)
[Probability]	[0.000]	[0.000]	[0.000]	[0.000]	[0.080]
Q Stat. (Lag)	0.403 (1)	0.585 (1)	4.229 (5)	3.603 (4)	18.659 (12)
[Probability]	[0.526]	[0.444]	[0.517]	[0.462]	[0.097]
LM Stat. (Lag)	NA	NA	NA	2.257 (2)	12.259 (12)
[Probability]	NA	NA	NA	[0.323]	[0.140]
Arch Stat. Lag)	11.861 (11)	0.729 (1)	0.709 (1)	2.514 (1)	7.255 (4)
[Probability]	[0.374]	[0.393]	[0.400]	[0.113]	[0.123]
Jarque-Bera	11.077	0.292	1.166	240.20	7.733
[Probability]	[0.004]	[0.864]	[0.558]	[0.000]	[0.021]
Residuals^2					
Q Stat. (Lag)	9.499 (11)	12.674 (11)	0.738 (1)	2.586 (1)	7.750 (4)
[Probability]	[0.576]	[0.315]	[0.390]	[0.108]	[0.101]

* Significant at 5 percent. ** Significant at 1 percent.

Table 4
Continued

Product/Ports Test	HW13 Gulf-Japan 75:9-81:10	DNS Gulf-PP 74:1-99:4	HWO Gulf-PP 74:1-86:4	DNS PP-Japan 75:9-81:10	WW PP-Japan 75:9-81:10
ADF (Lag)	-1.119 (6)	-2.986 (12)	-3.079 (0)	-0.619 (4)	-1.080 (7)
[Probability] Significance	[0.704]		 *	[0.859]	[0.719]
Garch	0,0	1,1	1,0	0,0	0,0
PP (Lag)	-2.861 (6)	-5.370 (12)	-4.529 (1)	-1.554 (4)	-1.061 (7)
[Probability]	[0.055]	[0.000]	[0.000]	[0.501]	[0.727]
Q Stat. (Lag)	0.012 (1)	0.178 (1)	4.580 (4)	5.131 (7)	0.027 (1)
[Probability]	[0.912]	[0.673]	[0.333]	[0644]	[0.869]
LM Stat. (Lag)	5.020 (5)	NA	NA	5.219 (2)	5.708 (7)
[Probability]	[0.413]	NA	NA	[0.074]	[0.574]
Arch Stat. (Lag)	1.338 (1)	7.076 ((8)	1.341 (2)	1.078 (1)	2.477 (1)
[Probability]	[0.247]	[0.528]	[0.512]	[0.299]	[0.116]
Jarque-Bera	32.539	51.290	164.52	5.234	0.416
[Probability]	[0.000]	[0.000]	[0.000]	[0.073]	[0.812]
Residuals^2					
Q Stat. (Lag)	1.413 (1)	5.731(7)	0.983 (2)	1.137 (1)	2.603 (1)
[Probability]	[0.235]	[0.572]	[0.612]	[0.286]	[0.107]

In Table 4, which reports the results of estimating eq. (3) with grain prices, none of the tests for structure in the residuals except the one for normality are significant. Usually at least one test rejects a unit root at the 1 percent level or better. In three cases neither test rejects at 5 percent or better. The three are HW13 between Gulf ports and Japan, DNS between Pacific Ports and Japan, and WW between Pacific ports and Japan. Simply recognizing that commodity arbitrage takes time and lagging the export price by one month produces clear rejection of the null. With export prices lagged one month, PP tests reject the null for HW13 and DNS at the 1 percent level, and WW at the 5 percent level.

Table 5
Unit Root Tests for Price Differentials: Petroleum Products, Rubber and Metals

Product/Ports Test	Diesel Gulf-LA 95:5-07:10	Diesel Gulf-NY 95:5-07:10	Diesel Gulf-Rott 95:5-07.10	Diesel Gulf-Sing 95:5-07:10	Diesel LA-NY 95:5-07:10	Diesel LA-Rott 95:5-07:10
ADF (Lag)	-6.440 (1)	-4.455 (2)	-8.729 (0)	-3.299 (12)	-4.171 (11)	-4.264 (7)
[Probability] Significance	[0.000]	[0.000]	[0.000]	 *	[0.001]	 **
Garch	NA	NA	NA	1,1	NA	2,2
PP (Lag)	-9.340 (1)	-9.039 (2)	-8.728 (1)	-6.070 (4)	-10.38 (11)	-8.940 (11)
[Probability]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Q Stat. (Lag)	6.903 (7)	0.029 (1)	12.836 (10)	0.470 (2)	0.094 (2)	0.698 (2)
[Probability]	[0.438]	[0.865]	[0.233]	[0.791]	[0759]	[0.705]
LM Stat. (Lag)	7.901 (7)	1.210 (1)	13.607 (10)	NA	3.993 (3)	NA
[Probability]	[0.341]	[0.271]	[0.192]	NA	[0.262]	NA
Arch Stat. (Lag)	1.860 (2)	0.038 (1)	0.195 (1)	0.219 (1)	4.075 (2)	6.121 (5)
[Probability]	[0.394]	[0.846]	[0.658]	[0.639]	[0.130]	[0.295]
Jarque-Bera	8.126	1574.8	1088.3	18.009	4.582	3,230
[Probability]	[0.000]	[0.000]	[0.000]	[0.000]	[0.101]	[0.199]
Residuals^2						
Q Stat. (Lag)	2.026 (2)	0.039 (1)	0.201 (1)	0.225 (1)	4.221 (2)	3.439 (5)
[Probability]	[0.363]	[0.844]	[0.654]	[0.635]	[0.121]	[0.633]

* Significant at 5 percent. ** Significant at 1 percent.

Table 5
Continued

Product/Ports Test	Diesel LA-Sing 95:5-07:10	Diesel NY-Rott 95:5-07:10	Diesel NY-Sing 95:5-07:10	Diesel Rott-Sing 95:5-07:10	Fuel Oil Gulf-LA 93:10-07:2	Fuel Oil Gulf-NY 93:10-07:2
ADF (Lag)	-6.082 (6)	-5.728 (1)	-3.450 (12)	-3.593 (8)	-2.710 (5)	-3.902 (4)
[Probability] Significance	**	**	*	**		[0.003]
Garch	1,1	1,1	1,1	2,2	1,1	NA
PP (Lag)	-8.264 (12)	-9.060 (1)	-6.754 (1)	-6.899 (1)	-6.416 (5)	-7.657 (4)
[Probability]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Q Stat. (Lag)	0.8181 (1)	14.428 (11)	0.253 (2)	0.061 (1)	0.076 (1)	8.529 (12)
[Probability]	[0.366]	[0.210]	[0.881]	[0.805]	[0.783]	[0.743]
LM Stat. (Lag)	NA	NA	NA	NA	NA	1.267 (2)
[Probability]	NA	NA	NA	NA	NA	[0.530]
Arch Stat. (Lag)	7.522 (7)	0.600 (2)	1.673 (1)	4.633 (9)	11.242 (10)	0.676
[Probability]	[0.377]	[0.741]	[0.196]	[0.865]	[0.339]	[0.414]
Jarque-Bera	4.963	15.294	12.945	1.421	1.510	2.483
[Probability]	[0.084]	[0.000]	[0.002]	[0.491]	[0.470]	[0.289]
Residuals^2						
Q Stat. (Lag)	12.836 (12)	0.623 (2)	1.718 (1)	4.546 (9)	4.627 (4)	0.693 (1)
[Probability]	[0.381]	[0.732]	[0.326]	[0.872]	[0.328]	[0.405]

Table 5
Continued

Product/Ports Test	Fuel Oil Gulf-Rott 95:5-07.10	Fuel Oil Gulf-Sing 95:5-07:10	Fuel Oil LA-NY 93:10-07:02	Fuel Oil LA-Rott 93:10-07:02	Fuel Oil LA-Sing 93:10-07:02	Fuel Oil NY-Rott 93:10-07:02
ADF (Lag)	-3.546 (3)	-5.270 (1)	-1.551 (11)	-4.205 (0)	-3.467 (1)	-5.005 (3)
[Probability] Significance	**	[0.000]	[0.505]	[0.002]	[0.013]	**
Garch	1,1	NA	NA	NA	NA	1,1
PP (Lag)	-5.969 (1)	-6.660 (1)	-7.126 (11)	-4.081 (1)	-6.085 (1)	-8.258 (3)
[Probability]	[0.000]	[0.000]	[0.000]	[0.002]	[0.000]	[0.000]
Q Stat. (Lag)	13.736 (12)	8.042 (6)	0.090 (1)	2.223 (2)	2.292 (4)	11.295 (11)
[Probability]	[0.318]	[0.235]	[0.764]	[0.329]	[0.682]	[0.419]
LM Stat. (Lag)	NA	2.861 (1)	2.837 (1)	2.225 (1)	1.537 (4)	NA
[Probability]	NA	[0.091]	[0.092]	[0.136]	[0.338]	NA
Arch Stat. (Lag)	0.613 (1)	1.141 (1)	0.723 (1)	1.587 (1)	3.383 (4)	13.175 (12)
[Probability]	[0.454]	[0.708]	[0.395]	[0.208]	[0.496]	[0.356]
Jarque-Bera	1.459	14.645	7.458	0.476	3.412	1.754
[Probability]	[0.482]	[0.001]	[0.024]	[0.788]	[0.182]	[0.416]
Residuals^2						
Q Stat. (Lag)	0.626 (1)	0.144 (1)	0.736 (1)	1.376 (1)	3.094 (4)	15.127 (11)
[Probability]	[0.429]	[0.704]	[0.391]	[0.241]	[0.542]	[0.177]

Table 5
Continued

Product/Ports Test	Fuel Oil NY-Sing 93:10-07:02	Fuel Oil Rott-Sing 93:10-07:02	Gas Reg Gulf-LA 92:7-07:10	Gas Reg Gulf-NY 92:7-07:10	Gas Reg Gulf-Rott 92:7-07:10	Gas Reg Gulf-Sing 92:7-07:10
ADF (Lag)	-3.526 (7)	-1.981 (9)	-5.290 (3)	-1.340 (11)	-6.142 (4)	-4.319 (2)
[Probability] Significance	[0.008]	[0.295]	**		**	**
Garch	NA	NA	1,1	1,1	1,1	NA
PP (Lag)	-6.014 (7)	-5.411 (9)	-10.136 (3)	-11.107 (11)	-10.238 (4)	-8.375 (3)
[Probability]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Q Stat. (Lag)	0.004 (1)	0.061 (1)	4.345 (5)	7.368 (10)	0.541 (1)	0.232 (1)
[Probability]	[0.951]	[0.804]	[0.500]	[0.690]	[0.462]	[0.630]
LM Stat. (Lag)	12.687 (12)	8.796 (7)	NA	NA	NA	NA
[Probability]	[0.392]	[0.268]	NA	NA	NA	NA
Arch Stat. (Lag)	10.580 (8)	5.614 (8)	9.600 (6)	1.782 (3)	0.104 (1)	4.105 (5)
[Probability]	[0.227]	[0.690]	[0.142]	[0.619]	[0.747]	[0.534]
Jarque-Bera	18.293	86.376	28.963	20.746	0.348	2.377
[Probability]	[0.000]	[0.000]	[0.000]	[0.000]	[0.840]	[0.305]
$Residuals^2$						
Q Stat. (Lag)	10.860 (8)	5.663 (8)	10.583 (6)	1.862	0.106 (1)	4.431 (5)
[Probability]	[0.177]	[0.685]	[0.102]	[0.602]	[0.744]	[0.489]

Table 5
Continued

Product/Ports Test	Gas Reg LA-NY 92:7-07:10	Gas Reg LA-Rott 92:7-07:10	Gas Reg LA-Sing 92:7-07:10	Gas-Reg NY-Rott 92:7-07:10	Gas Reg NY-Sing 92:7-07:10	Gas Reg Rott-Sing 92:7-07:10
ADF (Lag)	-6.456 (4)	-5.233 (4)	-3.096 (3)	-5.511 (2)	-3.601 (3)	-4.708 (2)
[Probability] Significance	**	**	*	[0.000]	[0.007]	**
Garch	1,1	1,1	1,1	NA	NA	2,2
PP (Lag)	-10.748 (4)	-9.987 (4)	-8.898 (3)	-10.087 (2)	-8.748 (3)	-6.617 (2)
[Probability]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Q Stat. (Lag)	6.030 (8)	0.344 (2)	12.981 (12)	4.196 (7)	5.454 (7)	13.757 (12)
[Probability]	[0.644]	[0.842]	[0.370]	[0.757]	[0.605]	[0.317]
LM Stat. (Lag)	NA	NA	NA	8.976 (7)	11.522 (6)	NA
[Probability]	NA	NA	NA	[0.254]	[0.074]	NA
Arch Stat. (Lag)	11.408 (11)	0.120 (1)	0.848 (1)	6.223 (4)	0.382 (1)	9.118 (8)
[Probability]	[0.410]	[0.729]	[0.357]	[0.183]	[0.536]	[0.332]
Jarque-Bera	15.379	27.483	25.503	182.50	175.46	1.494
[Probability]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.473]
$Residuals^2$						
Q Stat. (Lag)	10.791 (11)	13.265 (11)	0.865 (1)	6.670 (4)	0.390 (1)	9.786 (8)
Probability]	[0.461]	[0.276]	[0.352]	[0.154]	[0.532]	[0.280]

Table 5
Continued

Product/Ports Test	Jet Fuel Gulf-LA 90:9-07:10	Jet Fuel Gulf-NY 90:9-07:10	Jet Fuel Gulf-Rott 90:9-07:10	Jet Fuel Gulf-Sing 90:9-07:10	Jet Fuel LA-NY 90:9-07:10	Jet Fuel LA Rott 90:9-07:10
ADF (Lag)	-2.621 (8)	-3.053 (9)	-5.817	-4.126 (4)	-3.962 (11)	-3.661 (8)
[Probability] Significance	[0.090]	*	**	**	**	**
Garch	NA	1,1	2,2	1,1	1,1	1,1
PP (Lag)	-10.352 (8)	-12.028 (5)	-9.865 (4)	-6.962 (10)	-11.179 (1)	-9.496 (8)
[Probability]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Q Stat. (Lag)	0.046 (1)	0.343 (1)	0.570 (1)	0.592 (1)	0.090 (1)	9.704 (10)
[Probability]	[0.831]	[0.558]	[0.450]	[0.442]	[0.764]	[0.467]
LM Stat. (Lag)	1.924 (1)	NA	NA	NA	NA	NA
[Probability]	[0.165]	NA	NA	NA	NA	NA
Arch Stat. (Lag)	6.691 (3)	0.130 (1)	0.528 (1)	3.879 (4)	0.284 (1)	0.027 (1)
[Probability]	[0.082]	[0.719]	[0.467]	[0.422]	[0.594]	[0.869]
Jarque-Bera	30.170	651.89	120.19	3.440	8.656	16.772
[Probability]	[0.000]	[0.000]	[0.000]	[0.179]	[0.013]	[0.000]
Residuals^2						
Q Stat. (Lag)	6.688 (3)	0.132 (1)	0.538 (1)	0.461 (1)	0.289 (1)	0.027 (1)
[Probability]	[0.094]	[0.716]	[0.463]	[0.497]	[0.591]	[0.868]

Table 5
Continued

Product/Ports Test	Jet Fuel LA-Sing 90:9-07:10	Jet Fuel NY Rott 90:9-7:10	Jet Fuel NY-Sing 90:9-07:10	Jet Fuel Rott-Sing 90:9-07:10	Rubber† Malay-U.K. 1-2-74 to 12-26-79	Silver† U.S.-U.K 7-5-72 to 5-28-80	Tin† U.S-U.K 1-2-74 to 7-30-80
ADF (Lag)	-2.139 (10)	-6.317 (5)	-4.245 (5)	-2.044 (9)	-3.210 (0)	-7.683 (3)	-3.684 (1)
[Probability] Significance		[0.000]	[0.001]		*	**	**
Garch	1,1	NA	NA	1,1	2,2	2,2	2,2
PP (Lag)	-7.260 (10)	-10.952 (5)	-8.362 (5)	-7.235 (12)	-2.859 (3)	-14.869 (8)	-8.187 (6)
[Probability]	[0.000]	[0.000]	[0.000]	[0.000]	[0.051]	[0.000]	[0.000]
Q Stat. (Lag)	0.413 (1)	0.028 (1)	11.179 (11)	0.315 (1)	1.212 (1)	15.357 (15)	3.103 (1)
[Probability]	[0.520]	[0.866]	[0.428]	[0.575]	[0.271]	[0.426]	[0.078]
LM Stat. (Lag)	NA	0.979 (1)	11.795 (11)	NA	NA	NA	NA
[Probability]	NA	[0.322]	[0.379]	NA	NA	NA	NA
Arch (Lag)	1.062 (2)	0.771 (1)	2.129 (2)	0.090 (1)	14.546 (12)	60.135 (49)	1.262 (1)
[Probability]	[0.588]	[0.380]	[0.345]	[0.764]	[0.265]	[0.132]	[0.261]
Jarque-Bera	13.580	239.49	53.174	9.167	7.514	107.610	251.258
[Probability]	[0.000]	[0.000]	[0.000]	[0.010]	[0.023]	[0.000]	[0.000]
Residuals^2							
Q Stat. (Lag)	1.083 (2)	0.786 (1)	2.240 (2)	0.092 (1)	17.174 (13)	10.577 (9)	1.276 (1)
[Probability]	[0.582]	[0.375]	[0.762]	[0.762]	[0.191]	[0.306]	[0.259]

† Weekly data, Wednesday.

In Table 5, which reports the results of estimating eq. (3) with the other prices, none of the error tests except the one for normality are significant. Except for Rubber, at least one test rejects a unit root at the 1 percent level. Often both tests reject at the 1 percent level. For Rubber only one test rejects and it at only 5 percent. That relatively weak rejection is probably because rubber prices are not for identical products.

Rejecting a unit root for price differentials provides only weak support for the efficacy of international auction markets. Differentials could be stationary, but half lives so long that the LOP is irrelevant. The next subsection reports estimates of half lives.

3.5. Half Lives.

Following Andrews (1993), I estimate half lives using eq. (4).

$$X_t = \alpha + \beta X_{t-1} + \sum_{i=1}^{N} \gamma_i \Delta X_{t-i} \qquad (4)$$

X_t is the price differential measured as either $Ln(p_t^F) - Ln(p_t^D)$ or $Ln(p_{t+1}^F) - Ln(p_t^D + f_{t-1})$. When X_t is AR(1), I calculate half lives using Ln(0.5)/Ln(β). When X_t is AR(2) or longer, I calculate half lives using impulse responses as Murray and Papell (2002) suggest.

Table 6 reports estimates of eq. (4) using $Ln(p_t^F) - Ln(p_t^D)$ and grain prices. To save space, I report only the first six lags. I also report the number of any additional lags. Among the residual tests, only Jarque-Bera tests are ever significant. Table 7 reports the same estimates for grain prices using $Ln(p_{t+1}^F) - Ln(p_t^D + f_{t-1})$. Again only Jarque-Bera tests for normality are significant.

Table 6
Estimates of Equation 4:
Grain Price Differentials without Freight Rates or Lagged Export Prices

Product/Ports Estimate	WW PP-Japan 75:9-81:10	DNS PP-Japan 75:9-81:10	DNS Gulf-Japan 75:9-81:10	HW13 Gulf-Japan 75:9-81:10	DNS Gulf-PP 74:1-99:12
β	0.949	0.722	0.801	0.825	0.799
(Standard Error)	(0.040)	(0.092)	(0.059)	(0.078)	(0.044)
Garch	NA	1,1	1,1	1,1	1,1
γ (Lag)			-0.257 (1)	-0.339 (6)	-0.171 (3)
(Standard Error)			(0.114)	(0.134)	(0.067)
γ (Lag)			0.339 (12)		-0.176 (4)
(Standard Error)			(0.114)		(0.059)
γ (Lag)					-0.268 (5)
(Standard Error)					(0.068)
γ (Lag)					-0.156 (6)
(Standard Error)					(0.05)
γ (Lag)					0.195 (7)
(Standard Error)					(0.070)
Additional Lags	0	0	0	0	3
Q Stat. (Lag)	2.119 (1)	0.609 (11)	6.208 (4)	1.264 (1)	0.025 (1)
[Probability]	[0.145]	[0.435]	[0.184]	[0.261]	[0.874]
LM Stat. (Lag)	2.322 (1)	NA	NA	NA	NA
[Probability]	[0.128]	NA	NA	NA	NA
Arch Stat. (Lag)	6.236 (4)	0.319 (11)	9.169 (5)	9.958 (10)	5.658 (8)
[Probability]	[0.182]	[0.572]	[0.102]	[0.476]	[0.685]
Jarque-Bera	1.508	0.832	20.296	21.464	69.433
[Probability]	[0.471]	[0.660]	[0.000]	[0.000]	[0.000]
Residuals^2					
Q Stat. (Lag)	3.683 (4)	10.673 (11)	5.093 (4)	0.316 (1)	5.726 (8)
[Probability]	[0.451]	[0.471]	[0.278]	[0.574]	[0.678]

Table 6
Continued

Product/Ports Estimate	HWO Gulf-PP 87:1-98:6	DNS Gulf-Rott 74:1-90:12	DNS* Gulf-Rott 89:6-94:4	DNS Gulf-Rott 94:7-01:12	Corn Gulf-Rott 87:1:98:06
β	0.778	0.680	0.294	0.683	0.624
(Standard Error)	(0.072)	(0.056)	(0.122)	(0.087)	(0.078)
Garch	1,0	1,1	NA	2,2	NA
γ (Lag)		0.119 (12)	-0.335 (5)		-0.131 (1)
(Standard Error)		(0.065)	(0.114)		(0.084)
γ (Lag)			-0.223 (6)		
(Standard Error)			(0.120)		
Q Statistic (Lag)	4.580 (4)	0.093 (1)	4.144 (4)	6.351 (7)	3.603 (4)
[Probability]	[0.462]	[0.761]	[0.387]	[0.499]	[0.462]
LM Stat. (Lag)	2.257 (2)	NA	9.994 (6)	NA	2.257 (2)
[Probability]	[0.323]	NA	[0.125]	NA	[0.323]
Arch Stat. (Lag)	2.514 (1)	5.648 (7)	10.629 (9)	6.360 (5)	2.514 (1)
[Probability]	[0.113]	[0.581]	[0.302]	[0.498]	[0.113]
Jarque-Bera	240.196	16.587	2.425	5.852	240.196
[Probability]	[0.000]	[0.000]	[0.297]	[0.054]	[0.000]
Residuals^2					
Q Stat. (Lag)	2.586 (1)	5.315 (7)	10.307 (9)	3.890 (5)	2.586 (1)
[Probability]	[0.108]	[0.622]	[0.326]	[0.565]	[0.108]

*Rotterdam wheat prices are from U.S. Department of Agriculture.

Table 7
Estimates of Equation 4: Grain Prices with Freight Rates and Lagged Export Prices

Product/Ports Estimate	WW PP-Japan 75:9-81:10	DNS PP-Japan 75:9-81:10	DNS Gulf-Japan 75:9-81:10	HW13 Gulf-Japan 75:9-81:10	DNS Gulf-PP 74:1-99:12
β	0.491	0.481	0.436	0.392	0.583
(Standard Error)	(0.105)	(0.118)	(0.123)	(0.110)	(0.096)
Garch	0,0	1,1	2,2	0,0	0,0
γ (Lag)			0.114 (1)		
(Standard Error)			(0.123)		
Q Statistic (Lag)	5.616 (6)	0.162 (1)	19.793 (12)	11.294 (7)	11.002 (12)
[Probability]	[0.468]	[0.687]	[0.071]	[0.126]	[0.529]
LM Stat. (Lag)	0.801 (6)	NA	NA	1.366 (6)	0.501 (2)
[Probability]	[0.573]	NA	NA	[0.236]	[0.608]
Arch Stat. (Lag)	2.407 (2)	0.248 (1)	0.412 (1)	1.278 (10)	1.637 (11)
[Probability]	[0.098]	[0.602]	[0.523]	[0.268]	[0.116]
Jarque-Bera	1.513	2.908	2.418	0.907	1.951
[Probability]	[0.469]	[0.234]	[0298]	[0.635]	[0.377]
Residuals^2					
Q Stat. (Lag)	5.373 (2)	0.268 (1)	0.443 (1)	0.664 (1)	16.190 (11)
[Probability]	[0.068]	[0.605]	[0.506]	[0.415]	[0.134]

Table 7
Continued

Product/Ports Estimate	HWO Gulf-PP 87:1-98:6	DNS Gulf-Rott 74:1-90:12	DNS* Gulf-Rott 89:6-94:4	DNS Gulf-Rott 94:7-01:12	Corn Gulf-Rott 87:1:98:06
β	0.543	0.496	0.482	0.553	0.444
(Standard Error)	(0.085)	(0.064)	(0.109)	(0.081)	(0.084)
Garch	0,1	1,1	0,0	1,1	0,0
γ (Lag)		0.030*	0.273 (1)		-0.196 (2)
(Standard Error)		(0.012)	(0.123)		(0.075)
γ (Lag)					
(Standard Error)					
Q Stat. (Lag)	3.714 (3)	17.559 (12)	9.898 (5)	2.903 (3)	0.223 (1)
[Probability]	[0.294]	[0.130]	[0.078]	[0.407]	[0.637]
LM Stat. (Lag)	NA	NA	2.012 (1)	NA	0.198 (1)
[Probability]	NA	NA	[0.161]	NA	[0.161]
Arch Stat. (Lag)	1.512 (4)	1.279 (2)	1.768 (11)	0.929 (1)	0.754 (1)
[Probability]	[0.209]	[0.281]	[0.082]	[0.338]	[0.387]
Jarque-Bera	0.790	3.741	2.232	2.104	61.199
[Probability]	[0.674]	[0.154]	[0.328]	[0.349]	[0.000]
$Residuals^2$					
Q Stat. (Lag)	3.262 (2)	2.175 (2)	12.489 (11)	0.951 (1)	0.781 (1)
[Probability]	[0.196]	[0.337]	[0.328]	[0.330]	[0.377]

*Rotterdam wheat prices are from U.S. Department of Agriculture and there is a September dummy..

Table 8
Estimates of Equation 4: Petroleum Products, Rubber and Metals

Product/Ports Estimate	Diesel Gulf-LA 95:5-07:10	Diesel Gulf-NY 95:5-07:10	Diesel Gulf-Rott 95:5-07:10	Diesel Gulf-Sing 95:5-07:10	Diesel LA-NY 95:5-07:10	Diesel LA-Rott 95:5-07:10	Diesel LA-Sing 95:5-07:10
β	0.259	0.432	0.318	0.556	0.116	0.297	0.438
(Standard Error)	(0.079)	(0.097)	(0.078)	(0.077)	(0.076)	(0.076)	(0.068)
Garch	NA	NA	NA	1,1	2,2	2,2	3,3
γ (Lag)		-0.202 (1)					
(Standard Error)		[0.082]					
Additional Lags	0	0	0	0	0	0	0
Q Stat. (Lag)	6.504 (4)	2.239 (3)	12.836 (10)	11.588 (10)	7.980 (7)	10.794 (7)	16.571 (11)
[Probability]	[0.165]	[0.524]	[0.233]	[0.314]	[0.334]	[0.148]	[0.121]
LM Stat. (Lag)	8.714 (4)	3.460 (1)	13.608 (10)	NA	NA	NA	NA
[Probability]	[0.069]	[0.063]	[0.192]	NA	NA	NA	NA
Arch Stat. (Lag)	3.893 (2)	0.510 (2)	0.195 (1)	0.181 (1)	0.300 (1)	4.300 (9)	5.309 (9)
[Probability]	[0.143]	[0.775]	[0.658]	[0.671]	[0.584]	[0.507]	[0.505]
Jarque-Bera	18.412	1465.63	1088.2	41.603	1.097	5.034	1.260
[Probability]	[0.000]	[0.000]	[0.000]	[0.000]	[0.578]	[0.081]	[0.532]
$Residuals^2$							
Q Stat. (Lag)	4.258 (2)	0.536 (2)	0.201 (1)	0.185 (1)	0.307 (1)	9.033 (9)	9.780 (9)
[Probability]	[0.119]	[0.765]	[0.654]	[0.667]	[0.579]	[0.434]	[0.369]

Table 8
Continued

Product/Ports Estimate	Diesel NY-Rott 95:5-07:10	Diesel NY-Sing 95:5-07:10	Fuel Oil Gulf-LA 93:10-07:2	Fuel Oil Gulf-NY 93:10-07:2	Fuel Oil Gulf-Rott 93:10-07:2	Fuel Oil Gulf-Sing 93:10-07:2	Fuel Oil LA-NY 93:10-07:2
β	0.426	0.546	0.793	0.627	0.691	0.604	0.732
(Standard Error)	(0.100)	(0.818)	(0.083)	(0.096)	(0.059)	(0.075)	(0.092)
Garch	1,1	1,1	1,1	NA	1,1	NA	NA
γ (Lag)	-0.164 (?)		-0.355 (1)	-0.345 (1)		-0.153 (1)	-0.283 (1)
(Standard Error)	(0.097)		(0.095)	(0.104)		[0.078]	(0.102)
γ (Lag)			-0.288 (2)	-0.194 (2)			-0.268 (2)
(Standard Error)			(0.097)	(0.100)			(0.092)
γ (Lag)			-0.198 (3)	-0.167 (3)			-0.150 (3)
(Standard Error)			(0.096)	(0.094)			(0.083)
γ (Lag)				-0.082 (4)			0.188 (11)
(Standard Error)				(0.079)			(0.069)
Additional Lags	0	0	0	0	0	0	0
Q Stat. (Lag)	14.428 (11)	8.980 (5)	0.072 (?)	8.529 (12)	1.618 (1)	8.042 (6)	10.378 (10)
[Probability]	[0.210]	[0.395]	[0.789]	[0.743]	[0.203]	[0.235]	[0.408]
LM Stat. (Lag)	NA	NA	NA	1.269 (2)	NA	2.861 (1)	7.213 (5)
[Probability]	NA	NA	NA	[0.530]	NA	[0.091]	[0.205]
Arch Stat. (Lag)	0.600 (2)	4.219 (6)	0.434 (8)	0.676 (1)	6.531 (5)	0.141 (1)	3.318 (2)
[Probability]	[0.741]	[0.647]	[0.392]	[0.411]	[0.258]	[0.708]	[0.190]
Jarque-Bera	15.294	10.336	2.207	2.483	1.361	14.645	6.253
[Probability]	[0.000]	[0.006]	[0.332]	[0.289]	[0.506]	[0.000]	[0.044]
Residuals^2							
Q Stat. (Lag)	0.623 (2)	4.378 (6)	13.285 (11)	0.692 (1)	8.105 (5)	0.144 (1)	3.695 (2)
[Probability]	[0.732]	[0.447]	[0.275]	[0.405]	[0.151]	[0.158]	[0.158]

Table 8
Continued

Product/Ports Estimate	Fuel Oil LA-Rott 93:10-07:2	Fuel Oil LA-Sing 93:10-07:2	Fuel-Oil NY-Rott 93:10-07:2	Fuel-Oil NY-Sing 93:10-07:2	Fuel-Oil Rott-Sing 93:10-07:2
β	0.789	0.562	0.373	0.687	0.687
(Standard Error)	(0.069)	(0.139)	(0.075)	(0.090)	(0.058)
Garch	NA	1,1	NA	NA	NA
γ (Lag)	-0.245 (1)	-0.216 (1)	0.216 (11)	-0.212 (1)	
(Standard Error)	(0.089)	(0.152)	(0.064)	(0.097)	
γ (Lag)	-0.106 (2)	-0.222 (2)		-0.212 (2)	
(Standard Error)	(0.082)	(0.123)		(0.086)	
γ (Lag)		-0.163 (3)		-0.224 (3)	
(Standard Error)		(0.104)		(0.078)	
γ (Lag)		-0.181 (4)		0.159 (7)	
(Standard Error)		(0.096)		(0.070)	
Additional Lags	0	0	0	0	0
Q Stat. (Lag)	6.001 (7)	9.678 (12)	0.344 (1)	5.627 (9)	8.468 (6)
[Probability]	[0.540]	[0.644]	[0.557]	[0.777]	[0.206]
LM Stat. (Lag)	8.696 (4)	NA	3.887 (2)	0.343 (1)	10.242 (6)
[Probability]	[0.069]	NA	[0.144]	[0.558]	[0.115]
Arch Stat. (Lag)	3.462 (5)	19.244 (12)	11.900 (11)	9.947 (8)	6.520 (9)
[Probability]	[0.629]	[0.083]	[0.371]	[0.269]	[0.687]
Jarque-Bera	1.282	7.629	0.878	19.905	27.852
[Probability]	[0.527]	[0.022]	[0.644]	[0.000]	[0.000]
Residuals^2					
Q Stat. (Lag)	3.102 (5)	16.219 (12)	13.790 (11)	10.745 (8)	7.272 (8)
[Probability]	[0.684]	[0.181]	[0.245]	[0.217]	[0.508]

Table 8
Continued

Product/Ports Estimate	Gas Reg Gulf-La 92:07-07:10	Gas Reg ♦ Gulf-NY 92:07-07:10	Gas Reg Gulf-Rott 92:07-07:10	Gas Reg Gulf-Sing 92:07-07:10	Gas Reg LA-NY 92:07-07:10
β	0.327	0.468	0.390	0.636	0.286
(Standard Error)	(0.127)	(0.110)	(0.068)	(0.084)	(0.076)
Garch	1,1	1,1	2,2	1,1	1,1
γ (Lag)	-0.054 (1)	-0.156 (1)	0.196 (3)	-0.250 (1)	0.079 (4)
(Standard Error)	(0.123)	(0.079)	(0.055)	(0.084)	(0.060)
γ (Lag)	-0.029 (2)	0.160 (12)	0.113 (4)	-0.193 (2)	
(Standard Error)	(0.114)	(0.051)	(0.047)	(0.075)	
γ (Lag)	-0.024 (3)				
(Standard Error)	(0.089)				
Additional Lags	0	0	0	0	0
Q Stat. (Lag)	4.345 (5)	10.964	8.163 (6)	0.232 (1)	4.969 (5)
[Probability]	[0.501]	[0.089]	[0.226]	[0.630]	[0.420]
LM Stat. (Lag)	NA	NA	NA	NA	NA
[Probability]	NA	NA	NA	NA	NA
Arch Stat. (Lag)	9.600 (6)	1.028 (1)	2.348 (4)	4.105 (5)	11.626 (12)
[Probability]	[0.143]	[0.311]	[0.672]	[0.534]	[0.476]
Jarque-Bera	28.963	19.284	0.252	2.377	13.277
[Probability]	[0.000]	[0.000]	[0.881]	[0.305]	[0.000]
Residuals^2					
Q Stat. (Lag)	10.583 (6)	1.049 (1)	2.610 (4)	4.431 (5)	11.000 (11)
[Probability]	[0.102]	[0.306]	[0.625]	[0.489]	[0.443]

♦ Schwarz Criterion

Table 8
Continued

Product/Ports Estimate	Gas Reg LA-Rott 92:07-07:10	Gas Reg LA-Sing 92:07-07:10	Gas-Reg NY-Rott 92:07-07:10	Gas Reg NY-Sing 92:07-07:10	Gas Reg Rott-Sing 92:07-07:10
β	0.375	0.722	0.281	0.687	0.666
(Standard Error)	(0.086)	(0.090)	(0.071)	(0.093)	(0.071]
Garch	1,1	1,1	NA	NA	2,2
γ (Lag)		-0.388 (1)		-0.427 (1)	-0.196 (1)
(Standard Error)		(0.110)		(0.102)	(0.080]
γ (Lag)		-0.237 (2)		-0.392 (2)	-0.131 (2)
(Standard Error)		(0.109)		(0.100)	[0.059]
γ (Lag)		-0.196 (3)		-0.228 (3)	
(Standard Error)		(0.087)		(0.091)	
γ (Lag)				-0.099 (4)	
(Standard Error)				(0.075)	
γ (Lag)				-0.122 (6)	
(Standard Error)				(0.060)	
Additional Lags	0	0	0	0	0
Q Stat. (Lag)	3.644 (5)	12.981 (12)	5.018 (3)	0.024 (1)	13.757 (12)
[Probability]	[0.602]	[0.370]	[0.170]	(0.877)	[0.317]
LM Stat. (Lag)	NA	NA	5.104 (3)	4.551 (2)	NA
[Probability]	NA	NA	[0.164]	[0.103]	NA
Arch Stat. (Lag)	15.279 (11)	0.848 (1)	6.526 (4)	0.400 (1)	9.118 (8)
[Probability]	(0.170)	[0.370]	[0.163]	[0.527]	[0.332]
Jarque-Bera	33.718	25.503	142.417	113.846	1.494
[Probability]	[0.000]	[0.000]	[0.000]	[0.000]	[0.473]
Residuals^2					
Q Stat. (Lag)	16.939 (11)	0.866 (1)	6.858 (4)	0.409 (1)	9.786 (8)
[Probability]	[0.110]	[0.352]	[0.144]	[0.523]	[0.280]

Table 8
Continued

Product/Ports Estimate	Jet Fuel Gulf-LA 90:09-07:10	Jet Fuel Gulf-NY 90:09-07:10	Jet Fuel Gulf-Rott 90:09-07:10	Jet Fuel Gulf-Sing 90:09-07:10	Jet Fuel LA-NY 90:09-07:10
β	0.651	0.334	0.361	0.696	0.357
(Standard Error)	[0.100]	(0.065)	(0.112)	(0.058)	(0.079)
Garch	1,1	1,1	2,2	1,1	1,1
γ (Lag)	-0.251 (1)				0.087 (9)
(Standard Error)	[0.099]				(0.952)
γ (Lag)	-0.205 (2)				
(Standard Error)	[0.058]				
γ (Lag)	-0.140 (30				
(Standard Error)	[0.089]				
γ (Lag)	-0.122 (6)				
(Standard Error)	[0.058]				
Additional Lags	0	0	0	0	0
Q Stat. (Lag)	5.704 (8)	12.176 (11)	3.877 (4)	15.235 (11)	13.388 (12)
[Probability]	[0.680]	[0.351]	(0.423)	[0.172]	[0.341]
LM Stat. (Lag)	NA	NA	NA	NA	NA
[Probability]	NA	NA	NA	NA	NA
Arch Stat. (Lag)	3.324 (3)	0.018 (1)	0.375 (1)	0.524 (1)	16.966 (12)
[Probability]	[0.344]	[0.892]	[0.540]	[0.469]	[0.151]
Jarque-Bera	23.712	864.726	326.546	6.586	15.934
[Probability]	[0.000]	[0.000]	[0.000]	[0.032]	[0.000]
Residuals^2					
Q Stat. (Lag)	3.611 (3)	0.019 (1)	0.382 (1)	0.534 (1)	19.348 (12)
[Probability]	[0.307]	[0.891]	[0.537]	[0.465]	[0.080]

Table 8
Continued

Product/Ports Estimate	Jet Fuel LA Rott 90:9-07:10	Jet Fuel LA-Sing 90:9-07:10	Jet Fuel NY Rott 90:9-7:10	Jet Fuel NY-Sing 90:9-07:10	Jet Fuel Rott-Sing 90:9-07:10
β	0.467	0.687	0.276	0.629	0.805
(Standard Error)	(0.073)	(0.059)	(0.066)	(0.117)	(0.051)
Garch	1,1	1,1	NA	NA	1,1
γ (Lag)	-0.149 (2)	0.069 (7)		-0.162 (1)	
(Standard Error)	(0.080)	(0.056)		(0.092)	
γ (Lag)		0.116 (11)		-0.147 (2)	
(Standard Error)		(0.055)		(0.089)	
γ (Lag)		0.122 (12)		-0.173 (3)	
(Standard Error)		(0.054)		(0.083)	
γ (Lag)				-0.095 (4)	
(Standard Error)				(0.075)	
γ (Lag)				0.005 (5)	
(Standard Error)				(0.066)	
Additional Lags	0	0	0	0	0
Q Stat. (Lag)	5.441 (7)	11.883 (9)	4.548 (6)	11.179 (11)	0.384 (1)
[Probability]	[0.606]	[0.220]	[0.603]	[0.428]	[0.536]
LM Stat. (Lag)	NA	NA	0.754 (1)	2.956 (3)	NA
[Probability]	NA	NA	[0.385]	[0.398]	NA
Arch Stat. (Lag)	0.040 (1)	3.478 (4)	1.670 (1)	2.129 (2)	0.220 (1)
[Probability]	[0.841]	[0.487]	[0.196]	[0.345]	[0.639]
Jarque-Bera	68.717	3.410	181.830	53.174	13.369
[Probability]	[0.000]	[0.182]	[0.000]	[0.000]	[0.001]
Residuals^2					
Q Stat. (Lag)	0.041 (1)	3.262 (5)	1.701 (1)	2.240 (2)	0.224 (1)
[Probability]	[0.840]	[0.660]	[0.192]	[0.326]	[0.636]

Table 8
Continued

Product/Ports Estimate	Rubber† Malay-U.K. 1-2-74 to 12-26-79	Silver† U.S.-U.K 7-5-72 to 5-28-80	Tin† U.S-U.K 1-2-74 to 7-30-80
β	0.942	0.382	0.901
(Standard Error)	(0.018)	(0.066)	(0.032)
Garch	2,2	1,1	2,2
γ (Lag)		-0.324 (1)	-0.383 (1)
(Standard Error)		[0.067]	[0.075]
γ (Lag)		-0.169 (2)	-0.071 (2)
(Standard Error)		[0.057]	[0.071]
γ (Lag)		-0.132 (3)	
(Standard Error)		[0.060]	
Additional Lags	0	0	0
Q Stat. (Lag)	1.213 (1)	17.755 (15)	1.963 (1)
[Probability]	[0.271]	[0.276]	[0.161]
LM Stat. (Lag)	NA	NA	NA
[Probability]	NA	NA	NA
Arch Stat. (Lag)	14.585 (12)	40.761 (31)	0.929 91)
[Probability]	[0.265]	[0.113]	[0.335]
Jarque-Bera	7.515	252.858	255.386
[Probability]	[0.023]	[0.000]	[0.000]
Residuals^2			
Q Stat. (Lag)	17.173 (13)	13.625 (9)	0.940 (1)
[Probability]	[0.192]	[0.136]	[0.332]

† Weekly.

Table 8 reports the same estimates for petroleum, rubber and metals prices using $Ln(p_t^F)$ - $Ln(p_t^D)$. Only tests for normality are ever significant. The largest β in Table 8 is for Rubber, but even it is three standard errors below 1.0.

Table 9
Half Lives Measured in Months for Grains without Freight Rates and no Lagged Export Prices

Product	Ports	Interval	Half Life	Product	Ports	Interval	Half Life
DNS	Gulf-Rott	74:1-90:12	1.9	HW13	Gulf-Japan	75:9-81:10	3.9
DNS	Gulf-Rott	89:6-94:10	0.3	DNS	Gulf-PP	74:1-99:4	2.3
DNS	Gulf-Rott	94:7-01:12	1.9	HWO	Gulf-PP	74:1-86:4	2.8
Corn	Gulf-Rott	87:4-98:6	1.0	DNS	PP-Japan	75:9-81:10	9.3
DNS	Gulf-Japan	75:9-81:10	3.9	WW	PP-Japan	75:9-81:10	13.2

Table 9 reports the half lives for grains implied by Table 6. The average half life is four months. The two longest half lives are for DNS and WW between Pacific ports and Japan, 9.3

and 13.2 months. The two shortest are for DNS between Gulf ports and Rotterdam and corn between the same ports: 0.3 and 1.0 months.

Table 10
Half Lives Measured in Months for Grains with Freight Rates and Lagged Export Prices

Product	Ports	Interval	Half Life	Product	Ports	Interval	Half Life
DNS	Gulf-Rott	74:1-90:12	1.0	HW13	Gulf-Japan	75:9-81:10	0.7
DNS	Gulf-Rott	89:6-94:10	1.5	DNS	Gulf-PP	74:1-99:4	1.3
DNS	Gulf-Rott	94:7-01:12	1.2	HWO	Gulf-PP	74:1-86:4	1.1
Corn	Gulf-Rott	87:4-98:6	0.9	DNS	PP-Japan	75:9-81:10	0.9
DNS	Gulf-Japan	75:9-81:10	1.8	WW	PP-Japan	75:9-81:10	1.0

Table 10 uses the estimates for grains from Table 7. While the average half life in Table 9 is four months, in Table 10 it is only 1.1 months. Omitting transportation costs and ignoring time substantially increases half lives for grains and, one would presume, substantially increases other half lives.

All of the half lives in Table 10, except for DNS between Gulf ports and Rotterdam for 1989 to 1994, are smaller than the corresponding half lives in Table 9. The difference is particularly large for the two longest half lives in Table 9. In Table 9, the half life for DNS between Pacific ports and Japan is 9.3 months. But when estimates include transportation costs and account for the fact that commodity arbitrage takes time, the half life is only 0.9 months. For WW between Pacific ports and Japan, the estimated half life without those adjustments is 13.2 months. Including those adjustments reduces that half life to only one month. Transportation costs and time in transit can be very important for evaluating the LOP and the efficacy of arbitrage.

Table 11 reports the half lives for petroleum products, rubber and metals implied by Table 8. The average half life for $Ln(p_t^F) - Ln(p_t^D)$ in Table 11 is 1.1 months.

Table 11
Half Lives Measured in Months for Petroleum Products, Rubber and Metals

Product	Ports	Interval	Half Life	Product	Ports	Interval	Half Life
Diesel	Gulf-NY	95:5-07:10	0.5	Gasoline	LA-Sing	92:7-07:10	0.7
Fuel Oil	Gulf-NY	93:10-07:2	0.6	Jet Fuel	LA-Sing	90:9-07:10	1.9
Gasoline	Gulf-NY	92:7-07:10	0.6	Diesel	LA-Rott	95:5-07:10	0.6
Jet Fuel	Gulf-NY	90:9-07:10	0.6	Fuel Oil	LA-Rott	93:10-07:2	1.1
Diesel	Gulf-LA	95:5-07:10	0.5	Gasoline	LA-Rott	92:7-07:10	0.7
Fuel Oil	Gulf-LA	93:10-07:2	0.9	Jet Fuel	LA-Rott	90:9-07:10	0.9
Gasoline	Gulf-LA	92:7-07:10	0.8	Diesel	Gulf-Sing	95:5-07:10	1.2
Jet Fuel	Gulf-LA	90:9-07:10	0.8	Fuel Oil	Gulf-Sing	93:10-07:2	0.9
Diesel	LA-NY	95:5-07:10	0.3	Gasoline	Gulf-Sing	92:7-07:10	0.8
Fuel Oil	LA-NY	93:10-07:2	0.7	Jet Fuel	Gulf-Sing	90:9-07:10	1.9
Gasoline	LA-NY	92:7-07:10	0.6	Diesel	NY-Sing	95:5-07:10	1.2
Jet Fuel	LA-NY	90:9-07:10	0.7	Fuel Oil	NY-Sing	93:10-07:2	1.0
Diesel	Gulf-Rott	95:5-07:10	0.6	Gasoline	NY-Sing	92:7-07:10	0.5
Fuel Oil	Gulf-Rott	93:10-07:2	1.9	Jet Fuel	NY-Sing	90:9-07:10	0.9
Gasoline	Gulf-Rott	92:7-07:10	0.8	Diesel	Rott-Sing	95:5-07:10	1.1
Jet Fuel	Gulf-Rott	90:9-07:10	0.7	Fuel Oil	Rott-Sing	93:10-07:2	1.8
Diesel	NY-Rott	95:5-07:10	0.5	Gasoline	Rott-Sing	92:7-07:10	0.9
Fuel Oil	NY-Rott	93:10-07:2	0.7	Jet Fuel	Rott-Sing	90:9-07:10	1.2
Gasoline	NY-Rott	92:7-07:10	0.6	Rubber	Malay-U.K.	1-2-74 to 12-26-79	2.9
Jet Fuel	NY-Rott	90:9-07:10	0.5	Silver	NY-London	7-5-72 to 5-28-80	0.1
Diesel	LA-Sing	95:5-07:10	0.8	Tin	NY-London	1-2-74 to 7-30-80	0.3
Fuel Oil	LA-Sing	93:10-07:2	0.7				

Ignoring rubber where the prices may not be for identical products, the two longest half lives in Table 10 are for fuel oil between Gulf ports and Rotterdam and for jet fuel between Los Angeles and Singapore, just 1.9 months. The two shortest half lives are for silver and tin between New York and London, 0.1 and 0.3 months.

Half lives in Tables 9 to 11 do not show any obvious signs of a border effect. Half lives between international ports like New York and Rotterdam are not obviously larger than between New York and Los Angeles. The next section, for the first time, uses auction prices to evaluate "Border Effects".

3.6. Border Effects.

Although the Borders literature uses other explanatory variables, it concentrates on how distance and borders affect the variance or standard deviation of changes in logs of ratios of prices like p_t^F / p_t^D. The log of p_t^F / p_t^D is usually denoted P_t with the first difference denoted ΔP_t.

That literature presumably does not use half lives because it is often impossible to reject an infinite half life for retail price differentials even when the products are identical. See for example Asplund and Friberg (2001, 1077).

Standard deviations of ΔP_t and half lives of P_t are both natural measures of market integration, but they measure different things. Consider the spectrum for ΔP_t. The area under the spectrum for ΔP_t is the variance. The half life for P_t reflects how quickly that spectrum falls as frequency falls. As a result, half lives for P_t and variances for ΔP_t can be very different.

An extreme case would be where variances in ΔP_t are small and spectra flat. Small standard deviations would reject segmentation. Flat spectra for ΔP_t would imply infinite half lives for P_t. Or variances for ΔP_t could be very large and spectra could fall rapidly as frequency goes to zero. Now standard deviations would support segmentation and half lives reject segmentation. The bottom line is that neither half lives nor standard deviations are ideal measures of integration. Here the two measures agree; both standard deviations and half lives imply that international commodity auction markets are highly integrated.

Although there are many auction markets for commodities, there are far fewer auction markets than retail markets. As a result, the number of commodities evaluated here is far smaller than in most of the Borders literature. To avoid unnecessary reductions in degrees of freedom, I use just borders and distance to evaluate border width.[15] When there is a border, the border dummy is one. Otherwise it is zero. Distance is the logarithm of the distance measure. There are three measures of distance: (1) distance by ship (Ship), (2) distance as the crow flies (Crow), and (3) distance by highway (Highway).[16] For Ship, distance is measured as the shortest distance by sea. The source for Ship is PORTWORLD.COM. For Highway it is MAPQUEST.COM. For Crow it is GeoBYTES.com/CityDistanceTool.htm.

Between ports like New York and Rotterdam, Ship is clearly the appropriate way to measure distance. Highways do not exist, and both great circle routes and "as the crow flies" can seriously understate the actual distance traveled. As a result, I use only distance by ship between international ports. I use all three measures between ports in the United States because it is not clear which is appropriate. To move products by ship from New York to Los Angeles they must either go through the Panama Canal or around South America. The alternative is to ship by train or truck, which is much shorter but more expensive per mile.

It seems unlikely that arbitrage would involve shipping grains or petroleum products between New York and Los Angeles by ship. If grain prices are higher in New York than Los Angeles, grain shipments from the Midwest would be diverted from Los Angeles to New York rather than shipped to Los Angeles by train or truck and then shipped to New York by ship.

Something similar applies to petroleum products. Oil refineries are scattered around the United States with production and refineries concentrated in Louisiana, Oklahoma and Texas. As a result, conventional arbitrage probably does not operate between New York and Los Angeles. If petroleum prices are relatively high in New York, shipments from Oklahoma or Louisiana are diverted from Los Angels to New York rather than sent to Los Angeles and then

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[15] Using dummies for classes of products such as grains, metals and oil produce similar results.

[16] Pacific ports are measured from Seattle, Gulf ports from New Orleans, Japan from Tokyo, Malay from Johor Baharu, and the U.K. from London.

shipped to New York. This difference in market structure between international and domestic ports may help explain the negative Border Effects reported below.

Table 12
Half Lives, Borders and Distance

	All prices $Ln(p_t^J)$-$Ln(p_t^P)$			Just grain prices use $Ln(p_t^J)$-$Ln(p_{t-1}^P+F_{t-2})$		
	All by Ship			All by Ship		
Intercept	-0.271	-3.955*	-3.756*	-0.385**	-4.228**	4.435**
(Std. Error)	(0.215)	(1.778)	(2.008)	(0.141)	(1.093)	(1.225)
Border	0.331		0.064	0.254		-0.053
(Std. Error)	(0.251)		(0.299)	(0.165)		(0.176)
Distance		0.456*	0.428†		0.468**	0.486**
(Std. Error)		(0.206)	(0.245)		(0.127)	(0.149)
$\bar{R}^2$	0.014	0.070	0.052	0.026	0.196	0.179
	As Crow Flies for U.S. Ports					
Intercept	-0.271	-2.605†	-3.440	-0.385**	-2.787**	-4.493**
(Std. Error)	(0.215)	(1.315)	(2.104)	(0.142)	(0.825)	(1.275)
Border	0.331		-0.227	0.254		-0.473†
(Std. Error)	(0.251)		(0.444)	(0.165)		(0.269)
Distance		0.306†	0.425		0.307**	0.505**
(Std. Error)		(0.155)	(0.281)		(0.097)	(0.170)
$\bar{R}^2$	0.014	0.052	0.032	0.026	0.146	0.178
	By Highway for U.S. Ports					
Intercept	-0.271	-2.928*	-3.684†	-0.385**	-3.099**	-4.606**
(Std. Error)	(0.215)	(1.410)	(2.116)	(0.142)	(0.881)	(1.282)
Border	0.331		-0.197	0.254		-0.403
(Std. Error)	(0.251)		(0.409)	(0.165)		(0.248)
Distance		0.343*	0.449		0.343**	0.555**
(Std. Error)		(0.166)	(0.277)		(0.104)	(0.168)
$\bar{R}^2$	0.014	0.059	0.044	0.026	0.160)	0.184

† Significant at 10% level. * Significant at 5% level. ** Significant at 1% level.

3.6.1. Half Lives. I use eq. (5) to evaluate the effect of borders on half lives.

$$Z_j = a + dD_j + bB \quad (5)$$

Z_j is the log of a half life, *e.g.*, for Diesel between Gulf and NY ports.[17] D_j is the log of the distance, e.g., the log of the distance between Gulf and NY ports. B is a border dummy.[18]

On the left-hand side of Table 12, all half lives are for logs of p_t^F/p_t^D from Tables 9 and 11. On the right-hand side of Table 12, half lives for just grains use logs of $p_{t+1}^F/(p_t^D+f_{t-1})$ from Table 10 while half lives for all other products are from Table 11. The first column on both sides excludes distance. The second excludes the border. The third includes both.

In the top of the table all distance is by Ship. In the middle, distance between U.S. ports is by Crow. In the bottom distance between U.S. ports is by Highway. Although cumbersome, this arraignment should reveal how different measures of distance affect the results.

There is no evidence of a positive border effect in Table 12. Whether or not D_j is included, b is never positive and significant even at the 10 percent level. In most cases it is negative.

How distance is measured does not appear to be important. The results for distance are similar in all three parts of Table 12.

But distance itself is important. In the left-hand side, when B is excluded, d is always significant. But when B is included, most of the significance disappears. That result suggests some multicollinearity. That multicollinearity largely disappears in the right-hand side. Whether or not B is included, in the right-hand side d is always significant at the 1 percent level. It again appears that accounting for freight rates and time is important.

Excluding tin, silver and rubber for which there is at most only one U.S. port generally reduces significance, but does not substantially change the results in Table 12.

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[17] Note that these half lives are not all for the same interval.

[18] Later Z_j is the log of the standard deviation of ΔP_t. Using actual half lives and standard deviations rather than their logs produces similar, but somewhat weaker, results.

When using half lives and spot auction prices, there is some suggestion of a negative border effect. Standard deviations produce stronger negative effects.

Table 13
Standard Deviation of ΔP_t: Petroleum Products, Metals and Rubber

Product	Ports	Interval	Standard Deviation	Product	Ports	Interval	Standard Deviation
Diesel	Gulf-NY	95:5-07:10	0.052	Gasoline	LA-Sing	92:7-07:10	0.151
Fuel Oil	Gulf-NY	93:10-07:02	0.076	Jet Fuel	LA-Sing	90:9-07:10	0.074
Gasoline	Gulf-NY	92:7-07:10	0.059	Diesel	LA-Rott	95:5-07:10	0.095
Jet Fuel	Gulf-NY	90:9-07:10	0.055	Fuel Oil	LA-Rott	93:10-07:2	0.094
Diesel	Gulf-LA	95:5-07:10	0.097	Gasoline	LA-Rott	92:7-07:10	0.136
Fuel Oil	Gulf-LA	93:10-07:2	0.111	Jet Fuel	LA-Rott	90:9-07:10	0.077
Gasoline	Gulf-LA	92:7-07:10	0.133	Diesel	Gulf-Sing	95:5-07:10	0.076
Jet Fuel	Gulf-LA	90:9-07:10	0.080	Fuel Oil	Gulf-Sing	93:10-07:2	0.109
Diesel	LA-NY	95:5-07:10	0.101	Gasoline	Gulf-Sing	92:7-07:10	0.104
Fuel Oil	LA-NY	93:10-07:2	0.117	Jet Fuel	Gulf-Sing	90:9-07:10	0.076
Gasoline	LA-NY	92:7-07:10	0.132	Diesel	NY-Sing	95:5-07:10	0.074
Jet Fuel	LA-NY	90:9-07:10	0.090	Fuel Oil	NY-Sing	93:10-07:2	0.103
Diesel	Gulf-Rott	95:5-07:10	0.063	Gasoline	NY-Sing	92:7-07:10	0.099
Fuel Oil	Gulf-Rott	93:10-07:2	0.076	Jet Fuel	NY-Sing	90:9-07:10	0.091
Gasoline	Gulf-Rott	92:7-07:10	0.072	Diesel	Rott-Sing	95:5-07:10	0.064
Jet Fuel	Gulf-Rott	90:9-07:10	0.060	Fuel Oil	Rott-Sing	93:10-07:2	0.091
Diesel	NY-Rott	95:5-07:10	0.056	Gasoline	Rott-Sing	92:7-07:10	0.081
Fuel Oil	NY-Rott	93:10-07:2	0.081	Jet Fuel	Rott-Sing	90:9-07:10	0.06
Gasoline	NY-Rott	92:7-07:10	0.070	Rubber	Malay-U.K.	1-2-74 to 12-26-79	0.026
Jet Fuel	NY-Rott	90:9-07:10	0.072	Silver	NY-London	7-5-72 to 5-28-80	0.025
Diesel	LA-Sing	95:5-07:10	0.094	Tin	NY-London	1-2-74 to 7-30-80	0.033
Fuel Oil	LA-Sing	93:10-07:2	0.092				

3.6.2. Standard Deviations. Presumably the Borders literature uses variances or standard deviations rather than half lives because it is difficult to reject a unit root for retail P_t. As shown earlier, auction P_t are stationary.

Table 13 reports standard deviations for ΔP_t for petroleum products, metals and rubber using $Ln(p_t^F) - Ln(p_t^D)$. Table 14 reports similar standard deviations for grains. Table 15 reports standard deviations for grains using $p_{t+1}^F/(p_t^D+f_{t-1})$.

Table 14
Standard Deviations for Grains without Freight Rates or Lagged Export Prices

Product	Ports	Interval	Standard Deviation	Product	Ports	Interval	Standard Deviation
DNS	Gulf-Rott	74:1-90:12	0.031	HW13	Gulf-Japan	75:9-81:10	0.034
DNS	Gulf-Rott	89:6-94:10	0.054	DNS	Gulf-PP	74:1-99:4	0.033
DNS	Gulf-Rott	94:7-01:12	0.040	HWO	Gulf-PP	74:1-86:4	0.025
Corn	Gulf-Rott	87:4-98:6	0.032	DNS	PP-Japan	75:9-81:10	0.020
DNS	Gulf-Japan	75:9-81:10	0.038	WW	PP-Japan	75:9-81:10	0.016

Standard deviations in Table 14 range from a high of 0.151 for gasoline between Los Angeles and Singapore to a low of 0.025 for silver between New York and London. For grains in Table 15 the highest standard deviation is 0.054 for DNS between Gulf ports and Rotterdam from 1989 to 1994. The lowest is 0.016, which is for WW between Pacific ports and Japan.

Table 15
Standard Deviations for Grains with Freight Rates and Lagged Export Prices

Product	Ports	Interval	Standard Deviation	Product	Ports	Interval	Standard Deviation
DNS	Gulf-Rott	74:1-90:12	0.055	HW13	Gulf-Japan	75:9-81:10	0.052
DNS	Gulf-Rott	89:6-94:10	0.056	DNS	Gulf-PP	74:1-99:4	0.052
DNS	Gulf-Rott	94:7-01:12	0.045	HWO	Gulf-PP	74:1-86:4	0.047
Corn	Gulf-Rott	87:4-98:6	0.055	DNS	PP-Japan	75:9-81:10	0.044
DNS	Gulf-Japan	75:9-81:10	0.049	WW	PP-Japan	75:9-81:10	0.044

When grain prices include freight rates and export prices are lagged one month as in Table 15, the highest standard deviation is 0.056, which is for DNS between Gulf ports and Rotterdam from 1989 to 1994. DNS and WW between Pacific ports and Japan from 1975 to 1981 are tied for lowest at 0.044.

The standard deviations in Tables 13 to 15 are much smaller than standard deviations for retail prices. For example, the variance of ΔP_t in Table 2 of Engel and Rogers (2001b) is 2.12. The implied standard deviation of 1.46 is almost 10 times larger than the *largest* standard deviation in Tables 13 to 15. The relatively large standard deviations in the Borders literature probably are the result of mixing retail and auction prices by converting sticky foreign retail prices into U.S. dollars using exchange rates from auction markets. I suspect that those standard deviations would drop substantially if the two markets were matched. That is, if foreign retail prices were converted into dollar prices using retail exchange rates.

Including freight rates and lagging export prices generally reduces half lives for grains. But in Tables 14 and 15 doing so generally increases standard deviations. The average standard deviation in Table 14 is 0.03. The average standard deviation in Table 15 is 0.05. This difference illustrates the point made earlier that half lives and standard deviations measure different things. Nevertheless, here they both reject wide borders.

Table 16
Standard Deviations, Borders and Distance

	$Ln(p_t^J)-Ln(p_t^P)$			$Ln(p_{t+1}^J)-Ln(p_t^P+F_{t-1})$		
	All by Ship			All by Ship		
Intercept	-2.594**	-4.909**	-6.368**	-2.516**	-4.621**	-5.939**
(Std. Error)	(0.140)	(1.169)	(1.238)	(0.104)	(0.853)	(0.870)
Border	-0.180		-0.470*	-0.162		-0.424**
(Std. Error)	(0.164)		(0.179)	(0.121)		(0.126)
Distance		0.254†	0.463**		0.231*	0.420*
(Std. Error)		(0.136)	(0.151)		(0.099)	(0.106)
$\bar{R}^2$	0.004	0.046	0.145	0.015	0.079	0.235
	As Crow Flies for U.S. Ports			As Crow Flies for U.S. Ports		
Intercept	-2.594*	-3.436**	-6.876**	-2.516**	-3.189**	-6.125**
(Std. Error)	(0.140)	(0.879)	(1.265)	(0.104)		(0.901)
Border	-0.180		-0.934**	-0.162		-0.792**
(Std. Error)	(0.164)		(0.267)	(0.121)		(0.190)
Distance		0.084	0.574		0.066	0.484**
(Std. Error)		(0.104)	(0.169)		(0.077)	(0.120)
$\bar{R}^2$	0.004	-0.007	0.175	0.015	-0.005	0.241
	By Highway for U.S. Ports			By Highway for U.S. Ports		
Intercept	-2.594*	-3.578**	-6.718**	-2.516**	-0.774**	-6.056**
(Std. Error)	(0140)	(0.945)	(1.289)	(0.104)	(0.114)	(0.917)
Border	-0.180		-0.819**	-0.162		-0.710**
(Std. Error)	(0.164)		(0.249)	(0.121)		(0.177)
Distance		0.101	0.543**		0.083	0.466**
(Std. Error)		(0.111)	(0.169)		(0.083)	(0.120)
$\bar{R}^2$	0.004	-0.004	0.158	0.015	-0.000	0.228

† Significant at 10% level. * Significant at 5% level. ** Significant at 1% level.

Table 16 is identical to Table 12 except that in Table 16 the Z_j are standard deviations rather than half lives. When B appears alone in Table 16, b is always negative, but never significant. When D_j appears alone, d is always positive, but significant only when by ship. When D_j and B appear together, d is positive and usually significant. But b is always negative and significant.

Negative and significant borders are not the result of including tin, silver and rubber. Excluding them reduces some of the significance, but it does not substantially change the results shown in Table 16. When D_j is included, all b are negative and significant, most at or near the 1 percent level.[19]

Whether I use Ship, Crow or Highway makes little difference. Although the results are not reported here, using the square, square root or the reciprocal of the logarithm of distance produces similar results. For auction prices, Border Effects appear to be negative. Conditional on distance, standard deviations for ΔP_t are larger between U.S. ports than between international ports.[20] Why?

It seems unlikely that arbitrage is less effective between U.S. ports. There are at least three potential explanations of the negative Border Effects: (1) The difference in market structure between U.S. ports and international ports discussed earlier. (2) Effective transportation costs are higher between domestic ports like New York and Los Angeles. It is cheaper per mile to ship by water than by land, but trains or trucks are probably the cheapest alternative for grains and petroleum products from places like Kansas and Oklahoma because the distance is much shorter.

[19] The significance for b for ship on the right-hand side falls to only 10%.

[20] Engel and Rogers (2001a) find something similar for their "traded" versus "nontraded" goods. Apparently the variability for ΔP is larger for their "traded" than "nontraded" goods because the variability for "traded" goods is larger than the variability of "nontraded" goods. They attribute this difference to the fact that prices are more sticky for "nontraded" goods.

Higher effective transport costs per mile would tend to increase standard deviations. (3) Prices in domestic ports are more volatile than prices in foreign ports.

I do not have the data necessary to explore (1) or (2), but auction prices appear to be slightly more volatile in U.S. ports. Table 17 reports average standard deviations by product and by port. Rubber is not included because there are no U.S. ports for rubber. For each product, the average standard deviation is slightly larger in domestic ports.

Table 17
Standard Deviations by Product and by Port

Ports	Petroleum Products	Grains	Metals
U.S.	0.119	0.048	0.096
Foreign	0.102	0.046	0.077

Auction prices produce no evidence of positive Border Effects. International auction markets for commodities appear to be highly integrated. Earlier research found wide borders and highly segmented markets using retail prices. But that segmentation does not reject effective arbitrage and the Law of One Price because it does not imply risk free profits.

3.7. Summary of Section 3.

What can we conclude about auction markets for commodities from this analysis of spot auction prices? First, unlike retail commodity markets, international auction markets are highly integrated. Second, although my results do not prove that arbitrage is effective and that the Law of One Price holds in auction markets for commodities, they are consistent with effective arbitrage and the LOP.

Providing more convincing evidence regarding international commodity arbitrage and the LOP will require the kind of careful detailed research in commodity markets that Akram et al (2008) conduct in financial markets. But such research will be more difficult in commodity markets. One can buy an asset in New York, sell it in London and convert the sterling back to dollars almost instantaneously because all that matters is ownership. In commodity markets location is important and arbitrage normally involves time in transit. As a result, commodity arbitrage usually involves forward rather than just spot transactions. In addition, while every share of Ford stock is identical, all shiploads of No. 2 Dark Northern Spring Wheat, 14% Protein are not identical. For example, the grain can be washed or not and water content is important. Humid grain tends to rot. The relevant contracts spell out these details and these details should be considered in future tests of commodity arbitrage and the LOP.

I expect that research to confirm that financial and commodity markets are far more alike than the current literature suggests. It will, I believe, find that, after accounting for institutional differences, higher transaction costs and time in transit, arbitrage is about as effective in auction markets for commodities as it is in auction markets for financial assets. Any other result would suggest that basic economic assumptions like utility and wealth maximization hold better in some markets than others.

5.0 Overall summary and conclusions.

Using retail prices, the Borders literature and part of the commodity LOP literature claim that arbitrage is ineffective and that the LOP fails. This view of commodity arbitrage and the LOP seems to be the conventional wisdom. But that conventional wisdom is mistaken.

Using auction prices, the finance literature and part of the commodity LOP literature support effective arbitrage and the Law of One Price. Using a wider range of commodity auction prices over longer intervals than before, my results reinforce that support for effective arbitrage and the Law of One Price. In addition, for the first time I look for Border Effects using auction prices. Both half lives and standard deviations reject positive Border Effects

One source of the confusion over the interpretation of the evidence is the framework for research in commodity markets. That research is based primarily on the pure theory of trade, which ignores retail, wholesale and auction markets. One result is an emphasis on so called "traded" versus "non-traded" goods when the appropriate distinction for commodity arbitrage and the LOP is between retail, wholesale and auction markets. At the retail level, all goods are "non-traded".

Another source of the confusion is that the Borders literature and the part of the LOP literature do not use the terms “arbitrage” and “Law of One Price” as they are defined in dictionaries and encyclopedias. When the Borders literature and some of the LOP literature claim that arbitrage and the LOP fail in international commodity markets, what they mean is that international *retail* markets are highly segmented. That literature cannot claim anything more than that because it uses retail prices. Highly persistent retail price differentials imply retail segmentation. But that segmentation does not reject effective arbitrage and the Law of One Price as they are defined in dictionaries and encyclopedias because it does not imply risk-free profits.

In spite of using only spot prices and the absence of detailed information about the relevant contracts, the evidence presented here shows that a wide range of international commodity markets are highly integrated with typical half lives of about 1.1 months. When future research solves those and other problems, it should substantially reduce that half life.

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