Storage, transport and the law of one price: evidence from nineteenth century U.S. corn markets.

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Abstract
This paper argues that localised price spikes should be a regular feature of competitive commodity markets. It develops a rational expectations model of physical arbitrage in which trade takes time, and shows that inventory management plays a crucial role in the way regional prices are determined. In equilibrium, arbitrageurs choose export quantities to ensure inventories in the importing centre regularly fall to zero. They earn enough profits from high prices on these occasions to offset small losses at other times. An analysis of detailed data from Chicago and New York corn markets provides empirical support for the model.

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INTRODUCTION

Many people detest price gouging. It is an anathema to them that merchants can make large profits at times that demand is unusually large or supplies are unusually short. This distaste has led to the enactment of statutes such as the Virginia Post-Disaster Anti-Price Gouging Act that prohibit merchants from raising prices during disasters. Such laws are still occasionally used to prosecute wayward merchants, most recently in the aftermath of the September 11 hijackings.

Episodes of price gouging are examples of a more general phenomenon, localised price spikes. These occur when the price in one location exceeds the price in another by more than it costs to ship goods between them. While such episodes appear to contradict the law of one price, this paper develops a model of commodity price arbitrage in which these price spikes must occur if arbitrage is to take place. Indeed, if markets are competitive, arbitrage activity will not occur unless there are localised price spikes at times when supplies are unusually tight —that is, unless from time to time there is price gouging — because arbitragers will not cover their costs.

The key feature of the model is that shipping takes time. This means arbitrageurs cannot immediately obtain additional supplies in a centre where local demand is unusually high or local supply is unusually low, so inventory management has a vital role in the arbitrage process. If competitive arbitrageurs simultaneously manage their shipments and inventories to maximise profits, prices in different cities will depend critically on inventory levels. If two cities both have large inventories, their spot prices will never exceed the difference between the transport cost and the storage cost. But if one city runs out of inventories, its spot price will spike upwards and exceed the spot price in the other centre by more than the difference between the transport cost and the storage cost. These spikes last until supplies are replenished and thus the local spot price will exceed the price for forward delivery as well. Moreover, exports will be managed to ensure that inventory levels regularly fall to zero in an importing city, so there will be occasions when the spatial price difference exceeds the difference between the transport cost and the storage cost.

The intuition of the model is straightforward. Rational, risk neutral arbitrageurs ship goods between centres if the expected future price in the importing centre exceeds the price in the exporting centre by the cost of transport. If there are sufficient inventories in the importing centre when the goods are sent, arbitrageurs in the importing centre run down their inventories until the spot price equals the expected future price minus storage costs, and thus the spot price difference between centres equals the transport cost minus the storage cost. If inventories in the importing centre are zero, however, the spot price cannot be arbitraged down and the price difference between the centres exceeds the difference between the transport cost and the storage cost until the shipment arrives. The spatial price difference should exceed the transport cost minus the storage cost on occasion because exporters limit their shipments to ensure that random variation in local supply or demand regularly cause inventories to fall to zero in the importing centre. Unless they do this, the exporters make negative profits because the price in the importing centre does not cover the full cost of exporting if the exports arrive when supplies are plentiful.

This paper finds evidence that localised price spikes were a regular feature of the New York and Chicago corn markets in the late nineteenth century. I examine these markets because they have data including spot and future prices, storage quantities, shipping quantities and transport costs that are ideally suited to detect the price relationships implied by the model. Such data are not often available, but exist in this setting because both cities had active futures markets for corn. The price relationships are strikingly consistent with the model. During the period, most corn was shipped to New York via the Great Lakes and the Erie Canal in a trip that took three weeks. The paper shows the New York price for future delivery was always very close to the Chicago spot price plus the cost of the lake and canal transportation, but that on numerous occasions the New York spot price spiked upwards and exceeded the Chicago price plus the transport cost. These price spikes were temporary and mostly occurred when corn inventories were extremely low in New York. The data therefore show that regular deviations from the law of one price occurred in one of the world's most organised markets, deviations that are consistent with the theoretical model and not explained by models of price arbitrage that ignore inventories.

A STRUCTURAL MODEL OF STORAGE AND ARBITRAGE

Models of price arbitrage can be traced to Cournot (1838). The basic approach, exemplified by Samuelson (1952), has been to link a set of equations representing supply and demand curves in different locations with a set of no-arbitrage conditions that preclude excess profits from the instantaneous shipment of goods. A set of prices P^i_t are found that equate aggregate demand with aggregate supply while ensuring profitable arbitrage opportunities do not exist:

$$P_t^i - P_t^j \le K^T; \qquad (P_t^i - P_t^j - K^T).T_t^j = 0 \tag{1}$$

where P_t^i is the price in centre i at time t, T_t^j is the quantity of exports from j to i at time t, and K^T is the transport cost.

Models of rational storage have a similar structure (see Williams (1936), Williams and Wright (1991), or Deaton and Laroque (1992).) Risk neutral arbitrageurs are assumed to predict future prices and purchase and hold inventories until the expected price increase just offsets the cost of storage; conversely, if the expected appreciation is less than the cost of storage, inventories will be zero. There are three possible storage costs. First, there can be an elevator charge K^S per unit to store goods each period. Secondly, the commodity depreciates at rate δ so if S_t is stored in period t, $(1-\delta)S_t$ will be available in period $t+1$. Thirdly, there is an interest cost r foregone when storage is undertaken. These relationships are represented by the following equations:

$$\left(\frac{1-\delta}{1+r}\right)E_t[P_{t+1}^i] - P_t^i \le K^S; \qquad \left[\left(\frac{1-\delta}{1+r}\right)E_t[P_{t+1}^i] - P_t^i - K^S\right].S_t^i = 0 \tag{2}$$

where E_t is the expectations operator conditioning on information known at t, and S_t^i is the quantity of inventories held at time t.

Williams and Wright (1991) solved a model combining both spatial arbitrage and storage. They investigated how prices in two locations would be determined if rational, forward looking, and risk neutral arbitrageurs could store goods or transport them instantaneously from one location to the other. They used numerical techniques to find the set of optimal storage and trade functions that generate a stationary rational expectations equilibrium. The model developed in this paper copies their approach but relaxes the assumption that trade is instantaneous. This is a crucial modification, for if transport is instantaneous (and there are no capacity constraints) the price in one centre will never exceed the price in the other by more than the cost of transportation.

The model is also related to those developed in the logistics management literature. This literature has examined the optimal ways for a company with sales in several locations to minimise total procurement, transport, and storage costs (see Baumol and Vinod (1970) for an original statement, or Tyworth (1991), McGinnis (1989) or de Jong (2000) for a review). The literature shows that careful inventory management enables a firm to substitute low cost but slow transport systems for faster but higher priced systems. Indeed, a cost-minimising firm will use fast transportation only when inventories unexpectedly fall to such low levels that it cannot use slow transportation to replenish them before they run out. The model in this paper extends this literature, as prices are determined endogenously in markets, rather than being set exogenously by the firm. In this model, therefore, unexpected shortages lead to price spikes rather than rationing.

The model

There are two centres, A and B, each with a separate inverse demand function for a commodity:

$$P_t^i = D_i^{-1}(Q_t^i) : \qquad D_i^{-1}(0) < \infty, \quad \lim_{Q\to\infty} D_i^{-1}(Q) = 0 \tag{3}$$

where Q_t^i is the amount purchased for final use at time *t* and i = A, B. The output produced each period is assumed to be price inelastic but stochastic, because it has a long gestation period. There are two ways that output is usually modeled in the literature: either it is serially autocorrelated or it varies seasonally. Since the analytical structure of the model does not depend on how output is modeled, in this paper I follow Deaton and Laroque (1996) and assume that output in each centre follows an independent first order autoregressive process around a constant mean:

$$(X_t^i - \bar{X}^i) = \rho^i (X_{t-1}^i - \bar{X}^i) + e_t^i \qquad i = A, B \tag{4}$$

where e_t^i is a white noise process and $|\rho^i|<1$[1].

All production, consumption, storage and trade activity takes place at the beginning of the period, and the length of a period is the time that it takes to ship goods from one centre to another[2]. It is assumed that unlimited quantities of the good can be stored in either centre, that goods produced at different times are indistinguishable and have the same price, and that the storage cost K^S is less than the transport cost K^T. A key determinant of prices is product availability, M_t^i, the total quantity of stored and imported goods in a centre at the beginning of the period,

$$M_t^i = (1-\delta)\left(S_{t-1}^i + T_{t-1}^j\right) \tag{5}$$

where S_{t-1}^i is the non-negative quantity stored in centre i and T_{t-1}^j is the non-negative quantity exported from centre j. The quantities stored and exported are such that $S_t^i + T_t^i \le X_t^i + M_t^i$.

It is assumed that risk neutral, profit maximising, and rational speculators in both cities undertake a mixture of trade and storage to take advantage of expected price differences. The speculators have rationally determined expectations about future prices that incorporate all information about output, storage, and trade in both centres. The behavior of risk neutral speculators can be represented by four inequalities. Let $y_t = \left[M_t^A, M_t^B, X_t^A, X_t^B\right]$ be the vector of state variables. Then, at each point y_t:

$$\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^A \mid y_t] - P^A(y_t) \le K^S; \ \left[\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^A \mid y_t] - P^A(y_t) - K^S\right].S^A(y_t) \ = 0 \quad 6a$$

$$\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^B \mid y_t] - P^B(y_t) \le K^S; \ \left[\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^B \mid y_t] - P^B(y_t) - K^S\right].S^B(y_t) \ = 0 \quad 6b$$

$$\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^B \mid y_t] - P^A(y_t) \le K^T; \ \left[\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^B \mid y_t] - P^A(y_t) - K^T\right].T^A(y_t) \ = 0 \quad 6c$$

$$\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^A \mid y_t] - P^B(y_t) \le K^T; \ \left[\left(\frac{1-\delta}{1+r}\right)E[P_{t+1}^A \mid y_t] - P^B(y_t) - K^T\right].T^B(y_t) \ = 0 \quad 6d$$

where

$$P^i(y_t) = D_i^{-1}(X_t^i + M_t^i - S^i(y_t) - T^i(y_t)),$$

$M^i_{t+1}(y_t) = (1-\delta)\left(S^i(y_t) + T^j(y_t)\right)$, and

$$E\left[P^i_{t+1} \mid y_t\right] = \iint_X D_i^{-1}(X^i_{t+1} + M^i_{t+1}(y_t) - S^i(y_{t+1}) - T^i(y_{t+1}))\, f\left(X^i_{t+1}, X^j_{t+1}\right) dX^i_{t+1} dX^j_{t+1} \quad (7)$$

The first two of these inequalities are the conditions for profitable storage in either centre, while the second two are the conditions for profitable trade between centres. Each of the four inequalities holds with equality if the control variables (storage or trade) are non-zero.

The model solution, which is found numerically, comprises two parts. The first part is the set of optimal storage and trade functions [$S^A(.)$, $S^B(.)$, $T^A(.)$, $T^B(.)$] that satisfy the four inequalities 6a - 6d. Each function depends on the vector of four state variables. The second part of the solution is the distribution of the state variables that occurs in equilibrium, which depends on the assumed stochastic process determining output and the optimal storage and trade functions. The solution fulfils two conditions: first, that storage and trading decisions are profit-maximising conditional on expectations of future prices; and, secondly, that price expectations are consistent with the storage and trading decisions and expectations of future output quantities.

The model solution technique

A numerical solution to the model is calculated over a discrete four-dimensional grid corresponding to the four state variables. The solution technique has four steps. First, a discrete joint probability distribution over the grid values for the stochastic variables X^A and X^B is chosen, and the double integral formula in equation 7 is replaced by the equivalent summation formula. The joint probability density for *X* is chosen to mimic an autocorrelated process with normal innovations, and is represented by an m^2 x m^2 Markov transition matrix Π specifying the probability of going from one point (X^A_{i1}, X^B_{j1}) to a second point (X^A_{i2}, X^B_{j2}).

The second step is to solve the optimal storage problem for the limiting "combined centre" case when transport costs are zero and trade is instantaneous, using techniques similar to those used by Deaton and Laroque (1995, 1996). Linear demand functions for each centre are specified:

$$D_i^{-1}(Q^i_t) = \begin{cases} \alpha^i & if \quad Q^i_t = 0 \\ \alpha^i - \beta^i Q^i_t & if \quad 0 < Q^i_t \le \alpha^i / \beta^i \\ 0 & if \quad Q^i_t > \alpha^i / \beta^i \end{cases} \quad (8)$$

The third step is an algorithm that calculates the optimal amounts of storage and trade in the two centres. The algorithm constructs a series of successive approximations to the optimal storage and trade functions, and is repeated until the difference between successive values of the control values is small.

The fourth step, once the optimal storage and trade functions are found, is the calculation of the invariant probability distribution of the model solution. The invariant distribution of the model is the unconditional probability of being at a particular grid point, which is used to calculate various statistics about the price distributions in each centre.

PROPERTIES OF THE MODEL

The model solution depends on the extent to which output is regionally specialised. When the centres are identical, they both tend to have large inventories, and goods are exported as frequently one direction as the other; but when one centre produces a disproportionate fraction of output, it tends to hold most of the inventories and export most of the time. The solutions are sufficiently distinctive that results corresponding to the two cases are presented.

Analytical Results

The key results of the paper are derived analytically by considering various combinations of the complementary conditions associated with equations 6a - 6d. The possible combinations are summarised in Table 1[3]. The probability of each combination occurring is a function of the underlying parameters of the model, and probability distributions corresponding to centre A producing either 50 per cent of total output or 35 per cent of total output are shown[4]. When centre A produces 50 per cent of total output, the most common combinations are:

positive inventories in both centres and zero trade (68 per cent);

positive inventories in the exporting centre, and positive inventories in the importing centre (13 percent each); and

positive inventories in the exporting centre and zero inventories in the importing centre (1.4 percent each).

The other combinations appear to occur rarely[5]. The set of conditions 6a - 6d indicates how prices adjust in each of these cases.

First, consider a point y_t when inventories are positive in each centre. Because inventories are positive, the price in each centre is expected to increase; more precisely, by equations 6a and 6b

$$E[P_{t+1}^i \mid y_t] = \left(\frac{1+r}{1-\delta}\right)\left(P^i(y_t) + K^S\right) \qquad i = A, B \tag{9}$$

and consequently

$$E[P_{t+1}^A - P_{t+1}^B \mid y_t] = \left(\frac{1+r}{1-\delta}\right)\left(P^A(y_t) - P^B(y_t)\right) \tag{10}$$

In addition, equations 6c and 6d imply the spatial price difference lies within the range $| P_t^A - P_t^B | \le (K^T - K^S)$. (Otherwise, profits could be made by reducing inventories in the low priced centre and exporting to the high priced centre.) Therefore, when inventories are positive in both centres, prices lie in the range $| P_t^A - P_t^B | \le (K^T - K^S)$ and are expected to diverge.

Secondly, consider a point y_t at which arbitrageurs in centre B export to centre A. If both centre A and centre B have positive inventories, equations 6a, 6b, and 6d hold with equality and imply

$$P^A(y_t) = P^B(y_t) + K^T - K^S \tag{11a}$$

$$E[P_{t+1}^A - P_{t+1}^B \mid y_t] = \frac{1+r}{1-\delta}(K^T - K^S) \tag{11b}$$

In this case, the spatial price differential is exactly $K^T - K^S$, and prices are expected to diverge. Alternatively, if centre B but not A has positive inventories, equations 6b and 6d hold and imply

$$P^A(y_t) > P^B(y_t) + K^T - K^S \tag{12a}$$

$$E[P_{t+1}^A - P_{t+1}^B \mid y_t] = \frac{1+r}{1-\delta}(K^T - K^S) \tag{12b}$$

In this case, the spatial price difference exceeds the difference between the transport cost and the inventory holding cost, as prices are unusually high in the importing centre. However, the centre A price is expected to fall when the goods arrive and thus prices are expected to converge.

When centre A produces 50 per cent of output, either equations 10, 11, or 12 apply most of the time. Furthermore, when output is highly autocorrelated, shipments are bunched sequentially.

Equations 11 and 12 determine how goods price arbitrage occurs when the exporting centre has large inventories and shipping occurs in sequential periods. Equations 11b and 12b imply that the price difference at time $t+1$ must exceed $K^T - K^S$ under some circumstances, if goods are to be exported at time *t*. Since the price difference at $t+1$ cannot exceed $K^T - K^S$ when the imports arriving in centre A are so plentiful that some are held over to the following period, on some occasions the imports must be sufficiently small relative to demand that inventories fall to zero and prices temporarily spike upwards (equation 12a, applied at $t+1$). For the zero profit condition to hold, exporters must export a sufficiently small quantity that on regular occasions the importing centre inventories are zero. Here the non-negativity constraint on inventories causes an important asymmetry. If output is higher than expected in the destination centre when the goods arrive, the surplus can be stored and prices fall but little; but if output is very low, there will be a shortage and prices will increase sharply. For the zero profit condition to hold, enough is shipped that a small number of sharp price increases offsets a large number of small price decreases. Consequently, if the output shocks are symmetric the median trade will be unprofitable, but the arbitrageur will obtain large profits from the few occasions that the exports arrive when supplies are unusually low. Furthermore, the importing centre will normally have positive inventories, because most of the imported shipments are larger than needed for immediate consumption.

When centre B produces most of the output, the most common combinations are that both centres have positive inventories and there is no trade, that B has positive inventories and exports, while A has positive inventories, and that B has zero inventories and exports, while A has positive inventories (see Table 1.) The last combination occurs when output in centre B is temporarily low: centre B still exports because it produces more than the other centre, but it does not hold inventories because output is expected to increase. The adjustment mechanism is slightly different in this case, but the logic is analogous to that described by equations 11 and 12, with exporters choosing to limit their exports to ensure that the importing centre occasionally has a localized price spike.

Models with capacity constraints or variable transport costs.

Since most logistics systems have capacity constraints, the set of equations 6a-6d may not always hold. Rather, the spot price may spike downwards when a capacity constraint binds, because the good must be consumed immediately or thrown away. Coleman (1998) examines a model with a storage capacity constraint: in the model, the good perishes after one period, so inventories are always lower than the previous period's output. There is an occasional downward price spike when a large quantity of the good must be used up immediately, but otherwise the solution is similar to the above model without storage capacity constraints.

The model is more difficult to solve if transport costs are time varying and predictable, because the solution depends on whether there are transport or storage capacity constraints. Suppose there are no capacity constraints and one centre primarily exports to the other. If transport costs are expected to increase substantially, arbitrageurs will ship all their goods at the low cost time and store them in the importing centre until they are needed. If capacity constraints limit the amount that can be shipped, however, the solution depends on whether transport capacity is allocated on a "first-come, first-served" basis or whether transport prices adjust to ensure that demand for transport just equals the available capacity. If transport prices respond to demand, they will adjust to ensure the set of inequalities 6a-6d still hold. If transport prices are not responsive and capacity is rationed, the inequalities will not hold. Rather, the expected future price in one centre will exceed the spot price in the other plus the transport cost, and the agents who obtain the transport capacity make windfall profits. Transport costs in the late nineteenth century grain markets appear to have adjusted to fluctuating demand, so the set of equations 6a-6d should have held.

Numerical Results

In the rest of this section, numerical simulations are presented to illustrate several features of the model, notably how trade flows, storage quantities, and prices depend on transport costs, the speed of transport, and the extent to which output is regionally specialised. The parameters are chosen so that the centres have identical demand functions, the price elasticity in each centre (at average consumption) is one, the storage cost K^S is zero, the period is one week, and the annual interest and depreciation rates are five per cent[6].

The Two Centre Model with Equal Centres

Table 2 shows how trade flows, storage quantities, and prices depend on transport costs when the centres are identical. Two features of the results stand out. First, prices are smoothed primarily through the adjustment of storage quantities, not the transport of goods. For each level of transport costs, mean exports were less than 4 per cent of mean weekly output and goods were exported less than 20 per cent of the time. In contrast, mean inventories in each centre were two to three times weekly output and inventories were positive in each centre over 96 per cent of the time. Secondly, the possibility of trade had a major effect on prices because storage behaviour was altered so that the spatial price difference between the centres was nearly always less than the cost of transporting goods. For each of the transport costs the spatial price difference exceeded K^T-K^S less than 4 per cent of the time.

The Two Centre Model with a Dominant Exporter

There are two cases to note when one centre is a dominant exporter: first, when the production asymmetry between the centres is small, so that both centres regularly export; and secondly, when production is sufficiently specialised that trade almost always flows from one centre to other. These cases are modeled by altering the fraction of total output produced in centre A from 50 per cent to 35 per cent, and the results are presented in Table 3.

When the production asymmetry is small, the solution is similar to the symmetric case and goods are regularly transported in both directions. The mean spatial price difference is less than the transport cost because cheap storage technology is used much more frequently than expensive transport technology to arbitrage prices. Average inventory levels are large in both centres.

The asymmetry in the solution becomes more pronounced as output becomes more regionally specialised. When centre A only produces 35 per cent of total output, it imports more than 80 per cent of the time, and exports less than 0.1 per cent of the time. Mean trade volumes from the exporting centre are close to the level that would prevail if there were no uncertainty. Although total storage declines as output is increasingly specialised, it is increasingly held in the exporting centre, and inventories in the importing centre are primarily held as part of the logistics process by which goods are exported from the other centre.

THE LATE NINETEENTH CENTURY U.S. CORN TRADE

During the late nineteenth century, corn was shipped from all over the Great Plains to Europe. Chicago was the preeminent inland shipping port, receiving and shipping 67 million bushels per year (on average) between 1878 and 1890. Most of this grain was sent to east coast ports prior to export. New York was the most important port, receiving 34 million bushels per year (on average) and exporting as much as Boston, Baltimore, and Philadelphia combined[7].

Corn was forwarded to New York one of three ways. The slowest method was to ship corn to Buffalo via the Great Lakes, and then to send it to New York via the Erie Canal. This method took three weeks, but was unavailable between November and late April when the lakes were frozen. A faster method, taking 10 days, was to ship corn to Buffalo via the Great Lakes and then to send it to New York by rail. The fastest and most expensive method was to send corn to New York by rail, a trip that took 3 or 4 days. Between 1881 and 1891, when average annual costs were reasonably stable, the average cost of shipping a bushel of corn from Chicago to New York was 7.7 cents by lake and canal, 10.3 cents by lake and rail, and 14.6 cents by rail[8]. The average price of a bushel of corn in Chicago during this time was 45 cents.

Between 1878 and 1890, 45 million bushels of corn per year (on average) were shipped from Chicago by lake, and 22 million were transported by rail. Of the latter, however, 15 million bushels were "through-shipments" — shipments that started west of Chicago, that were routed through Chicago, but that were never sold or handled in Chicago[9]. These through-shipments were included in the annual and weekly shipping statistics, creating a misleading picture of the true extent to which corn sold in Chicago was transported by rail. When the through-shipments are excluded, the fraction of corn sold in Chicago that that was shipped by lake increases from 67 per cent to 86 per cent. Lake transport was even more dominant during the open water season. Of the 7 million bushels of corn sold in Chicago and sent by rail, 4.3 million bushels were sent between December and March. Consequently, 95 per cent of corn that was transported in the open water season was shipped by lake[10].

There are no statistics directly showing that corn shipped from Chicago went to New York. Most Chicago corn was shipped through Buffalo, however, and since most New York corn came from Buffalo, it is possible to establish the link indirectly. In the longer version of the paper, it is demonstrated that the lake and canal route accounted for 87 per cent of the grain arriving in New York during the period that the lake and canal route was open[11]. High frequency shipping data suggests that corn was sent to New York on almost all of the weeks that the lake was open.

New York and Chicago Inventories

Grain arriving in New York was transferred to an elevator or a lighter and either sold or delivered in fulfillment of a futures contract. Grain was often stored temporarily, but the storage capacity was rarely fully utilised, even in winter[12]. Inventory levels never fell to zero, because the elevators always contained some grain in transit as they were used to transfer grain from arriving canal boats and rail cars to departing ocean vessels. Corn inventories typically fell to their low points each year in the middle of May, prior to the opening of the waterways, and in August.

Corn inventories in Chicago had a marked seasonal pattern. Receipts in Chicago occurred throughout the year, but were higher than shipments between December and March, when the lakes were closed, and in August and September. Inventories peaked in March, and averaged 4 million bushels on shore, with a further 2.2 million bushels on ships. Inventories reached seasonal lows in late July and November, when they averaged 1.4 million bushels.

Storage charges varied little during the period (Goldstein (1928); Ulen (1982)). In 1888, it cost ⅝ cents per bushel to deposit grain in an elevator, including the cost of 10 days storage; thereafter, storage cost ¼ cents per bushel per ten days. There were additional charges for trimming from canal boats and to ocean ships. Charges in Chicago were similar. Other costs of holding inventories included insurance and the opportunity cost of buying grain. Working (1929) estimated that in 1913 these costs were approximately 1.4 cents a bushel per month.

Transport prices between Chicago and New York.

There was a marked seasonal pattern in shipping costs (see Figure 1). Lake and canal and lake and rail prices were typically high at the opening of the season, but they declined during early summer before rising steadily between July and the end of the shipping season. Rail rates varied seasonally between winter and summer, particularly before 1886 when railroads competed aggressively with each other and with shipping lines for the grain business. The competition was sufficiently fierce that substantial quantities of grain were shipped by rail as through-shipments from locations west of Chicago, although not from Chicago itself. (Tunell (1897), United States Treasury (1898)). This price competition is understated in the rail price data collected by the Chicago Board of Trade and used in this paper, as much of the business was transacted at lower, unrecorded prices[13].

Market Prices

The standard spot and futures contracts in both New York and Chicago were settled by the delivery of grain to a warehouse or elevator. The main contracts were for immediate delivery (the spot contract) or for delivery at any time within the current month, the next month, two months' time, or in May of a particular year (the futures contracts). The seller had the option as to the date in a particular month the grain was delivered, so spot prices normally exceeded or were equal to the zero-month future price. This paper uses the Wednesday closing price for all of the analysis. (See Appendix 2 for the precise definition and source of the data.)

SPATIAL CORN PRICE ARBITRAGE, 1878-1891

Two features of the relationships between New York and Chicago prices implied by the model are examined. First, the link between the Chicago spot price, the transport cost, and the New York future price is analysed. Since exports left Chicago practically every week, the price expected to prevail in New York three weeks after the exports were sent — here proxied by the price for future delivery in New York — should equal the Chicago spot price plus the transport cost, irrespective of inventory levels in New York. Secondly, the difference between the Chicago and New York spot prices and the transport cost is examined. According to the model, the New York price should have equaled the Chicago spot price plus the transport cost minus the storage cost on any day corn was shipped if there were positive inventories in New York, but it should have exceeded this level if inventories in New York were zero.

Transport costs, the Chicago Spot Price, and the New York Future Price

According to equation 6c, when corn was shipped from Chicago at time *t* the spot price in New York three weeks later was expected to equal to the spot price in Chicago at time *t* plus the cost of transport. Although the expected spot price in New York at time *t+3* is not known, the price for future delivery in New York can be used as a proxy. Since the seller had the option of delivering any time during the month, and the trip took three weeks, the price for delivery "this month" was used if the date of the month was before the eleventh, and the price for delivery in the subsequent month was used if the date occurred on or after the eleventh[14]. Consequently, in the regression

$$(F_{t,t+3}^{NY} - P_t^{CH}) = \alpha + \beta \;\; Transport \;\; Cost_t + u_t$$

the coefficient β should equal 1 and the error should be uncorrelated with inventory levels. The data is plotted in Figure 2 for each week that lake and canal transport cost data are available, 1878 – 1891. Port handling charges in New York are not included in the transport cost[15]. The graph highlights the observations when New York inventories were less than 300 000 bushels. The observation for 23 September 1884 is omitted as there was a corner in the Chicago market and the Chicago price was 16 cents higher than the New York price.

The best fitting regression line including an indicator variable for weeks with low storage is:

$$(F_{t,t+3}^{NY} - P_t^{CH}) = 1.11 + 0.95 \;\; Transport \;\; Cost_t + 0.22 \;\; 1(Storage_t < 300{,}000) + u_t$$
$$\qquad (0.23) \;\; (0.044) \qquad\qquad\qquad (0.22)$$
$$u_t = 0.41 u_{t-1} + e_t \qquad\qquad R^2 = 0.74 \;\; N = 358$$

where 1(Storage <300,000) has a value of one if inventories were less than 300,000 and zero otherwise. The regression was estimated using feasible generalised least squares to take into account first order autocorrelation amongst the error process[16]. The slope of the coefficient on the transport cost variable is very close to, and insignificantly different from 1. In addition, the coefficient on the low inventory variable is both tiny and insignificantly different from zero, indicating that there was no systematic tendency for the future-spot price gap to be high when inventories were low. These estimates therefore provide clear evidence that the law of one price as described by equation 6c held in these markets.

Transport costs, the Chicago Spot Price, and the New York Spot Price

If the model is accurate, $P_t^{NY} - P_t^{CH}$ should have equaled $K^T - K^S$ when New York inventories were positive, but exceeded $K^T - K^S$ when New York inventories were zero. To examine this implication of the model, the spot price difference $P_t^{NY} - P_t^{CH}$ is plotted against the cost of lake and canal transport in Figure 3. Again, observations when New York inventories were less than 300,000 bushels are distinguished from those when inventories exceeded 300,000 bushels.

Two features of the graph stand out. First, as with figure 2, most of the observations lie above the 45-degree line, indicating that the spot price difference normally exceeded the transport cost. Secondly, there were a large number of occasions when the spot price difference exceeded the transport cost by more than 5 cents, and these were much more likely to occur when inventories were less than 300 000 bushels than when they exceeded 300 000 bushels. This is documented in Table 4, which analyses the distribution of the variable $P_t^{NY} - P_t^{CH} - K^T$ for six different inventory levels. On 62 per cent of the 21 occasions when inventories were less than 150 000 bushels, and 31 per cent of the 45 occasions when inventories were between 150 000 and 300000 bushels, the New York price exceeded the Chicago price plus transport cost by 5 cents or more. In contrast, the New York price exceeded the Chicago price plus transport costs by more than 5 cents on only 4 per cent of the 224 occasions when inventories exceeded 600 000 bushels.

Wilcoxon-Mann-Whitney statistics were calculated to test the hypotheses that the cumulative distribution functions of $P_t^{NY} - P_t^{CH} - K^T$ were the same for each of the six inventory groups, against the alternative that one distribution lay above the other. For each inventory group, the hypothesis that the distribution of $P_t^{NY} - P_t^{CH} - K^T$ was the same as that of the lowest inventory group is rejected. In addition, the hypotheses that the cumulative distribution functions of the first four inventory groups were the same were rejected, although the distributions were similar for all groups with more than a million bushels. Consequently, it is possible to conclude that the large spatial price differences that occurred when inventories in New York were low were not due to simple random variation.

In Table 5, the distribution of $F_{t,t+3}^{NY} - P_t^{CH} - K^T$ for the six different inventory categories is calculated. In contrast to the results for the New York spot price, the distributions show that the New York future price did not spike upwards when inventories were low; indeed, it is not possible to reject the hypothesis that the cumulative distributions of $F_{t,t+3}^{NY} - P_t^{CH} - K^T$ were the same for any of the six inventory categories.

The different behaviour of the New York spot and future prices can be further demonstrated by estimating the best fitting regression line corresponding to figure 3. The line, estimated using feasible generalised least squares to take into account first order autocorrelation, is[17]:

$$(P_t^{NY} - P_t^{CH}) = \underset{(0.29)}{1.75} + \underset{(0.06)}{0.85}\ \ Transport\ \ Cost_t + \underset{(0.29)}{2.05}\ \ 1(Storage_t < 300{,}000) + u_t$$

$$u_t = 0.45u_{t-1} + e_t \qquad\qquad R^2 = 0.69 \quad N = 368$$

The positive, statistically significant, and economically large coefficient on the low-inventory dummy variable is in sharp contrast to the small and statistically insignificant coefficient estimated when the future price was used. The difference between the two coefficients further confirms that the New York spot price, but not the future price, spiked upwards relative to the Chicago price and the transport cost when inventories were low.

The relationships evident in figure 3 and Table 4 can be summarised by constructing a "spatial arbitrage-storage" curve that plots the difference between the New York spot price and the Chicago spot price plus transport costs against inventory levels (see Figure 4)[18]. The graph resembles a traditional supply of storage curve, a graph of the difference between the spot price and the future price of a commodity versus the quantity of storage. In a supply of storage curve the spot price is typically higher than the future price when storage volumes are low, but when storage quantities are high the future price exceeds the spot price (Working (1949), Brennan (1958)). The theoretical model suggests that the spatial arbitrage-storage curve and the supply of storage curve should be closely related because when a centre has zero storage the spot price should exceed the local future price and the other spot price plus the transport cost. In a related paper, Coleman (2004) shows that the supply of storage curve for New York corn and the spatial arbitrage storage curves are indeed related in the suggested manner, and that the closeness of these curves may explain why commodity prices are frequently in backwardation.

CONCLUSIONS

This paper has attempted to enhance economists' understanding of how spatial arbitrage occurs by examining how the interaction of storage and trade affects prices in different locations. Its theoretical contribution has been to link the economics literature analysing spatial price arbitrage with the logistics management literature analysing how the speed of transport determines inventory holdings. It has made the link by relaxing the standard assumption in models of spatial arbitrage that transport is instantaneous; in doing so, it has emphasised the manner in which inventories are used to smooth price fluctuations. This role had long been recognised in the logistics management literature, but only at the level of the firm, rather than across competitive markets. Its empirical contribution has been to assemble a set of price, transport cost, and storage data that is detailed enough to detect how logistics issues have affected commodity prices in one specific market. It has shown that the spatial price difference frequently exceeded the cost of shipping goods, in a heavily traded commodity market in which there were large investments in logistics infrastructure and thick financial markets. In doing so, it has established that prices exceeded the transport cost when there were low supplies in the importing city, causing a temporary price spike followed by a price decrease when new supplies arrived from the exporting centre. The result can perhaps be best summarised by plotting a spatial arbitrage-storage curve that shows how the spatial price difference depends on inventory levels in the importing centre.

The theoretical model suggests that the process of physical arbitrage is significantly more complex than has previously been recognised. The central feature of the model is that the quantity of goods arbitrageurs ship each period will not be the amount necessary to ensure that the spatial price difference is always equal to the cost of transport. Rather, in order to make normal profits on average, arbitrageurs will ship an amount such that that there will be insufficient supplies and high prices in the destination centre on a regular but infrequent basis. The profits they make on these occasions offset the small losses they make on the more frequent occasions that the exports arrive when local supplies are adequate. Put more starkly, traders make normal profits on average only by obtaining high prices and extraordinary profits on occasions that supplies in the importing market are low. If this phenomenon is generally true in practice, it provides an argument against governments attempting to stabilise prices in times of shortage. Indeed, post-disaster anti-price gouging laws might raise the incidence of local shortages.

The paper has other implications for time series analyses of regional price dynamics. First, the data requirements to analyse episodes of physical arbitrage are large. In addition to the price data usually used in studies of arbitrage, it is necessary to know whether trade actually occurs between a pair of cities, the extent to which transport prices vary, and the level of inventories in each market. More generally, if cheap transport is slow, studies of market integration need to focus more on logistics issues — the way arbitrageurs use transport systems and storage to integrate markets — rather than just transport issues. Secondly, studies of market integration that assume that the spatial price difference is always equal to the transport cost need modification. For example, Spiller and Wood (1988) developed a popular methodology to estimate spatial transactions costs from price data that is explicitly predicated on the assumption that the price difference is always equal to the cost of transport, but that the cost of transport is variable. If that methodology were used on this data set, it would overestimate the mean and variability of transport costs because it wrongly assumes that the large price differences that occurred when one centre had low storage were due to temporarily high transport costs.

ENDNOTES

[1] The assumption that mean output is predetermined and price inelastic can be relaxed; see Williams and Wright (1991). Bailey and Chambers (1996) and Deaton and Laroque (1996) argue that if demand is linear any effect on prices stemming from a changes in the mean or variance of output can be replicated by a change in the demand function, so the shocks can be considered either demand shocks or supply shocks.

[2] This assumption is made for analytic convenience, as storage and trade decisions could be made at higher frequencies than the time it takes to ship goods. This would substantially complicate the model as all decisions would then depend on extra state variables representing quantities at different stages of transit.

[3] There are only 12 combinations because the centres will not export simultaneously since $K^S < K^T$.

[4] The probabilities are calculated using the parameters described in footnote 8, with $(X^A, X^B) = (100,100)$ if the centres are the same or (70, 130) if centre B mainly produces. The probabilities are representative of those pertaining to a wide variety of parameters, for a given level of regional specialization.

[5] As the stochastic process determining output is changed, the optimal storage and trade functions change but the solution still fulfills the set of conditions 6a-6d. Consequently, analytic statements about the solution will hold irrespective of the assumed stochastic process, but the distribution of the state variables in equilibrium will differ. As the modeling assumptions are changed, other combinations of the state variables might become more important.

[6] In the baseline case, the following model parameters are used: the demand function $D_i^{-1}(Q) = \alpha-\beta Q = 200 - Q$; the production conditional variance $\sigma^2 = 100$; the production autocorrelation $\rho = 0.9$; the weekly interest rate $r = 0.001$; the weekly depreciation rate $\delta = 0.001$; $K^S = 0$; and $K^T = 5$. The mean price is 100.

[7] Most corn was consumed where it was grown, and only a small fraction was shipped any distance. Illinois produced some 225 million bushels of corn annually, over 10 per cent of the U.S. crop. In contrast, total production in New York, New Jersey, and Pennsylvania was 75 million bushels per year.

[8] Chicago Board of Trade, 1892, p122.

[9] The through-shipments are calculated as the total of the monthly through-shipments on the Chicago and Northwestern, Illinois Central, Chicago, Burlington, &Quincy, Chicago, Rock Island, & Pacific and Chicago and Alton railroads that are reported in the Chicago Board of Trade Annual Reports each year.

[10] Unless most rail shipments were through-shipments there are two puzzles. First, rail and lake shipments took place simultaneously even though rail rates were considerably higher than lake rates. There are some reasons why rail shipment was preferred — it was faster, and had less risk of additional heat damage if the grain were already damaged — but ordinarily these did not justify the extra cost. Secondly, rail shipments during winter occurred when the price gap between New York and Chicago was lower than the rail cost.

[11] i.e. 21 million out of the 24 million bushels that arrived in New York during the lake and canal season.

[12] In 1888 there were 24 million bushels storage capacity in New York and Brooklyn, and a further 3 million in New Jersey. However, peak grain storage in New York and Brooklyn between 1887 and 1889 was just over 16 million bushels, of which 11 million bushels were wheat and 4 million bushels were corn.

[13] See the discussion by Nimmo in his reports on the internal commerce of the United States. (United States Bureau of Statistics, 1877, 1881, 1884). Porter (1983, 1985) discusses the pre-1886 price wars.

[14] Ten of the futures prices were not available, and these observations were omitted.

[15] It cost 0.15 cents per bushel for canal boat trimming, 0.625 cents for receiving, and discharging, and 0.25 cents for screening and blowing. (New York Produce Exchange Annual Report (1892). Official grain inspection, if required, cost $3 per canal boat. It cost 0.25 cents per bushel to store grain for 10 days.

[16] The errors are possibly autocorrelated because the data are sampled weekly, while shipping took 3weeks.

[17] The observation for 23 September 1884 was omitted.

[18] The scatter-plot of points is accompanied by a non-parametric kernel regression showing the average relationship between the future premium and the storage quantity The kernel regression is estimated with an Epanechnikov kernel with bandwith 300 000 bushels.

APPENDIX: DATA SOURCES

Six kinds of data have been assembled for this project: the spot price of corn in New York and Chicago; the future price of corn in New York and Chicago; transport costs between Chicago and New York; transport volumes between Chicago and New York; storage prices in Chicago and New York; and storage volumes in Chicago and New York.

Spot Price of Corn.
Prices were collected for Number 2 Yellow corn. Number 2 corn was the primary future grade and comprised a large fraction of the spot market. Grades were defined as follows.

New York: "YELLOW CORN shall be sound, dry, plump and well cleaned; an occasional white or red grain shall not deprive it of this grade. No.1 CORN shall be mixed corn of choice quality, sound, dry and reasonably clean. No.2 CORN shall be mixed corn, sound, dry and reasonably clean. " New York Produce Exchange (1882) p207

Chicago: "No. 1 YELLOW CORN shall be yellow, sound, dry, plump and well cleaned.
No. 2 CORN shall be dry, reasonably clean, but not plump enough for No. 1" Chicago Board of Trade (1882) p 79-80

Spot prices for both cities were collected in the Thursday edition of the New York Times, 1878-1891. The prices were for the preceding Wednesday. If the Wednesday were a public holiday, the Tuesday price was collected. If the markets were closed on both Wednesday and Tuesday, the data was skipped for that week.

Daily spot prices for New York are also available in some years in the Annual Report of the New York Produce Exchange. However, since The New York Times had to be used to collect the Chicago spot price and the New York future price, as well as the New York spot price in years where it was not reported in the Annual Report, the weekly New York Times data was used.

Future Price of Corn.
Prices were collected for Number 2 Yellow corn. The Chicago future price was collected from the Annual Report of the Chicago Board of Trade. The quotes is for seller delivery: the seller could choose any day to deliver within the said month. Wednesday quotes were collected.

The New York Wednesday future prices were collected from the Thursday edition of the New York Times. The seller also had the option as to the delivery date.

Corn Trade and Storage Data.
Storage and trade data for Chicago was sourced from the Chicago Board of Trade Annual Reports. The New York data came from a variety of sources. Where possible, it came from the New York Produce Exchange Annual Reports, but these documents had little data between 1882 and 1887. Storage data for these years came from the weekly Commercial and Financial Chronicle. Export data for several years came from the Chicago Board of Trade Annual Reports. Storage cost data come from the Chicago Board of Trade and New York Produce Exchange Annual Reports, and from Goldstein (1928).

Transport Data
The transport cost data were published by the Chicago Board of Trade and New York Produce Exchange Annual Reports.

Table 1: Analytical results corresponding to equations 6a-6d.

S_t^A	S_t^B	T_t^A	T_t^B	Prob(.) X^A=50%	Prob(.) X^A=35%	$\lvert P_t^A - P_t^B \rvert$	$E[\lvert P_{t+1}^A - P_{t+1}^B \rvert \lvert y_t]$
>0	>0	=0	=0	68.1%	17.5%	$<(K^T - K^S)$	$\frac{1+r}{1-\delta}(P_t^A - P_t^B)$
>0	>0	=0	>0	13.4%	72.9%	$=(K^T - K^S)$	$\frac{1+r}{1-\delta}(K^T - K^S)$
>0	>0	>0	=0	13.4%	0%	$=(K^T - K^S)$	$\frac{1+r}{1-\delta}(K^T - K^S)$
>0	=0	=0	=0	0.05%	0.5%	Uncertain	Uncertain
>0	=0	=0	>0	0.5%	6.9%	$=(K^T - K^S)$	$> \frac{1+r}{1-\delta}(K^T - K^S)$
>0	=0	>0	=0	1.4%	0.1%	$>(K^T - K^S)$	$\frac{1+r}{1-\delta}(K^T - K^S)$
=0	>0	=0	=0	0.05%	0%	Uncertain	Uncertain
=0	>0	=0	>0	1.4%	0.2%	$>(K^T - K^S)$	$\frac{1+r}{1-\delta}(K^T - K^S)$
=0	>0	>0	=0	0.5%	0%	$=(K^T - K^S)$	$> \frac{1+r}{1-\delta}(K^T - K^S)$
=0	=0	=0	=0	0.1%	0%	Uncertain	Uncertain
=0	=0	=0	>0	0.5%	1.9%	$>(K^T - K^S)$	$> \frac{1+r}{1-\delta}(K^T - K^S)$
=0	=0	>0	=0	0.5%	0%	$>(K^T - K^S)$	$> \frac{1+r}{1-\delta}(K^T - K^S)$

The table gives the absolute value of the price differential $P_t^A - P_t^B$ and the expected future price differential $E[\lvert P_{t+1}^A - P_{t+1}^B \rvert \lvert y_t]$ where they can be determined exactly by equations 6a - 6d, the arbitrage conditions describing storage and trade. The probabilities of each set of conditions occurring pertain to the case when both centres are the same and A produces 50 per cent of output or when A produces only 35 per cent of output.

Table 2: Price, storage, and trade statistics corresponding to the model. (Identical centres, changing transport costs.)

Statistic	Combined Centre	$K^T = 2.5$	$K^T = 5$	$K^T = 10$	$K^T = 20$	No Trade
Prices						
Mean(P^A)	100.2	100.2	100.3	100.3	100.4	100.4
S. Dev.(P^A)	8.5	8.6	8.5	8.6	9.4	10.4
Mean(P^A-P^B)	–	0	0	0	0	0
S. Dev.(P^A-P^B)	–	3.1	4.6	7.3	11.2	11.5
S.Dev(ΔP^A -Δ P^B)		2.35	2.84	3.58	4.59	5.51
% (| P^A-P^B| >K^T-K^S)	–	2.9%	3.1%	3.1%	3.2%	–
Storage						
Mean(S^A)	186	227	261	315	386	422
S. Dev.(S^A)	157	232	251	285	326	351
% (S^A = 0)	–	3.5%	3.1%	2.6%	2.0%	1.0%
% (S^A, S^B = 0)	3.1%	1.7%	1.1%	0.6%	0.2%	0.0%
Trade						
Mean(T^A)	–	3.9	3.2	2.3	1.2	–
S. Dev.(T^A)	–	10.6	10.5	10.2	8.9	–
% (T^A = 0)	–	80%	84%	90%	95.5%	–
% (T^A, T^B = 0)	–	61%	68%	81%	91.4%	–

The "combined centre" column refers to the case that trade is instantaneous and costless, and the "no trade" column refers to the case when trade is not possible.
P^A: the price in centre A. S^A: storage in centre A. T^A: trade from centre A to centre B.
% (| P^A-P^B| >K^T-K^S): the fraction of time the price difference exceeds the difference between the trade cost and the storage cost. Note K^S=0 in these simulations.
% (S^A[T^A] = 0): the fraction of time storage [exports] = 0.

Table 3: Price, storage, and trade statistics corresponding to the model.
(Different centres, mean output changes across columns.)

Statistic $\bar{X}^A =$ $\bar{X}^B =$	**100** **100**	**95** **105**	**90** **110**	**80** **120**	**70** **130**
Prices					
Mean(P^A)	100.3	101.2	101.9	102.5	102.8
S. Dev.(P^A)	8.5	8.4	8.5	9.0	9.3
Mean(P^B)	100.3	99.3	98.6	97.9	97.7
S. Dev.(P^B)	8.5	8.7	8.8	8.8	8.7
Mean(P^A-P^B)	–	1.9	3.3	4.7	5.1
S. Dev.(P^A-P^B)	4.6	4.4	3.8	2.7	2.0
S.Dev(ΔP^A -ΔP^B)	2.84	2.77	2.70	2.16	1.72
% (| P^A-P^B| >K^T-K^S)	3.7%	3.8%	3.2%	3.0%	2.1%
Storage					
Mean(S^A)	261	215	166	110	91
S. Dev.(S^A)	251	216	171	107	78
% (S^A = 0)	2.8%	3.1%	2.5%	2.4%	2.1%
Mean(S^B)	261	286	296	288	285
S. Dev.(S^B)	251	273	284	286	294
% (S^B = 0)	2.8%	3.8%	4.2%	7.7%	9.4%
% (S^A, S^B = 0)	0.9%	1.3%	1.3%	1.8%	1.9%
Trade					
Mean(T^A)	3.2	1.7	0.8	0.1	0.0
S. Dev.(T^A)	10.5	8.0	5.4	2.2	0.5
% (T^A = 0)	86%	92%	96%	99%	99.9%
Mean(T^B)	3.2	5.7	9.1	17.7	27.4
S. Dev.(T^B)	10.5	13.0	15.1	18.8	23.1
% (T^B = 0)	86%	73%	61%	32%	19%
% (T^A, T^B = 0)	72%	65%	56%	31%	18%

P^A: the price in centre A. S^A: storage in centre A. T^A: trade from centre A to centre B.
% (| P^A-P^B| >K^T-K^S): the fraction of time the price difference exceeds the difference between the trade cost and the storage cost. Note K^T= 5 and K^S=0 in these simulations.
% (S^A[T^A] = 0): the fraction of time storage [exports] = 0.

Table 4: Distribution of spot price difference adjusted for transport costs $(P_t^{NY} - P_t^{CH} - K^T)$ by storage level

Storage level bu	<150000	<300000	<600000	<1000000	<2000000	2000000 +
N	21	45	79	62	87	75
% obs < 0	0%	2%	2.5%	3%	10%	15%
% obs 0≤ x<5	38%	67%	85%	90%	87%	83%
% obs ≥ 5	62%	31%	12.5%	6.5%	2%	3%
Mean	6.01	3.84	2.70	1.73	1.45	1.10
Std	2.93	2.57	1.89	2.82	1.61	1.81
WMW test 1		-2.77*	-4.44*	-5.23*	-5.95*	-5.96*
WMW test 2		-2.77*	-2.43*	-2.52*	-1.94	-1.03

The table shows the fraction of observations in each group which are less than zero, between 0 and 5 cents, and more than 5 cents.
The first Wilcoxon-Mann-Whitney test, WMW test 1, tests whether the distribution is the same as the distribution of the group for which storage is less than 150000 bushels.
The second Wilcoxon-Mann-Whitney test, WMW test 2, tests whether the distribution is the same as the distribution of the group immediately to the left.
The WMW test is asymptotically distributed as N(0,1) and a * indicates significance at the 5% critical level i.e. that the two cumulative distributions lie above each other.

Table 5: Distribution of spot-future price difference adjusted for transport costs $(F_{t,t+3}^{NY} - P_t^{CH} - K^T)$ by storage level

Storage level bu	<150000	<300000	<600000	<1000000	<2000000	2000000 +
N	19	44	77	60	84	74
% obs < 0	21%	7%	10%	8%	7%	11%
% obs 0≤ x<5	74%	91%	86%	92%	92%	85%
% obs ≥ 5	5%	2%	4%	0%	1%	4%
Mean	1.04	1.60	1.60	1.29	1.45	1.55
Std	2.12	1.33	1.76	3.03	1.12	2.09
WMW test 1		1.00	1.07	0.92	0.73	0.90
WMW test 2		1.00	0.07	-0.31	-0.49	0.56

See Table 4. The table shows the fraction of observations in each group which are less than zero, between 0 and 5 cents, and more than 5 cents.

Figure 1

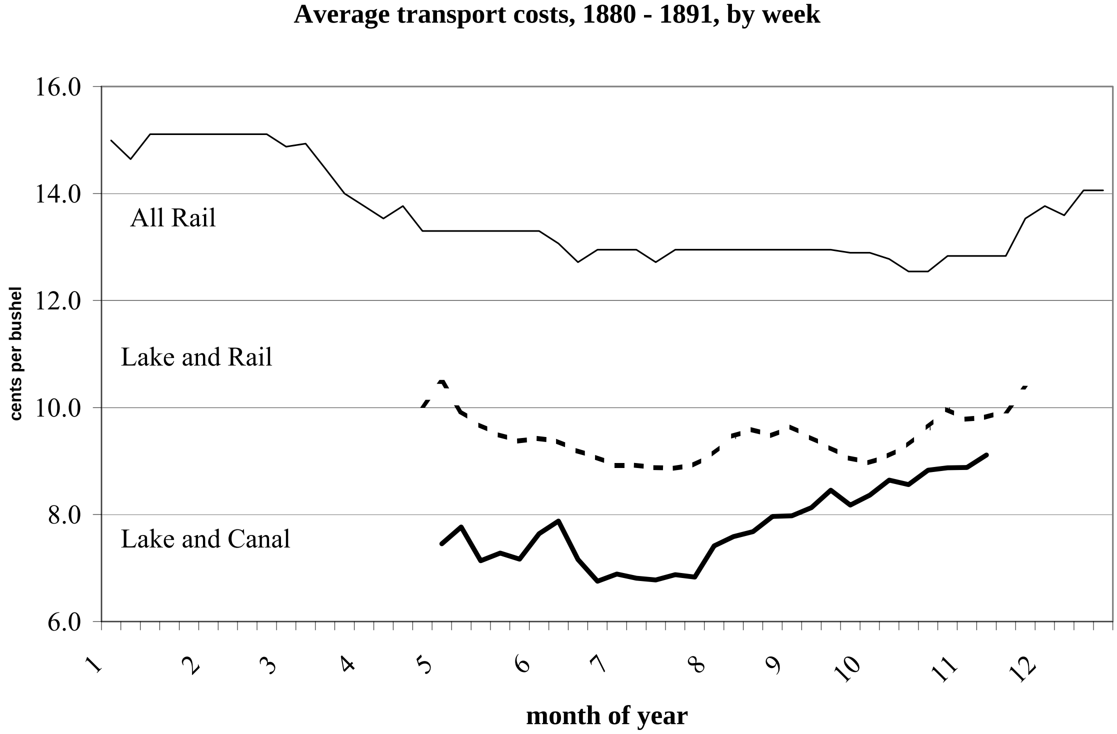


Figure 2

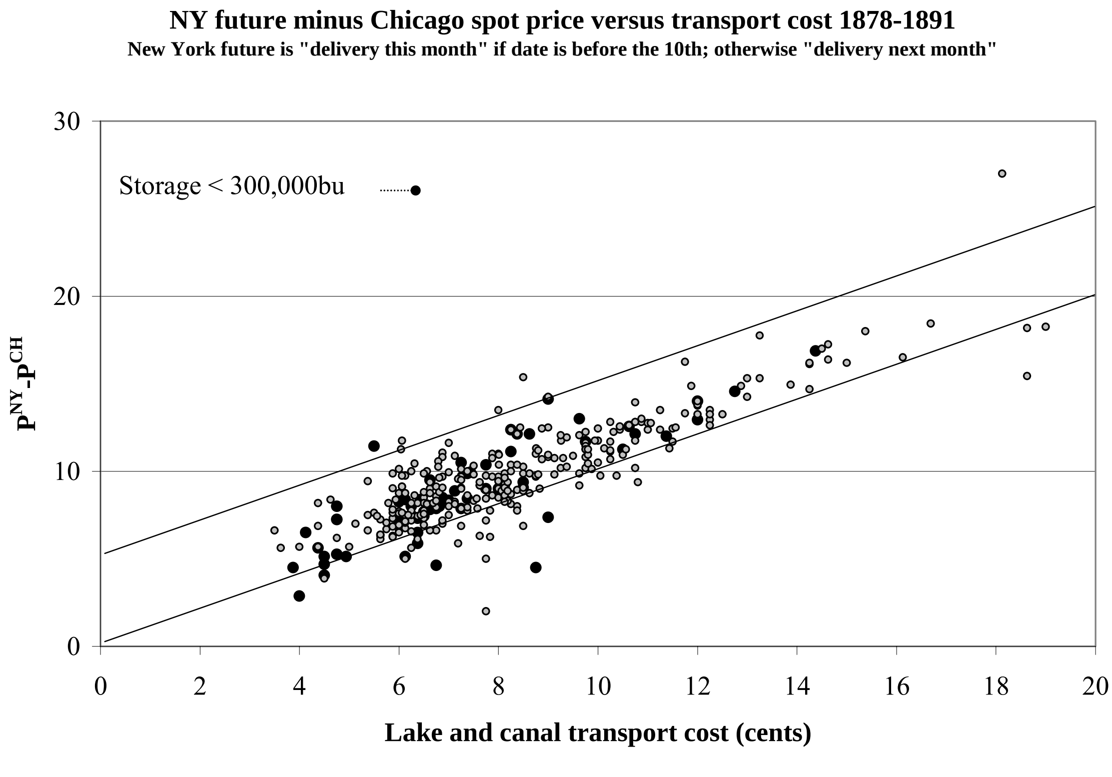


Figure 3

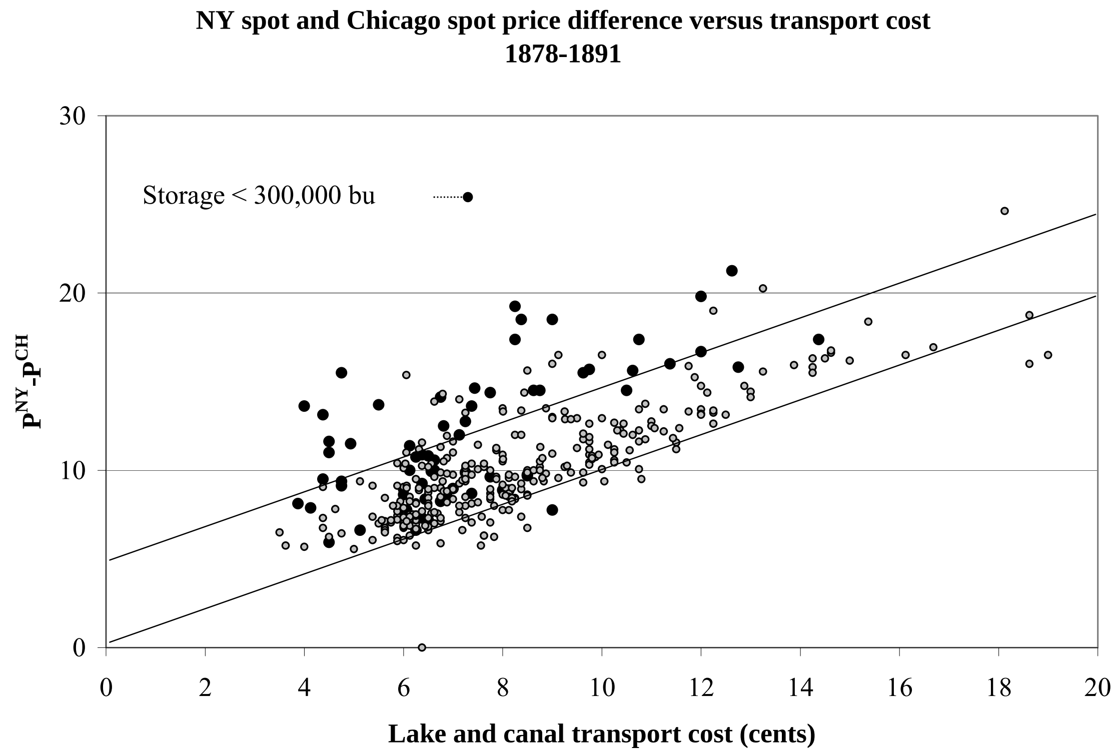
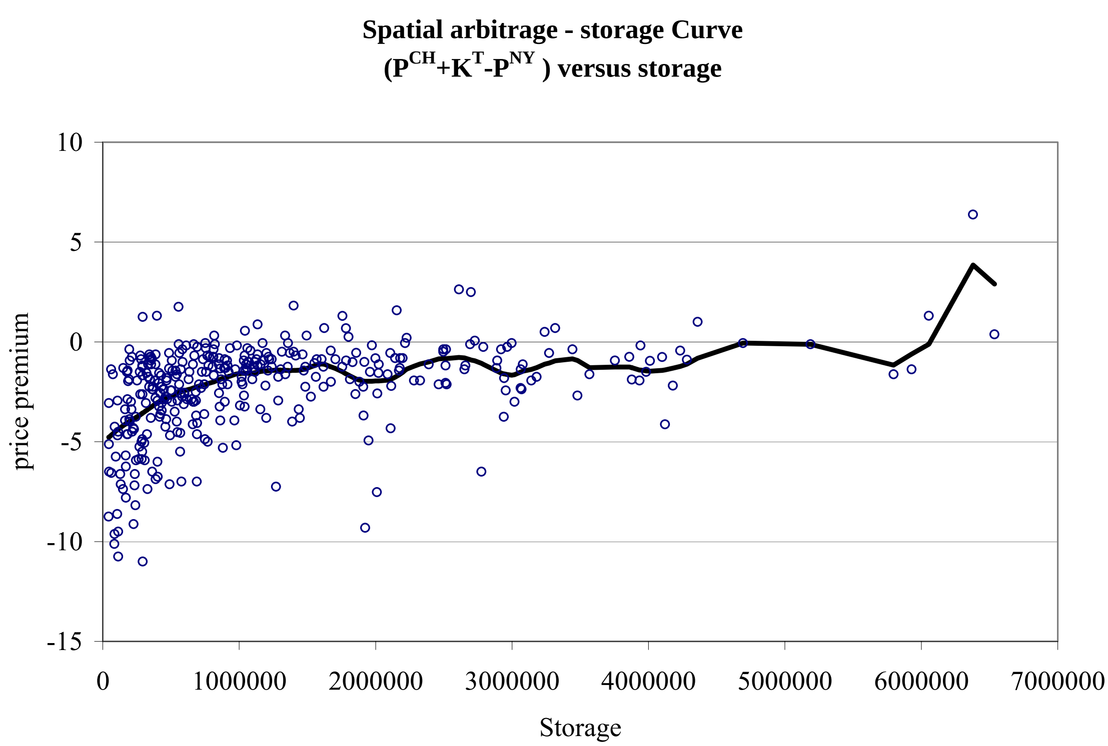


Figure 4



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