The impact of accessibility change on the geography of crop production:
A re-examination of the Illinois and Michigan canal using GIS

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Abstract

This article employs spatial analysis techniques to examine adjustments in crop production in response to the completion of the Illinois and Michigan (I&M) canal in 1848. The scope of the analysis is the particular geographical transportation system focused on St. Louis and Chicago in the mid-nineteenth century. At that time the rapid development of improved modes of transport transformed the ability of productive growing areas to reach the market with their surplus. Using geographical information systems (GIS) to develop the necessary data (parameters, coefficients, networks and so on), the article examines the redirection of Illinois’ agricultural production towards the Great Lakes transportation system then emerging at Chicago. The reactions are presented as a set of equilibrium adjustments, and are contrasted with previous efforts, such as a famous counterfactual analysis by Fogel. Rather than attempt to work backwards from a world with rail to a more primitive system of wagon and water transport, as Fogel does, this analysis works forward from a pre-existing system and shows that the impacts of the changes produced further reinforcing dynamics. The article aims to incorporate spatial analytic models into historical studies with the aid of GIS.

KEYWORDS: accessibility, canal, historical GIS, spatial equilibrium, transportation improvements
Introduction

The use of geographical information systems (GIS) in coordination with historical data analysis has prompted a lot of interest of late, in a variety of disciplines. For example, Healey and Stamp (2000) lay out a wide array of persuasive arguments for the use of GIS in historical research, particularly as a tool for integrating previously disconnected data sets. Such tools allow for spatial measurements and provide a detailed empirical basis for conceptual studies. It would be difficult, for example, to evaluate variations in cropping patterns across locations without considering a spatially referenced map of transportation and market accessibility. The Healey and Stamp (2000) case study, by exploiting GIS capability to integrate detailed railroad maps, provides the foundation for descriptive analysis of historical networks. The literature has only recently begun to employ these tools to aid in the elaboration of hypotheses or theoretically motivated questions (Knowles, 2002; Goodchild, 2004; Cunfer, 2005) although it is clear that the community of social science and historical researchers is ready to adopt these ideas with some interest. For example, Smith (2005) uses the notion of networks to describe ancient states, largely using mapping as a tool for reconstruction. The current article aims to expand the use of GIS, network analysis, and spatial modeling to assess the impact of transportation improvements in the past.

Specifically, this article employs techniques from spatial analysis and GIS to examine adjustments in crop production in response to the completion of the Illinois and Michigan (I&M) canal in 1848. The scope of the analysis is the particular geographical transportation system focused on St. Louis and Chicago (see Figure 1) in the mid-nineteenth century. At that time, the rapid development of improved modes of transport transformed the ability of productive growing areas to reach the market with their surplus. In delving into these basic factual issues, making use of the 1840 and 1850 census and other sources, GIS becomes an especially useful tool to develop the necessary data (parameters, coefficients, networks) needed to examine the redirection of Illinois’ agricultural production towards the Great Lakes transportation system then emerging at Chicago.

This analysis takes a somewhat different approach from Fogel’s (1964) well-known examination of the role of transportation in American economic development. Fogel (1964) examined the impact of the rail network as an improvement over canal/wagon for intra-regional agricultural shipments in the late 19th century. Fogel (1964) attempts to overturn the argument that rail development was essential to US Economic Development by exploring a truly intriguing question: what if the rail network had not developed? His question, essentially hinges on whether the preexisting water and wagon based transport systems could have evolved into a system with comparable capability. This article, in contrast, addresses this kind of question by reconstruction, within a well
defined study area, of the space-price adjustments in response to transport innovations.

As a step to filling in the stages of transportation development, this article takes the approach of working forward from the pre-canal system, to the immediate post canal era. It is clear that during that period a remarkable realignment of agricultural production took place in the Illinois Valley, setting preconditions for the take off in intra-regional transportation systems studied carefully by Cronon (1991). Shedding light on the transportation pattern of that era is an exercise that goes well beyond the routine use of GIS as a data integration tool, requiring equilibrium concepts from network economics (Nagurney, 1993) and careful construction of spatial network data. The present article addresses these problems, combining factual material from economic history, measurements made with the aid of GIS, and concepts from spatial equilibrium. The article also demonstrates the power of hybrid methods (using GIS/spatial analysis in social and historical research), which, as suggested by Kwan (2004), are needed in order to tackle complex analytical problems.

This article first sets some context by addressing basic questions about the changes in agricultural production in mid 19th century. In many cases the fundamental economic mechanisms were intuitively clear to early writers, but the computations and empirical measures were not readily made. For example, one gets a clear statement of reactions in terms of crop markets from this quotation from an early history of the Miami and Erie Canal north of Piqua, Ohio (McClelland, C.P. and C.C. Huntington, 1905, p 131):

Until the canal was completed there was no outlet to trade, and consequently little inducement to occupy lands or cultivate those already occupied. But after the completion of the canal, things changed. By the end of 1848 that wilderness district was in direct communication with northern and southern markets, and where three years before not a single barrel of flour or pork, or a single bushel of grain found a market beyond the immediate neighborhood there were during 1848 not less than $400,000 worth of those articles produced and transported on the canal, chiefly to the northern market.

In 1848, at the eve of explosive growth of rail networks, the Illinois and Michigan canal connected the Illinois River valley to the growing market at Chicago. This canal made possible the shipment of corn by water from central Illinois to Chicago. When the canal was completed in April 1848 it connected the Illinois River at Peru/La Salle to Bridgeport and from there via a short stretch of the Chicago River to Chicago harbor. The canal immediately became an important artery of trade (Taylor, 1917, vol 1, page 135). For a very brief time, before the growth in rail networks, it provided the only enhanced means of crop transportation to a receptive market place, crossing the stubborn physical barrier posed by moraines.
south west of Lake Michigan. As Irwin (1954, 69-70) states, prior to the canal’s opening:

There were no railroads at Chicago and all movements of grain into, or from, the city were by wagon or boat. Much of the grain arrived in farmers’ wagons or sleighs. Transportation was expensive. About 1844, when wheat prices were low, it appeared that the value of wheat was about equal to the cost of hauling it 60 miles. ... Corn was of less value per bushel than wheat and could not be hauled profitably as long distances as could wheat.

Starting immediately after the opening, receipts of corn at Chicago by canal increased dramatically, and these levels stayed high even in the face of competition from rail. But where did this corn come from? Did the transport improvement bring on completely new zones of production or did it simply intensify the production of corn in areas that had traditionally been allocated to that crop? It is worth noting, for example, that the State of Illinois produced sizeable quantities of grain for local use long before the canal opened; the 1840 census has county and township observations that allow close examination of the production of several crops prior to the canal (as well as other early industries).4 What the canal provided, however, was a new range of markets for these products, giving farmers easier access to higher prices, and in turn pumping more money into the region that was used in the intensification of settlements and the expansion of farm acreage. Because the canal linked a stretch of the Illinois River [which itself cut through the State of Illinois to join the Mississippi River near St. Louis], the canal’s impact was to provide a connecting linkage, completing a feasible pathway to eastern markets for much of central Illinois (Taaffe, Gauthier and O’Kelly, 1996; Vance, 1986). The canal, as the missing link in this chain, had an impact far in excess of its relatively short 96 miles. Indeed the initial canal was not especially capacious, efficient, or clean, and in subsequent years engineers revised the routeway to alter its direction of flow, flush larger quantities of water through, adding depth and capacity, and eventually giving rise to a massive ship canal that to this day carries enormous quantities of material in the Illinois River Valley. These impacts and data need to be examined, in context, for changes following the connection of the canal. There are many significant questions surrounding these changes including the reorganized spatial flow of crop exports to Chicago (rather than St Louis) and the apparent differential impact of the canal on two different crops – wheat and corn. The brief modal supremacy of canals was soon eclipsed by the much denser rail system. In those places where the two modes served as viable alternatives, the competitive forces kept transport rates low, and canal/barge transport handled a good share of the movement.

Background

Building the canal
The orientation of the Illinois River Valley to the south via the Mississippi was clear from Indian maps and knowledge (Lewis, 1996, 68). The benefits of connecting this south-flowing river, northwards via a short canal to the Great Lakes were obvious to the early white explorers. Mid-eighteenth century maps showed a tantalizingly small gap between the Des Plaines River and the nascent town of Chicago. The strategic importance of Chicago (and indeed the Illinois River) was noted in the 1795 Treaty of Greenville where small pockets of land were reserved for white settlement in what at the time was Indian Territory (Royce, 1971 reprint). Among these, from a lengthy list enumerated by Royce (1971), were three significant locations in the future transport corridor: including “[14.] Six miles square at mouth of Chikago river, emptying into the SW. end of Lake Michigan where a fort formerly stood. [15.] Twelve miles square at or near the mouth of Illinois river. [16.] Six miles square at the old Piorias fort and village, near S. end of Illinois lake on Illinois river.”

As documented in Goodrich (1961), many debates and much wrangling surrounded the creation of canals. The selection of the route and the pace of construction for the I&M canal and the subsequent alignment of later improvements along the same corridor involved years of surveys, negotiation, fund raising, and political intrigue [Putnam, 1918]. The location of the I&M canal as well as its successor improvements to navigability on the Illinois River all took advantage of a short cut through a moraine provided by the Des Plaines river valley. Initial plans for a deep cut were scaled back for reasons of high cost. Internal transportation improvements in the U.S. in mid 19th century were hampered by an exceptionally unstable period for capital formation. The canal had seemed to be a good idea on paper for many decades, but it was exceptionally difficult for Illinois, as it had been for Ohio in previous years (McClelland and Huntington, 1905), to raise the specie (security backed money) to pay for the laborers and materials needed for such a vast public works project. Cash strapped governments had to cobble together the money to pay for the costs of construction of capital improvements. Illinois, for example, did so by issuing bonds at a discount, persuading suppliers to take back notes in lieu of payment, and generally working the capital markets at home and abroad, in an often desperate attempt to pull together the needed cash (Putnam, 1918; Buley, 1950, vol II, 291-99). The project was eventually completed, and the earliest feasibility and engineering studies were vindicated when the waterway was later deepened and replaced by much larger channels. As suggested by Peet (1969), the daring vision of entrepreneurs able to see the consequence of transportation improvements led them to take the risks needed to fund the endeavor. And, lest there be any doubt that the risk was real, many went broke during the currency and fiscal crisis of the early 1840s though some, through a combination of good timing and the good sense to anticipate the winds of change, made considerable fortunes.

When the canal opened in 1848, as noted by Conzen and Carr (1988) and Conzen (1998), a highly important new phase in the history of Chicago began.
Once the canal entered operation, a rapid increase in revenue, as measured by the tolls collected on freight, was evident. In the case of the I&M canal, much of this revenue derived from shipments of corn from central Illinois (through canal towns such as LaSalle and Ottawa) to Chicago for export to the northeast. In the opposite direction, a large flow of manufactured goods, such as agricultural implements as well as lumber for building, went back down to the hinterland (Putnam, 1918, 101; Goodrich, 1961, 224). Bulky heavy material such as quarried stone was also moved with comparative ease after the canal opened. One basic physical factor explaining the ability of water borne transportation to provide enhanced efficiency is the often quoted ability of horse teams to pull 50 times more weight due to the lower friction of the canal drawn barges (Ringwalt, 1888; MacGill, 1917).

**Impacts and Open Questions**

As an initial example of the impact of the canal, note that in 1854, just 6 years after the opening, 4.5 million bushels of Corn was shipped on the canal, 3.3 m bushels of it from LaSalle (a distance of about 96 miles from Chicago); see Table 1. Throughout the period 1860-1885, each year hundreds of boats, logged hundreds of thousands of miles on the canal, and carried in the vicinity of 600,000 tons of material annually (in fact peaking at over 1m tons in 1882). The impact also reorganized the spatial flows from the region. Corliss (1934, 16) states that “the Illinois and Michigan canal was an important artery of commerce and travel between Chicago and the Illinois and Mississippi river basins. One important effect of the waterway was to make the Illinois River valley largely tributary to Chicago instead of St. Louis, as it had previously been.” To measure this redirection, the present article goes beyond the simple notion of canal buffer zones, and computes shortest paths from counties to markets, and along the way attempts to reconcile the predictions from a deductive model with as much of the factual record as possible.

The sense of surprise on the part of the merchants on the mix of the types of material arriving on the Chicago docks from the hinterland has left an open question that will be addressed in this research. Why did some products exceed expectations in their delivery and arrival at the port of Chicago, while others did not respond in the same way? Wheat for example did not show the same levels of activities as was observed for corn. An interesting observation, previously discussed in O’Kelly [1988 and 1989] is summarized here. The opening of the canal (Irwin, 1954, 70) resulted in a prompt response by farmers to the presence of a cash market for corn along the Canal and the Illinois River. Estimates of the volume of shipments and receipts at Chicago are provided in the Annual reports of the Chicago Board of Trade (1860, 1875) and are summarized in Taylor, 1917. However, as Taylor (1917, 139-140) eloquently points out, the impacts of the canal were not entirely as expected:
For a number of years prior to the completion of the canal, wheat had been the chief article of export from Chicago, and it must have been a disappointment to the grain dealers of the Board of Trade that the opening of the canal caused so little increase in the movement of wheat to this port, and that most of it continued to arrive in farmers' wagons as it had done ever since northern Illinois farmers began to raise a surplus. [emphasis added]

The key phrase here is that as much arrived as by farmers’ wagons as it ever had and this suggests that the mode and type of delivery to the market is clearly something which needs to be more fully analyzed. It is interesting to trace the time series of corn and wheat’s spatial extent in 19th century Illinois, taking into account the prices and location of markets and the emerging innovations in transport. The apparent anomaly of a great increase in receipts of corn as a result of the completion of the canal, and practically no increase in the movement of wheat by canal, will be shown below to be due to the growing region’s location relative to the waterway. Data must be analyzed to be able to gauge the impact of the canal and its success as a mode of transportation. What receipts were arriving by other modes? How much of the journey of the corn was still accomplished by farmers wagons from their fields to the canal? Was farming pushed to the margins of productive capability in the short 6 years between 1848 and 1854 or was there simply so much available land inside a reasonable hauling distance from the canal that the margin was uncultivated until later population pressure extended the growing region? One example, studied in detail by Hudson (1994, 137) shows that Bureau County, previously beyond the edge of the corn region, became a feasible cash crop producer with the arrival of the canal.

The test

Preliminary investigations

The data from the counties immediately in the path and adjacent to the path of this particular transportation linkage provide a key insight on the use of land in the period of the canal’s prime effectiveness. The land use changes set in motion by the initial innovation persisted and indeed were ramified by the subsequent rail nets. The rail networks also, of course, enabled a more widespread mesh of lines, branch lines, and direct access to storage facilities even in the center of Chicago.

Data Processing Steps

The data processing steps are now described in some detail. It may be assumed that the two extreme points of the river/canal network correspond to St. Louis and Chicago. At various times these nodes may be referred to as X (St. Louis) and Y
(Chicago). Refer to a vector of distances from a river node j to St. Louis as $R_X(j)$. The combined water route distance by canal and river from Chicago to St. Louis is 326.5 miles. Clearly the distance from any river node to Chicago may be defined as $R_Y(j) = [326.5 – R_X(j)]$. Also available is a matrix of direct or straight line distances from each county (centroid) to 53 river nodes.\(^8\)

Throughout this analysis a hypothetical discount factor for transportation along the river corridor is set at $a = 0.1$ suggesting that river transportation costs approximately $1/10^{th}$ of the straight line distance rate, as justified in the following brief explanation. The cost of overland transport in the early 19th century was very high, and limited the ability of farmers to reach markets. The average price for transporting grain by wagon teams in the Midwest was equal to about 15c/ton/mile (Ringwalt, 1888, p. 28). The rate calculation is based on the 20 cents charge for hauling a 55 pound bushel 50 miles. Overland rates of 10 to 20 cents per ton mile prevailed in the Midwest in mid-nineteenth century [Ringwalt, 1888; MacGill, 1917; citations in Locklin, 1938, 33].

The comparative costs by water/canal are represented in this research as one tenth of the over-land rate (i.e. 1c – 2c per ton mile). This parameter subsumes a wealth of intricate detail, but is consistent with the impacts measured in various canal projects. The broad basis for the generalized ratio is as follows: MacGill (1917, 80) cites an analysis by Robert Fulton which indicated that “The farmer or miller who lived 20 miles from market paid at least 22 cents to wagon a barrel of flour that distance. Fulton estimated that by canal it would have cost 2 cents.” The examples go on to show that this was not intended to apply merely to this particular short distance, but rather that journeys of 100 or 150 miles would enjoy similar proportionate savings. This is consistent with Segal's (1961) summary to the effect that “wagon rates in the period 1837-46 averaged about 25 cents while the canal rate was about 2 cents per ton mile.” The improvements in freight rates the Midwest were reported in Gamst (1997) show rates for canal transport in the 1.2 – 1.8 cent per ton mile range for wheat and 0.8 – 1.2 cent per ton mile range for corn (Gamst 1997 reprint of von Gerstner's 1842-43 report, pages 383-4). A footnote in Segal's (1961) paper in Goodrich, has a specific rate of 1.4c/ton/mile on the I&M canal.

These comparative rates are cited for a specific commodity over a particular route; clearly, an average computed from primarily longer haul routes would tend to reflect the lower per mile costs over long hauls. Thus, it is important to know the distance range of the shipment to derive the appropriate discount rate. It is clear that most canal shipments within Illinois and Ohio were relatively short, and the savings, while significant, were not as high as some of the effects measured on the Erie canal. Erie Canal rates dropped transport costs dramatically, (by 91% in the account of Segal, 1961, 228) and to as low as 5% of the prior rate as the canal was constantly improved.
As a blend of the wealth of these specific route rates, a summary ratio of one tenth the prevailing wagon rates is employed as a reasonable approximation for canal freight rates. Sensitivity to this assumption of a 90% saving requires some brief consideration. In the particular instance of the Illinois & Michigan canal, one assumes that the trip to the canal takes place at a prevailing rate and the completion of the trip follows at the discounted rate. Thus the entire journey costs from I to J might be some combination of an undiscounted portion and a discounted portion. The more a canal improves over prevailing rates, the more the farmer would have an incentive to make a direct path to the canal, to maximize the portion of the journey completed at the lower cost (Werner, 1968).

A discounted rate of one tenth the prevailing rate would essentially prompt the farmer to approach the canal at its closest point in the direction of the intended market. Sensitivity analysis to the discount factor is discussed in a related geometrical model by O’Kelly (1988) who shows the increase in supply as a function of lowering freight rates. Generally speaking, the greater the discount for water freight by canal the more the market and local prices converge, with the benefits apportioned by market forces between lower market center prices and higher farm gate prices. Interestingly, it can be shown that the steeper the discount the closer to the market is the location experiencing say a doubling of local prices.

The first step in the analysis is to range over all 53 river nodes to find the one that is best suited to transportation from a county to St. Louis and Chicago respectively. The lowest cost path from origin county \(i\) to St Louis is found by searching over all intermediate river nodes and selecting the minimum distance (through node \(j\)) of \([C_{ij} + a R_X(j)]\) where \(C_{ij}\) is the distance from \(i\) to the river node \(j\). Similarly the lowest cost path from county \(i\) to Chicago is found by searching over all intermediate river nodes and selecting the minimum distance (through node \(k\)) of \([C_{ik} + a R_Y(k)]\). It should be clear from the preceding definitions that the minimum resultant river distance to Chicago and St. Louis cannot exceed their respective straight line distances. This is because the Chicago node is itself one of the river nodes and any path that entailed a distance longer than the direct distance to Chicago would not by definition be a minimum path. (Mathematically \(C_{ik} + a R_Y(k) \leq C_{iY}\) with equality if \(k=Y\).)

As a byproduct of this calculation, we keep track of the node on the river which is used to reach the city market from each county (\(j\) and \(k\) respectively in the above notation example). This adaptation is significant and will prove to be very useful later when we come to determine the mode of transportation from each county to the city markets. If the shortest path distance to one of the markets involves a river or canal node, it is likely to use water transportation to reach the market. By adding up activities in such counties we can determine the fraction of total demand arriving at the city markets by direct and water means.

At this stage then we are in a position to make a very simple calculation for the pre- and post-canal shortest distances to the city of Chicago. The pre-canal
distance to Chicago is a straight line distance from the county to the city because prior to the canal’s existence there was no river-based waterway access to the city. The post canal distance to Chicago is the minimum of either the waterway distance (evaluated above) or the straight line distance. The distances to St. Louis are a little bit more difficult because St. Louis had a water route prior to the canal’s existence. Navigation on the Illinois River north of St. Louis was not easy before improvement of that waterway, so that as a surrogate for travel impedance we assume that only river nodes within 120 miles of St. Louis provided usable waterborne access to the city prior to 1848. After 1848, with the canal’s completion and the improvements of navigation and removal of various bottlenecks along the river, calculations for St. Louis become logically similar to those for Chicago: that is the distance is either the straight line distance or the distance by the shortest intermediate river town. Realizing that the waterway enters St. Louis from the northeast it’s clear that any town south of St. Louis does not have a sensible pathway via the Illinois waterway to that city – this would involve backtracking over a portion of the river (see Clusters 3 and 6 in Figure 1). So cities to the south would invariably reach St. Louis by straight line or in fact might even be selling their goods southwards into the Mississippi river valley. Similarly, towns and cities to the north of Chicago (Cluster 1, Figure 1) were much less likely to be able to use the improved waterway than say a town or city in the middle of the range of the river (such as Peoria, Cluster 2, Figure 1). For this reason that spatial impact of the river and waterway improvements are expected to be differentiated over various parts of the state.

Having determined a number of distance calculations and performed some basic validation steps to ensure that the geometrical and spatial relationships between the entities are accurate, the data are now ready to be used as pre- and post-waterway distances from each county in Illinois to the two major markets of St. Louis and Chicago. By regionalizing the counties into those that experienced a variety of different transportation cost changes, it is possible to determine and validate the relative spatial locations of these demand areas with respect to the markets. The resultant clusters of counties (shown on Figure 1) contrast areas that experienced a potential improvement in transport cost to Chicago (Clusters 1, 2, 4, and 5, refer to Figure 1), to those which experienced relatively little impact from the canal (Clusters 3, and 6, see Figure 1). Furthermore, it is evident that the distance calculations described above accurately pick up the preferred corridor through the center of Illinois. This area -- stretching from the southwest to the northeast -- is one which saw dramatically better access to the city of Chicago upon completion of the relatively short connector system to that city.

These various classifications produce a series of county groupings each of which had a similar travel cost experience. The crop adaptations to the changing transportation circumstances might be expected to be reflective of their location relative to the two markets.
Equilibration

The conceptual idea of equilibrium is fairly straightforward: any market that is being actively supplied from a particular origin (growing area) cannot be out of kilter with the rest of the system. If there is a particular set of places that deliver material to a particular destination market (such as Chicago) they must all, in theoretical equilibrium, do so for about the same delivered price. The complication comes in the fact that the price at the destination depends on how much material is delivered there, and the prices at the sources depend on the amount that they are able to produce for sale. In this equilibrium model the demand and quantity supplied from each growing area to each intermediate market are determined as a function of transportation costs and other parameters: a realistic assumption given the previously cited facts about cropping responses to available/accessible markets.

Single market and multiple sources

The simplest case of equilibration occurs for the delivery of material supplies to a single market such as Chicago, from a series of separate source regions (Illinois counties). In the method described by Nagurney (1993) the sources or origins are labeled L = 1, ..., M. But these origins are geographically dispersed with respect to the market and so each has its own identifiable transportation or access cost. Assume that the sources are sorted in increasing transportation costs from a particular port or market. The basic idea is to set a price at the final market which will bring forth precisely the correct amount of supply from the sources to balance final market demand at that price (Nagurney, 1993). The calculations for one market (call it market k) equilibrium from multiple origins are shown in Figure 2, reflect the data in the small example shown in Table 2.

Because we are dealing with just one market in this example, we omit the subscript k for each market. Suppose the price that the market is a simple inverse demand curve:

\[ P^* = q - r X \]

where \( X = \sum_i x_i \), is the quantity delivered to the market from the surrounding sources and where \( q \) is the prevailing price at the market, and \( r \) is a slope term that determines the rate at which the market price falls with extra supply. [Think of this as price decreasing with increasing delivered supplies, the inverse of demand increasing with lower prices.] We will address in a moment the question of which sources can supply the market but for now presume that the number of sources is \( v \). Each local source supplies a quantity that is determined by the local price \( P^* - h_i \) and which is equal to \( x_i = (P^* - h_i)/g_i \), where the two important parameters, \( h_i \) and \( g_i \) define the local price and supply coefficient respectively.

So substituting into the other expression for \( P^* \) we see that

\[ P^* = q - r \sum_i (P^* - h_i)/g_i \]
By adding up $\sum (P^* - h_i)/g_i$, we are determining how much comes into the market from the surrounding sources and the greater this number the lower the expected equilibrium price in that market, as reflected in the amount that is subtracted off the “base” price (q).

Since $P^*$ appears on both sides in this equation is necessary to solve for that variable and some basic algebra reveals:

$$P^* = \frac{q/r + \sum (h_i/g_i)}{1/r + \sum (1/g_i)}$$

and in this equation market center price is determined as a function of the known “exogenous” parameters q, r, h, and g. As explained by Nagurney (1993), in the case of trade between the pair of markets, “a spatial price equilibrium is obtained if the supply price at a supply market plus the cost of transportation is equal to the demand price at the demand market.” It remains to define the supply price and the demand price. The supply price is (in this formulation) simply a reflection of the fact that local supply increases at higher prices, so that inverting this relationship, price increases with supply. A small numerical example of a solution to such a problem will help (Figure 2). Given a market with a demand price of $P = 28 - 2X$, where X is the quantity of material delivered to the market, suppose that the price at that market is $P = 14$, and the Figure 2 demonstrates that the solution is indeed in equilibrium, calling forth a supplied quantity of $X = 7$. The fact that this is an equilibrium price can be seen by adding up the appropriate three quantities from the supply sources (i.e. 3 from source 1, 2.2 from source 2, and 1.8 from source 3) given the local price at each source associated with this central market price.

While derivation of this solution technically requires an explanation at the level of network equilibrium, the idea of which counties are active as supply sources is quite simple. First sort the origins in increasing order of transport cost. Then proceed by including first one, and two, and three, and so on of the sources. At each of these steps the equation for $P^*$ (market price) can be solved and one keeps going until a potential source reaches an infeasible (negative) local price. One includes all the sources up to the last valid one. At that stage $P^*$ is set, all the local production levels may be computed, and the aggregate delivery to the market satisfies the market demand.

**Multiple markets and sources**

Assume that a set of supply areas (the counties or towns of Illinois) are producing materials for sale to multiple regional market demand centers at Chicago, St Louis, and perhaps a few other intermediate locations. Thinking of these spatially separated demand centers, the distribution of material produced from the supply counties to these places is to be determined. At each major iteration, one progresses through each of the demand centers in turn. At the kth step, when we come to the jth demand center, we use kth iteration data where it is available (typically for places we have already processed in step k). For those places where we have not yet made a kth stage determination, we use the
information from the previous or k-1st step. The iterations progress by starting with temporary holding values for all the unknowns, eventually updating and replacing these with iteratively improved values. After convergence, each origin and market pair has a particular price and transport combination that allows the markets to determine which places supply which cities.

The complex interdependencies can be illustrated as follows. Assume for now that the equilibration steps have been worked out, and that the prices at the final markets are determined. For any particular county, the local price is the market price minus the cost of transportation to each market. These local signals may or may not call forth some amount of production. It is the aggregate of all such production and shipping decisions that influence the quantity delivered to each market, which is where the need for equilibration comes in: the prices have to be worked out so that the delivered quantities are warranted by the market price. The role of transportation improvement in all of this is obvious; variations in transport costs serve to alter the localized version of the market price.

**SPE applied to the I&M canal**

The data collected so far are now used in a space-price equilibrium framework that will determine the before and after equilibrium prices for crops at the two market destinations, the production of the crop in each of the counties, the direction of that crop’s flow for the two markets, and an inference about the probable mode of transportation for the county based on the nodal connectors described in the preceding paragraphs.

The critical assumptions and parameters in this experiment are set as follows. Prior to the canal’s construction, no water access to Chicago was possible. After the completion of the linkage to Chicago the remainder of the Illinois River valley gained access to the market in Chicago. Therefore, after the completion of the canal, river and canal access to Chicago was available for any county where the logistics offered a reasonable route and distance combination by comparison to the default straight-line distance.

The river provided access to St. Louis even before the completion of the canal but navigation over the water was not easy prior to the development and improvement of locks and channels. Therefore as a limitation on the access to St. Louis, only those river access points within 120 miles of that city were assumed to provide a feasible route prior to 1850. On and after 1850 it was assumed that the completion of the canal and simultaneous improvement of locks and basins along the river greatly facilitated the movement of traffic in both directions on the river between LaSalle, Peoria and St. Louis.

The second assumption in the simulation is that the market price for grain at Chicago exceeded that of the market in St. Louis in view of the capability of shippers at Chicago to forward produce to East Coast markets where demand
was adequate to absorb as much excess production as could be delivered. Chicago was the entry point to an all water route via the Great Lakjes and the Erie canal, that while extending for over 1500 miles was much more practical that reaching the east coast via St. Louis (which required connection through the Port of New Orleans, and a lengthy sea journey to market).

Various subsets of the results can be devised once the flows from origins to markets are determined. In other words the origin to market flow is expected to follow the path distance that was devised for that node at the outset of this analysis. Since we keep track of the particular intermediate path steps between the origin and destination we are in a position to determine the routing and mode and destination of all nodes in the system by making a series of summations from the output in the spatial equilibrium model.

**Equilibrium total flow**

The total flow to each market is

\[ D_k = \sum_i \sum_j X_{ijk} \]

where \( X_{ijk} \) is the flow from county \( i \) to market \( k \) through river node \( j \).

We know that the price and quantity at equilibrium, in market \( k \), is determined by

\[ P_k = r_k - q_k \cdot [D_k] \]

The total flow from all sources and modes to each city shows us the relative flows to both markets for commodities and can be sensibly tabulated for before and after conditions. After the canal was completed the flows to Chicago increased by almost 50 percent. The units are hypothetical relative values, not specifically calibrated to actual tonnage. Prior to the canal, St. Louis dominated transport from Clusters 2, 3, 6, and Chicago was the closer alternative for Clusters 1, 4, and 5 (refer to Figure 1).

Prior to the completion of the canal, by definition, no material arrived by river to Chicago and after the completion of the canal it is interesting that almost the entire supplied quantity is shown in this model to be optimally delivered by water. St Louis on the other hand saw a less dramatic increase in arriving quantities after the canal.

**Spatial distribution of production – output**

The total supply from each source is computed by adding up over all destinations and river nodes:
$S_i = \sum_j \sum_k X_{ijk}$ is the total production from each origin, regardless of mode or destination for ultimate distribution.

More useful is the productivity of each of the counties towards the two markets, recognizing that some counties may produce for sale to both markets. The flow from each county to each market is computed as:

$S_{ik} = \sum_j X_{ijk}$

This is the flow at each origin to destination $k$, and it tells us the orientation of each county to the two markets no matter which way it is routed (direct or by river). The results of this computation are shown in Figures 3(A) and 3(B) which simply demonstrate the regionalization of the production of crops towards the two markets across 102 origin zones in the state of Illinois. It makes sense to show this diagram for both the before and after conditions. Before the introduction and completion of the canal both St. Louis and Chicago had relatively confined spatial market supplies and after the linkage was completed the dramatic opening of a central Illinois for production to Chicago is evident in the model result.

The main application of these measures is to determine the orientation of the total production to each of the two destinations by adding up the percentage of crop distributed to each center:

$Z_{kl}^{(a)} = \sum_{i \in R_a} \left[ \frac{S_{ik}}{S_i} \right] \times Y_{il}$

Where $R_a$ is the list of county membership in cluster $a$, $Y_{il}$ is the total output of crop $l$ in zone $i$, and $Z_{kl}^{(a)}$ is the aggregate arrival of crop $l$ in city $k$ from zone $a$.

The changes in flow are shown in Figures 4(A) and 4(B). It is interesting to note that areas where the canal had the greatest impact produce increases in supply over the pre-existing conditions. Because of the increased aggregate supply, the downward pressure on prices at the markets actually reduced the ability of some counties to supply the adjacent market and in these cases the portion of the circle before exceeds the portion after. A county with no change would show as an evenly divided circle.) The resulting aggregates are shown in Table 3. Note that the Clusters numbered 1, 4 and 5 experienced considerable increased production, and given their orientation to Chicago, delivered crops to that market in large quantities. The data in Table 3 show for example that the share of regional corn production (obtained by weighting the orientation to each market by the aggregate production observed in the counties over time) to St. Louis dropped from 66 percent in 1840, to 45 percent in 1850, and 40 percent on 1860. Conversely, Chicago gained larger shares of the burgeoning production of corn as a cash crop (Hudson, 1994).
How much traffic at each river node (by destination)?

The amount of flow at each river node regardless of origin or destination is

\[ R_j = \sum_i \sum_k X_{ijk} \]

This quantity is useful in telling us how busy the river nodes would be and may help to explain the relative success of selected river nodes and towns by virtue of their fortuitous location that particular points on the river. A better way to compare these results, is to maintain the disaggregate flow to the final markets.

The flow from each river node to each market is computed as:

\[ R_{jk} = \sum_i X_{ijk} \]

This is the flow at river node j to destination k – tells us what parts of the waterway predominantly looked to each city. The results of this computation show the St. Louis catchment area stretching northward by about 60 miles and the reach of Chicago well into central Illinois. A number of subtle effects are also captured by this calculation. One might wonder why a node might show complete dedication to one destination or the other. A lot depends here on the position of the county on the sinuous river. Routing conditions for each origin determine the best river node to use on the path to one of the destinations. If a pair of river nodes is close together it is not surprising that the one closer to St. Louis will handle St. Louis traffic and the one closer to Chicago will be the destination for Chicago bound traffic. Why then do some nodes handle traffic in both directions? The answer is simply that river nodes are well positioned to be on the shortest path from origins to both destinations.

Link flow

The network also permits a very simple assignment of flow to the network links. Since every origin is connected to a particular river node and the river node in turn is linked to each of the two ultimate destinations, a simple matrix of origin to destination flows for St. Louis and Chicago respectively can be loaded onto the network to produce link flows that show how much material ultimately reaches the two destinations. A useful cross check on the analyses above showed that the link immediately preceding Chicago and St. Louis each handles the sum total of expected river flow to those cities. This amount is not quite the same as the total demand for each city because some flow is still expected to reach the destinations by direct means. Arithmetically, sum of the inbound flow on the river to each of the cities plus the direct flow matches the total demand projected from the spatial equilibrium model. The data analysis step involves doing the network assignment, producing a matrix of origin to destination flows for the destination of St. Louis and separately for the destination of Chicago.
The equilibrium traffic assignment procedure using an all-or-nothing allocation, assigns the link flow based on the river node to destination path. In another words the river nodes are already preloaded with their total expected interaction with each of the two river ends and these flows then [given the simple linearity of the network] are assigned to an obvious path along the river to the end. These patterns have an intuitively reasonable increasing concentration of flow towards the market center. They also provide an opportunity to make a useful cross check with one of the elements that are available for the canal and river. Since the river data collected during operations of the canal include the relative quantities of materials passing lock points, it is possible to determine the fraction of total inbound flow arriving in Chicago that passes each of the preceding major lock points. While the data here are perhaps too crude to permit a precise validation, it is certainly reassuring that the link flows are consistent with comparatively busy loads through the towns of LaSalle and Lockport.

Conclusions

This article takes a small part of the transport/land use interdependence problem and simplifies it to the addition of a single network connector just before 1850, and then examines the impact of that connection on distribution and transportation usage. The obvious direct test of showing the complete agricultural shipment system before and after Illinois & Michigan canal is impossible because the coincidental rapid growth of rails. Rail accounted for over half the delivery of wheat to the Port of Chicago as early as 1852 and by the late 19th century, the impact of rail had reached irreversible dominance. Precisely because rail was so ubiquitous and intermeshed with all aspects of freight distribution, it is impossible to disentangle step-by-step the impact of canal from rail and to evaluate what might have happened if each of these incremental steps had not taken place. By 1890 (the key year in Fogel’s (1964) analysis) the cumulative impact of 40 years of transportation improvements were so intermeshed, that one could not isolate the effect of specific modes. Without the rails, the agricultural production patterns would have been quite unlike the world as it evolved by 1890, just as the 1850s and 1860s could not have been sustained by the pre-canal systems. Moreover the idea of working forward from 1850 with the impact of rail presents a formidable challenge in terms of the complexity of the new networks (see again Healey and Stamp 2000). Fogel’s solution to this interdependence is to use a counterfactual approach (re-optimize with constant supply and demand) which relies on an assumption that spatial supply and demand can be held constant. This current article however clearly shows that it is possible to relax the constant supply and demand background, by equilibrating the flows. In this sense this current analysis offers a more complex approach to the equilibration of flows that surround a transport innovation. It is still partial equilibrium in the sense that the sizes of the markets in St. Louis and Chicago were driven by their own endogenous population growth, some portion of which was undoubtedly due to the vibrant economy resultant from transportation innovations. Whether it is possible to re-examine Fogel’s ideas directly with a
more complete general equilibrium model is the subject of further research. An
extension to this present article to use a two-mode (rail vs water) space price
equilibration with competition and endogenous trade flows is the next logical
analytical step needed to provide a more complete answer to what is already a
complex set of issues.

Two conclusions may be gleaned from this study. First, the introduction of an
improved transportation corridor sets in motion a series of changes to the
locations and regions that supply the spatial markets. The prices at those
sources adjust to the supply situation and the demands of the market center.
This approach is in fact consistent with the observed changes that would be
expected to occur under the change transportation development and
infrastructure. Second, the benefits of these early steps in integrating GIS and
historical social and economic spatial analyses is that they underpin a more
complete cost/benefit assessment of the social impacts of transportation.


3 An earlier effort to determine the land use impact of canal development using pre-GIS mapping was in Leaman and Conkling (1975).


5 As early as 1673 Marquette and Jolliet followed the Illinois from its mouth at the Mississippi up to the Desplaines “and ascended that source to the Chicago Portage.” (Boylan, 1933, page 6).

6 Page 42, Board of Trade 28th Annual Report, Year Ending 31 December 1885. Published 1886.

7 The precedents for such a combined historical-spatial view are well established in geography; see Peet (1969), Chisholm (1962), and Hudson (1985 and 1994).

8 The nodes were created by joining the point layer to the river using a technical step in TransCad.

9 The role of river transport to St. Louis is reviewed in superb detail by Mahoney (1990). He, however, pays relatively little attention to the post canal impact, preferring to focus on the important role of the upper Mississippi valley on the trade area of St. Louis.

10 While von Gerstner (Gamst, 1997) stated that the Illinois River provided a navigable channel from its mouth to LaSalle (and even Ottawa at high water) the analysis in Putnam (1918) suggests that the river was in need of substantial improvement in
channels, especially for steamboat traffic. Because these improvements were not in place until the mid 1800s the pre-canal model is run with an assumption that the river provided limited access to St. Louis. Other support for the notion of the river’s limited impact at the earlier dates is in MacGill (1917, 514) when she states that the interior of the state, is “without natural means of transportation” with the exception of comparatively small areas tributary to the Illinois and Kankakee Rivers. See also Mahoney (1990).

11 Convergence to a unique equilibrium is guaranteed under some reasonable mathematical conditions. A full treatment is beyond the scope of this article, but see Nagurney (1993) for the conditions for existence, uniqueness, convergence, and stability of the derived equilibrium. Future work is intended to follow up this issue and to exploit the many advantageous mathematical properties explained in Nagurney (1993). It turns out that formulation of this problem in price terms (as we do here) requires only weak conditions on the supply and demand functions (which ours meet) and that as a useful by-product of the formulation one gains access to some powerful qualitative “what if” results and sensitivity analysis.

12 This effect was noted previously in Chisholm (1962) and O'Kelly (1988).

13 Cronon, 1991, page 67. In this case Cronon is referring to the rapid uptake in the Galena and Chicago Union railroad.
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References


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Figure Captions

Figures

Figure 1 Route of Illinois and Michigan Canal

Notes to Figure 1.

CLUSTER 1: Improved access to Chicago; Not within river access to St. Louis pre 1848; River access to St. Louis improved after 1848.

CLUSTER 2: Improved access to Chicago; River useful for St. Louis pre 1848 and River access to St. Louis improved after 1848.

CLUSTER 3: Improved access to Chicago; River not useful for St. Louis

CLUSTER 4: Not much improvement in Chicago access; Not within river access to St. Louis pre 1848; and River access to St. Louis improved after 1848.

CLUSTER 5: Not much improvement in Chicago access; Not within river access to St. Louis pre 1848; and River access to St. Louis improved after 1848.

CLUSTER 6: Not much improvement in Chicago access; River not useful for St. Louis.

Figure 2: Equilibrium example from 3 sources to 1 market. Source: Author’s hypothetical example.

Figure 3(A): Flows from each county to the two markets, before transportation improvement. Source: Author’s calculations. Transcad graphics.

Figure 3(B): Flows from each county to the two markets, after transportation improvement. Source: Author’s calculations. Transcad graphics.

Figure 4(A): Changes in flow to St Louis from each county, after transportation improvement. Source: Author’s calculations. Transcad graphics.

Figure 4(B): Changes in flow to Chicago from each county, after transportation improvement. Source: Author’s calculations. Transcad graphics.
The Illinois and Michigan Canal

- Illinois and Michigan Canal
- Illinois River
- Clusters

Legend:
- St. Louis
- Chicago

Cluster 1
Cluster 2
Cluster 3
Cluster 4
Cluster 5
Cluster 6

Miles
0 30 60 90
The Illinois and Michigan Canal

- Illinois and Michigan Canal
- Illinois river
- Clusters

Legend:

- 2
- 1
- 0.5

- Before
- After

Miles:

0 30 60 90

Clusters:

- Cluster 1
- Cluster 2
- Cluster 3
- Cluster 4
- Cluster 5
- Cluster 6

Cities:

- Chicago
- St. Louis