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Simulating the Two Views of the British Industrial Revolution

C. KNICK HARLEY AND N. F. R. CRAFTS

This study examines technical change, trade, economic structure, and growth during the British Industrial Revolution by means of computational general equilibrium (CGE) modeling. It rejects Peter Temin's contention that our "new view" of sectorally concentrated productivity growth is inconsistent with industrial export data. A CGE trade model with diminishing returns in agriculture and realistic assumptions about consumer demand shows that while technical change in cottons and iron were major spurs to exportation of those specific goods, the need for food imports also stimulated exports generally. Incorporating trade data thus enriches our "new view."

The British Industrial Revolution coincided with the beginning of "modern" economic growth, meaning sustained increases in per capita income. Modern growth was clearly well underway in Britain by the middle of the nineteenth century. Population had been growing at an unprecedented rate for about a century, but real wages were not falling as in earlier demographic upswings; by mid-century, at least, they were increasing steadily. Half the population of this growing economy now lived in cities, the fastest growing of which mushroomed in the North and the Midlands to accommodate the new factories created by the technology of the age: spinning machinery, steam engines, and coal-based metallurgy. The male population had become largely industrial, with less than 30 percent remaining engaged in agriculture. The association between the Industrial Revolution and modern economic growth was so close in both time and place that causation seems obvious. We know, however, that industrialization and affluence are not always the same thing. Prior to the Industrial Revolution, indeed, the two were often inversely related. Many protoindustrial regions of early modern Europe, and perhaps New England as well, developed manufacturing as part of a Malthusian process of rising population encountering limited agricultural resources. Low implicit wages attracted industrial entrepreneurs, and

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the export of manufactures financed food imports that provided partial relief to the straitened population.

To be sure, the famous inventions of the British Industrial Revolution provided a powerful supply-side push to industrial production and real incomes. There is no question that Arkwright's and Crompton's spinning machinery greatly increased productivity. Watt's steam engine clearly improved power production. At the same time, however, even though agricultural progress was notable, very rapid population growth put pressure on Britain's natural resources. Assessment of the impact of the spectacular technical breakthroughs of the late eighteenth century requires analysis of the national economy as whole. More than 40 years ago, Walther Hoffmann, Phyllis Deane, and W. A. Cole used the highly imperfect statistical information surviving from the late eighteenth and early nineteenth centuries to construct aggregate estimates of economic activity. Their quantitative research supported the view that the Industrial Revolution had played a crucial role in accelerating aggregate growth. Hoffmann's index of industrial production showed impressive acceleration after the 1770s, driven primarily by the acceleration of growth of those industries affected by the famous textile and metal-working innovations. Deane and Cole's national-income estimates reinforced this conclusion, finding that both industrial output and national income per capita accelerated at the time of the Industrial Revolution. These quantitative estimates supported traditional accounts of the British Industrial Revolution by T. S. Ashton and David Landes, wherein the Industrial Revolution was characterized as technical change occurring widely through the economy, as the engine that initiated modern economic growth.[1] This interpretation is still advanced by Landes, and has strong support from other scholars such as Maxine Berg and Pat Hudson.[2]

Reassessment of the quantitative evidence, however, suggests that Hoffmann, Deane, and Cole substantially overestimated British growth before 1840, and particularly the extent of the discontinuity around 1770. Our own reworking of the quantitative evidence arrived at a revised view—the "new" or "Crafts-Harley" view—indicating that during the Industrial Revolution technical change was in aggregate much slower, and more concentrated in a few industries, than most historians had previously believed. The new view recognizes that the structure of the British economy underwent a rapid structural transformation during the classical period of the Industrial Revolution (1770 through 1830), culminating in a very low share of agricultural employment by 1850; but it maintains that aggregate growth was considerably slower than earlier narratives and quantitative estimates had suggested.[3] The new quantitative work suggests that the origins of mod-

[1] Hoffmann, *British Industry*; Deane and Cole, *British Economic Growth*; Ashton, *Industrial Revolution*; and Landes, *Unbound Prometheus*.

[2] Berg and Hudson, "Rehabilitating"; and Landes, "What Room?"

[3] Harley, "British Industrialization"; Crafts, *British Economic Growth*; and Crafts and Harley, "Output Growth."

ern economic growth extend over a longer time period and a wider geographic area than are traditionally encompassed in studies of the Industrial Revolution.

The Crafts-Harley view has been widely supported, but it has nevertheless disturbed many commentators who find its implications hard to reconcile with Britain's rapidly changing economic structure and trade patterns in the mid-nineteenth century. Initial unease focused on Crafts's conclusion that the rate of technical change in agriculture exceeded that of the economy as a whole, with the obvious exception of the textile and metal industries at the heart of the Industrial Revolution. If British agriculture was so productive, why did its share of national product diminish so sharply?[4] Recently, Peter Temin has extended the challenge using a theory of international trade that emphasizes technical differences between countries. He argues, contrary to the Crafts-Harley view, that ongoing export successes—and, by implication, continued vigor within the British economy—of sectors beyond those famously transformed by the Industrial Revolution implies that technical change was widespread among British industries during the early nineteenth century. He concludes that

> the traditional, "old-hat" view of the Industrial Revolution is more accurate than the new, restricted image . . . The spirit that motivated cotton manufactures extended also to activities as varied as hardware and haberdashery, arms, and apparel . . . The low rate of productivity change shown [by Crafts and Harley] for other activities is too low. There must have been more technical progress outside the listed sectors.[5]

An understanding of the economic forces driving the Industrial Revolution has remained somewhat elusive, although we have tried in earlier works to provide some insights.[6] The structure of the British economy evolved via general-equilibrium adjustment in an open economy. In this study we shall develop a computational general equilibrium (CGE) model of the Industrial Revolution in which structural change arises out of resource reallocation among industry, agriculture, and services, in response to population growth and uneven innovation in an economy deeply involved in international trade. The major structural changes in Industrial-Revolution Britain—the growth of the famous textile and metal industries and the contraction of agriculture—both owed a great deal to foreign trade. Furthermore, as Temin has observed, modeling the evolution of trade may provide important insights into productivity growth.

Any realistic model of the Industrial Revolution must include two key features. First, British population grew very rapidly, whereas land resources grew only slowly.[7] Second, the output of leading industrial sectors—par-

[4] Williamson, "Debating," p. 275.

[5] Temin, "Two Views," p. 79.

[6] Crafts, *British Economic Growth*; and Harley, "Reassessing."

[7] For textbook affirmations of this point see McCloskey, "Industrial Revolution," p. 107; and Overton, *Agricultural Revolution*, p. 88.

ticularly cotton textiles—became very large relative to world markets and crucially affected world prices. In addition, the model must accommodate the available evidence. Specifically, individual "industries" as conventionally defined produced a variety of goods that were at best imperfect substitutes for one another; as such, goods within categories of the trade statistics were heterogeneous bundles of imperfect substitutes.

Our model provides an explanation of the evolution of Britain's foreign trade and its economic structure. Population growth in the face of limited land resources, even with improving agricultural technology, put upward pressure on British food prices. In the absence of international trade, British food prices would have risen above world levels. But trade was possible, so the demand for imports increased. Food imports had to be paid for; in general equilibrium, increased demand for imports leads to increased exports. Without the Industrial Revolution, British exports of various products probably would have expanded in approximate proportion to their levels around 1770. Of course, British cotton textiles experienced spectacular technical change at this time and quickly captured export markets, independent of the demand for food imports. But we must keep in mind that the export success of British cotton textiles rested on the dramatic fall in their price. Exports increased enormously, but prices fell dramatically as well. As a result export revenues grew much more slowly than export volumes, suggesting that the export of other commodities remained necessary to pay for food imports.[8]

Technical advance was an important influence on British foreign trade, as textiles and metal goods rapidly conquered foreign markets; and yet many "old" exports persisted, because technology alone did not determine the evolution of Britain's trade. Growing population pressure also encouraged agricultural imports. The CGE model indicates that financing these imports required sustained exports from many industries, because a downward-sloping demand curve limited earnings from cotton textiles. This argument stands in contrast with Temin's claim that rising exports by industries other than those in which we identified rapid productivity gains implies that substantial technical change must actually have been widely diffused.

TECHNOLOGY, DIMINISHING RETURNS, AND THE PATTERN OF TRADE

Estimates of productivity growth in the Industrial Revolution derive from incomplete data and leave room for continuing debate about the details of technical advance. In an innovative contribution, Temin has suggested that data on exports and imports of goods produced by industries about which there is little direct evidence can shed important light on the breadth of technical change in British industry at this time. Joining mid-nineteenth-century trade data to a Ricardian model of the effect of technical change on interna-

[8] In fact, if the elasticity of foreign demand had been unity or less, then the revenue from cotton exports, and thus the volume of food that could be purchased with it, would not have expanded at all.

tional trade, he argues that the continued export of manufactures from the "unmodernized" sectors implies that technical change among British industries was widespread in the early nineteenth century. The Ricardian model is a useful starting point, but we believe that it does not adequately represent the determinants of international trade during the Industrial Revolution, and that Temin's inferences from it are therefore unjustified.

Figure 1 contains the essence of the Ricardian model, which emphasizes only technical differences between countries. In it, a continuum of goods is produced with a single factor of production, labor, under constant returns to scale. The goods are identical in the two countries and consumers do not discriminate by country of origin. Thus each good (with a possible exception on the margin) is produced only where its cost is lowest. The low-cost producer exports to satisfy demand in the other country. Each good's production technique is represented by a single parameter a_n, the number of hours of labor needed to produce a single unit of good n at home (Britain in this case). Similarly, a^*_n is the number of hours needed to produce a single unit of the good abroad. For any given ratio of British to foreign wages, the cost-competitiveness of British goods depends on the ratio a^*/a—Britain's relative technical advantage. The continuum of goods may be arrayed along the horizontal axis accordingly. At a high relative wage (w / w^*), British costs will be lowest only for those goods in which its technical superiority (a^*/a) is greatest; but as w / w^* declines, Britain produces and exports more goods. Curve A in Figure 1 traces the goods produced in Britain as a function of the relative British wage rate given the relative state of technology in the two countries.

As Britain produces more goods, its share in world income increases, and since all income from production accrues to wages in the producing country, its relative wages rise. If Britain produces all of the goods with a value of a^*/a less than z and the share of world income devoted to its aggregate output is $B(z)$, then $B(z)(wL + w^*L^*) = wL$, or

$$\frac{w}{w^*} = \frac{L^*B(z)}{L(1-B(z))} \tag{1}$$

Thus we obtain the upward-sloping curve B in Figure 1, where the relative wage rate is a function of the proportion of production occurring in Britain. Equilibrium occurs at the intersection of curves A and B, which determines Britain's relative wage and output mix. Britain exports all goods to the left of x_0 and imports all goods to the right.

Temin uses this model to analyze the effects of technical change. Relative improvement in overall British technology shifts curve A to A' while leaving curve B unaffected. This increases the range of British exports to include all goods to the left of x_j. He also considers the case of technical changes restricted to a narrow range of goods already exported. In this case demand

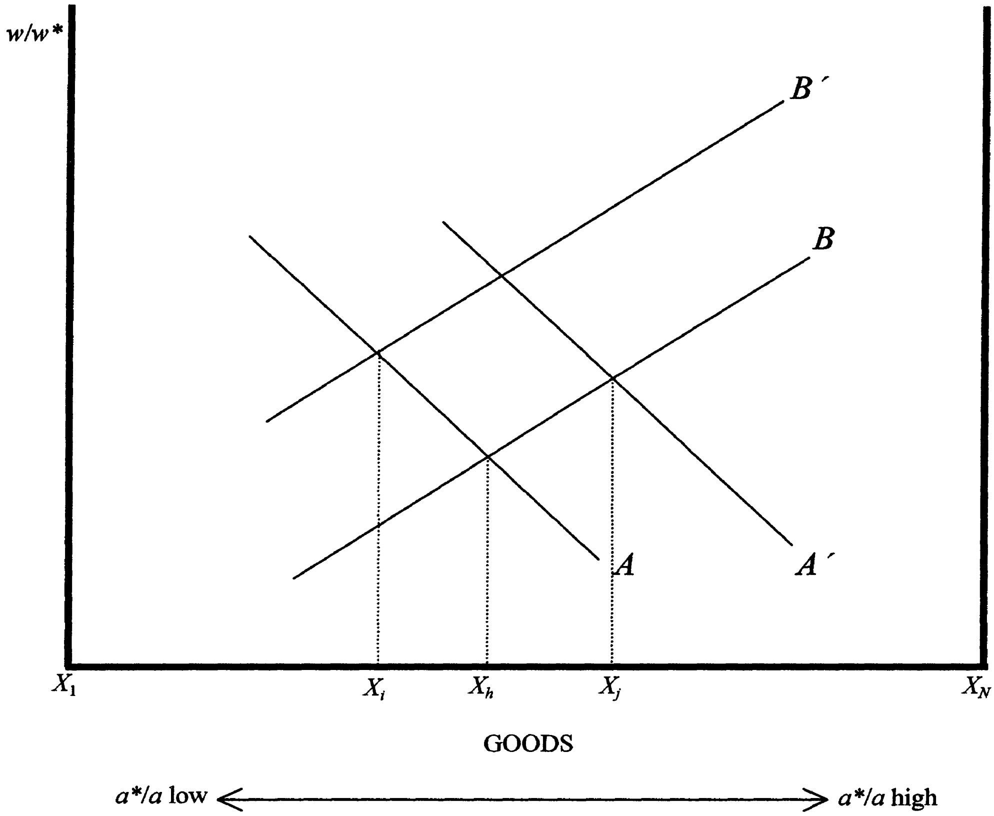

FIGURE 1
THE RICARDIAN TRADE MODEL

Note: This rendition of the model diverges in several respects from Temin's figure 1. Among other things, Temin shows Curve *B* rotating from the origin; in our view, however, an increase in import earnings from one (or a few) goods would shift the curve up horizontally.

shifts to these now-cheaper goods, shifting curve *B* to *B′* because factor incomes, which equal wages in the model, increase along with sales. The new equilibrium is at x_i, to the left of x_h, and the range of exports falls. He concludes: "General technical change causes the list of exports to rise, while restricted technical change causes it to fall. This difference provides a test of [the two] views."[9]

In the Ricardian model, a country produces and exports those goods in which it has relative technical advantage. Relative technical change, as Temin emphasizes, does clearly affect the historical evolution of trade; but other factors will come into play as well, even within this simple framework.

First, relative labor-force growth will alter trading patterns. If a country's labor force grows more rapidly than its trading partners', the country will increase its share of total demand and must also increase its share of the total value of output. A fall in relative wages (w/w^*) increases the range of goods a country produces and leads to exports of some goods previously im-

[9] Temin, "Two Views," pp. 70–73.

ported.[10] If we modify the Ricardian model to incorporate an agricultural sector subject to diminishing returns, relative population growth will have an even greater impact. The increase in demand, pressing against inelastic supply, will tend to increase agricultural prices. In an open economy, world agricultural prices will be driven up somewhat, but the main effect will be an increase in agricultural imports (or a reduction in agricultural exports or a combination of the two). The increase in net agricultural imports will require an increase in the range and value of exports, which will again require a fall in relative wages.

Second, demand elasticities matter. Temin's argument that technical change in a subset of goods narrows the range of exports rests on an assumption that the elasticity of export demand for such goods is greater than unity.[11] In such a case, the value of exports of these goods will increase and the economy will adjust to a new equilibrium in which a narrower range of goods is exported. But if demand is inelastic, export revenue will fall and some imports will become exports.

Finally, actual trade data force us to consider the issue of industries producing differentiated goods. In principle, their existence does not invalidate the Ricardian model. Each specific product can be considered separately and placed individually on the continuum. An industry will then encompass a range of differentiated products, both domestic and imported, which will be imperfect substitutes for one another. Intraindustry trade is likely, particularly if there are economies of scale, and trade of this kind was indeed a prominent feature of the British Industrial Revolution, as Temin's own data confirm.[12] But the extant data, which are more aggregated than we might like, will mask all those shifts between import and export that occurred within product categories.

Temin's attempt to use trade data to discriminate between the two views of the Industrial Revolution, then, would only be valid in special circumstances that did not obtain in actuality. Diminishing returns in agriculture, population growth, and imperfect substitution between domestic and imported goods are all factors that confound his simple Ricardian deductions. A possible way forward is to examine trade and technical change in more complicated cases using simulations from a CGE model.

A TRADE MODEL WITH DIMINISHING RETURNS IN AGRICULTURE

We now describe one such CGE model structured to relate technical change and trade flows in an extension of Temin's argument.[13] Simulations

[10] Grossman and Helpman, "Technology," discusses various properties of the Ricardian model.

[11] The formal model embodied in Figure 1 is constructed on the assumption that the share of income spent on each good is constant in the face of price changes, that is, that demand elasticities are unitary.

[12] Temin, "Two Views," tables 3 and 5.

[13] Harley, "Reassessing," contains a simple CGE model showing that given diminishing agricultural returns, Britain's growing food imports are consistent with Crafts's findings of rapid technical change

on the basis of this model explore his assertion that trade data refute the "new view" of narrow technical change during the Industrial Revolution. The simulations reject that assertion and confirm the following points. First, limits to agricultural growth and British technical precocity were *both* significant causes of the growth of exports of textiles and metal goods; specifically, with diminishing returns in agriculture and realistic demand elasticities for textiles and metal goods, exports of "other manufactures" grow even if one assumes no total factor productivity (TFP) growth in that sector. Second, without diminishing agricultural returns, the model cannot replicate the extent of the modernized sectors' growth. And third, if rapid TFP growth in "other manufactures" is hypothesized, as in the "old view," exports of these goods appear to grow far too much.

In outline the model is as follows. There are two trading countries, Britain (excluding Ireland) and Rest-of-World. For Britain, the model is benchmarked to Deane and Cole's national-income estimate for 1841. There are seven production sectors in Britain: agriculture (including forestry), cotton textiles, other textiles, metals, other traded manufactures, nontraded manufactures (primarily food processing and construction), and services. All but the last two are traded internationally.[14] Rest-of-World has eight sectors: the abovementioned seven, plus a tropical-commodities sector that produces both raw cotton and foodstuffs imported into Britain.

Rest-of-World is benchmarked as a large, but not overwhelming, international trading partner. Its overall size is set in proportion to the ratio of European to British population. The size of its modern industrial sectors is calibrated relative to the corresponding British sectors using Paul Bairoch's estimates.[15] Other manufactures and services are assigned slightly smaller shares of national income than in Britain. The balance of national income is assigned to agriculture.

Modeling starts with a consistent accounting matrix of product output, factor demand by product, factor incomes, and product demand (presented in Table 1). The accounting matrix is assumed to represent a full general equilibrium for the modeled economy. Total factor incomes equal the benchmark factor supplies. Benchmark prices are all taken to be 1.0, with the exception of the British price of tropical foodstuffs, which is set at 1.5 to allow for a 50 percent import tariff. The model redistributes the tariff revenue to British consumers. Simulated 1770 equilibria result from calculations of consumption and production shifts in response to price changes caused by altered technology and factor supplies. The extent of the response depends on elasticities of substitution in production and consumption.

Production techniques are modeled quite simply and are similar for both Britain and Rest-of-World. In services, other traded manufactures, and non-

in agriculture. This earlier model is set out in detail in Harley and Crafts, "Productivity Growth." Temin correctly points out limitations to the earlier model, which should be regarded as superseded.

[14] An export of international services balances Britain's international payments in the 1841 benchmark.

[15] Bairoch, "International Industrialization Levels."

TABLE 1

ACCOUNTING MATRIX FOR THE CGE MODEL (percentage of 1841 British national income)

	Good (positive values denote production thereof, negative values denote purchased inputs thereof)										Factor Payments		
	Cotton Textiles	Other Textiles	Metals	Other Traded	Non-Traded	Agriculture	Services	International Services	Tropical Raw Materials	Tropical Foods	Labor	Capital	Rent
						Britain							
Sector													
Cotton textiles	10.3				−2.3				−2.7		−2.1	−3.2	
Other textiles		12.7				−3.4			−0.9		−3.4	−5.0	
Metal			4.2	−0.4							−1.5	−2.3	
Other traded				8.7							−5.2	−3.5	
Nontraded					8.7						−5.2	−3.5	
Agriculture						22.1					−8.8	−4.4	−8.8
Service							41.8				−25.1	−16.7	
Int'l Services								1.2			−0.7	−0.5	
Imports	0.1	0.2	0.2	0.4		7.1			3.6	4.5			
Total	10.4	12.9	4.4	8.7	6.4	25.8	41.8	1.2	0.0	3.0	−52.1	−39.1	−8.8
Consumption	4.2	10.1	2.9	5.8	6.4	25.8	41.8	0.0	0.0	3.0	−52.1	−39.1	−8.8
Exports	6.2	2.8	1.5	2.9				1.2					
						Rest-of-World							
Sector													
Cotton textiles	3.4				−0.8				−0.9		−0.7	−1.0	
Other textiles		17.4				−4.7			−1.2		−4.6	−6.9	
Metal			3.7	−0.4							−1.3	−2.0	
Other traded				12.9							−7.7	−5.1	
Nontraded					15.8						−9.5	−6.3	
Agriculture						297.0					−118.5	−59.4	−118.8
Service							214.2				−128.5	−85.7	
Tropical Agric.									22		−8.8	−4.4	−8.8
Imports	6.2	2.8	1.5	2.9				1.2					
Total	9.6	20.2	5.2	15.4	15.0	292.3	214.2	1.2	19.9		−279.9	−170.9	−127.6
Consumption	9.5	20.0	5.0	15.0	15.0	285.2	214.2	1.2	13.3		−279.9	−170.9	−127.6
Exports	0.1	0.2	0.2	0.4		7.1			3.6	3.0			

traded manufactures, the production functions are Cobb-Douglas with a labor share of 0.6 and a capital share of 0.4. Cotton textiles, other textiles, and metals are modeled as having a fixed-proportion technical requirement for raw material inputs, and Cobb-Douglas value-added. Although production techniques in industry involve capital as well as labor, the industries use the factors in similar proportions so the specification approximates the Ricardian model. With the key exception of agricultural goods, relative cost and price changes between the 1841 benchmark and the 1770 simulation arise almost entirely from differential rates of technical change, as in the Ricardian model. Production functions for temperate agriculture in both Britain and Rest-of-World have a land input that generates diminishing returns. They are modeled with a production function featuring constant elasticities of substitution of 0.5 between labor and capital, and 0.3 between the capital-labor composite and land. In the 1841 benchmark the value of agricultural output is shared among labor, capital, and land in proportions of 0.4, 0.2, and 0.4 respectively.

The demand side of the model is moderately complex. Relating British trade data to the model requires that we recognize the heterogeneity of industrial output and distinguish between domestic and imported goods, making them imperfect substitutes. CGE trade models have generally recognized that heterogeneity requires differentiation between domestic and imported goods within the same industry. The so-called Armington utility function models the import good and its domestic counterpart as imperfect substitutes that are aggregated with a relatively high elasticity of substitution into a composite good which then enters a higher-level utility function. This higher-level utility function has lower substitutability between categories of goods.[16]

Demand behavior is modeled with two consumers, one in Britain and one in Rest-of-World. Although the benchmark consumption patterns of the two differ somewhat, the basic structure of their utility functions are identical, as summarized in Figure 2. At all stages, aggregation occurs in a constant-elasticity utility aggregate. At the top level, consumers choose manufactured goods, temperate agricultural goods, services, and tropical foodstuffs. Substitution elasticities of 0.5 are used to calculate the new equilibria.

Services, tropical commodities, and temperate agricultural goods are not further disaggregated. Tropical foodstuffs are all produced in Rest-of-World. Temperate agricultural goods (which include food, industrial raw materials, and timber) are produced in both Britain and Rest-of-World, and the goods from each region are modeled as perfect substitutes in consumption.

Modeling the Industrial Revolution requires several disaggregations of the manufactured goods that enter into the final utility function. Failure to do so would mask essential distinctions among industries in terms of technical change and demand. The first disaggregation separates textiles, metal goods,

[16] See, for example, the discussion in Shoven and Whalley, *Applying General Equilibrium*, p. 81.

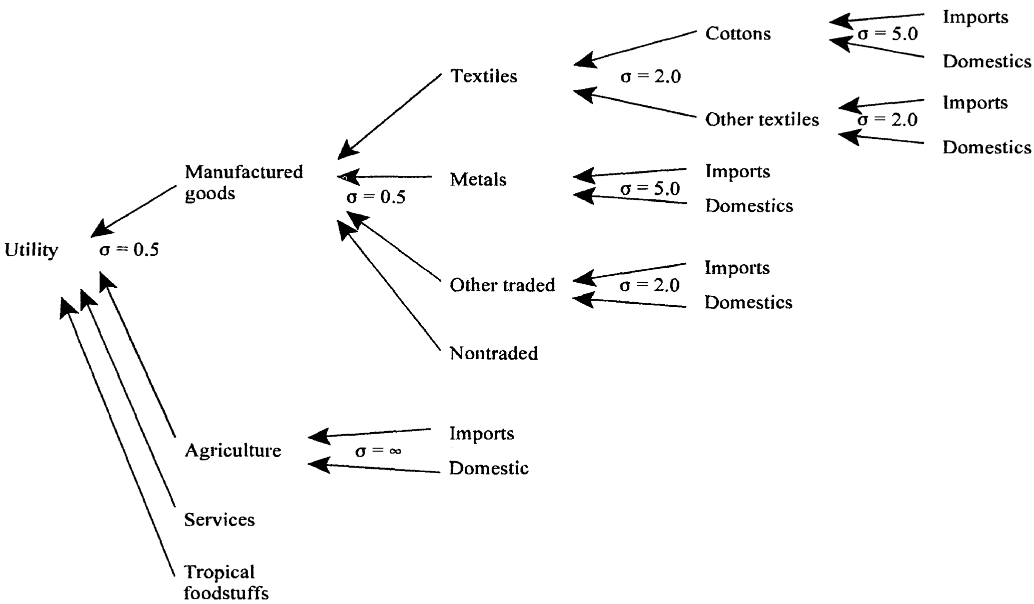

FIGURE 2
STRUCTURE OF UTILITY

Source: See the text.

other traded manufactures, and nontraded manufactures. These goods aggregate into a composite manufactured good using an aggregation (or utility) function with an elasticity of substitution of 0.5 (the same value as the top-level utility aggregation). Our understanding of the Industrial Revolution emphasizes the special nature of the changes in cotton textiles, so textiles are further disaggregated into cotton and other textiles. Because the various textiles are good substitutes in consumption, we have created a textile aggregate with a higher elasticity of substitution (2.0).

Since the simulation focuses on international trade in the various commodities that entered into consumers' utility functions, it is necessary to pay attention to the degree of substitutability between imports and domestic goods. Even at our level of disaggregation the various categories of goods are quite heterogeneous aggregates; as such, it is inappropriate to consider imports and domestic goods to be perfect substitutes. We assume the Armington elasticity of substitution between domestic and imported goods within a category to be larger, the more homogeneous the product in question. The elasticity of substitution between British and Rest-of-World cottons and metals is assumed to be 5.0, while those between other textiles and between other traded manufactures are both assumed to be 2.0.

We do not have direct empirical estimates of these substitution elasticities. We have, though, been able to make educated guesses that are in line with values commonly used in CGE modeling,[17] and are also plausible in the context of the historiography of consumption and of the textile industries in particular.[18]

SIMULATING THE INDUSTRIAL REVOLUTION

A Simulation of the "New View"

Simulating our view of the Industrial Revolution involves solving the CGE model with the lower factor supplies and inferior techniques that we take to represent the economic *ancien régime*.[19] Both the 1841 benchmark and the simulated 1770 results are represented as long-run equilibria. In the calculated equilibrium, factors earn the same return in all uses (although returns may differ between countries) and all markets clear.

The intertemporal discrepancies in productive potential are based on our earlier estimates of changes during the Industrial Revolution. The simulation therefore embodies the Crafts-Harley view of the pattern of productivity growth, which Temin has suggested is incompatible with the trade data. Specifically, we introduce the following changes to factor supplies and technology. British labor supply is reduced from 52.1 (the 1841 benchmark) to 22.8 (the 1770 estimate), capital from 39.1 to 14.4, land by 15 percent from 8.8 to 7.5. Factor inputs in Rest-of-World are reduced by about 30 percent: labor falls from 279.9 to 200, capital from 170.9 to 120, and land from 127.6 to 87. A unit of agricultural output is modeled as using 1.5 times its 1841 inputs of land, capital, and labor.[20] Technical change in British manufacturing is calculated to correspond approximately to Donald McCloskey's calculations (as corrected by Harley).[21] Table 2 summarizes the changes in input requirements of various components of value-added in industries over the Industrial Revolution. We assume that the improved technology resulted

[17] Compare the values selected by the authors of the papers in Srinivasan and Whalley, *General Equilibrium Trade Policy Modeling*; and by Harley, "Antebellum American Tariff."

[18] Thus, for example, Allen's recent review of demand elasticities for agricultural goods ("Tracking") implies a substitution elasticity between agricultural products and all other spending well below unity. Discussions of the cotton trade stress that while cottons were imperfect substitutes for linens, silks, and woolens because of differences in durability, ease of washing, and appearance, there was nevertheless fierce competition as cottons gradually displaced other fibers (see Farnie, *English Cotton Industry*, pp. 129–30). In the eighteenth century fine British cottons were usually regarded as inferior to their Indian counterparts by the fashion-conscious, but there was direct competition (Edwards, *Growth*, p. 44). By the mid-nineteenth century American and Continental producers could challenge British production in coarse cotton textiles but not in fine.

[19] Simulated equilibria are calculated using the MPS-GE software produced by Tom Rutherford. For more information on MPS-GE see Rutherford's internet home page (http://nash.colorado.edu/tomruth). It is available commercially, as an add in to the GAMS software package. The specific industrial-revolution model is available from Harley on request (e-mail: charley@julian.uwo.ca).

[20] Allen, "Agriculture." For a detailed review of the evidence on agricultural TFP growth see Allen, "Tracking." We second his rejection of Clark's estimates (in "Too Much Revolution"), on the grounds of flaws in the sample of land prices used in constructing the price-dual measure of TFP.

[21] McCloskey, "Industrial Revolution," p. 114; and Harley, "Reassessing," p. 200.

TABLE 2
MODEL FACTOR INPUTS PER UNIT OF OUTPUT, 1840 AND 1770

	Britain						Rest-of-World					
	1840			1770			1840			1770		
	Labor	Cap.	Land	Labor	Cap.	Land	Labor	Cap.	Land	Labor	Cap.	Land
Agriculture	0.4	0.2	0.4	0.6	0.3	0.6	0.4	0.2	0.4	0.5	0.25	0.5
Cotton Textiles	0.21	0.31		2.40	3.60		0.21	0.31		0.96	1.44	
Other Textiles	0.26	0.40		0.80	1.20		0.26	0.40		0.80	1.20	
Metal Products	0.36	0.54		0.68	1.36		0.36	0.54		0.56	0.84	

Source: See the text.

in savings of capital and labor, but not of intermediate inputs. Real costs in cotton textiles are estimated at about six times their 1841 level in 1770,[22] in other textiles about double, and in metallurgy about 70 percent higher. We assume that techniques advanced also in Rest-of-World, though at a slower pace. Calculating the 1770 equilibrium also involves removing the tariff on tropical imports, as well as eliminating British service exports so that commodity imports and exports are of equal value.

Table 3 reports the 1770 solution for the model (in Column 3), the 1841 benchmark data (Column 1), and indices of simulated changes between those dates (Column 4). Comparison of the latter with estimates of actual historical estimates (Column 2) provides a check on the plausibility of the model. In general, the model replicates the growth in output and trade reasonably well, although in cases where 1770 volumes were very small the multiples are less exact. In particular, the model captures two key features of structural change during the Industrial Revolution: the relative decline of domestic agriculture, and the rapid expansion of cotton textile output and exports.

Temin argues that trends in the volume of trade in "other traded manufactures" support the "old view" of the Industrial Revolution against our "new" one. Notice, however, that the model generates significant growth in the exports of "other traded manufactures" even though the simulation allows no TFP growth in that sector. In fact, the model's predicted export growth mirrors the historical result quite accurately. As might be expected for a sector lying near the margin of importation and exportation, and whose component goods were imperfect substitutes, *both* exports *and* imports increased. The simulation suggests that the observed behavior of exports is consistent with the Crafts-Harley account of productivity growth in the Industrial Revolution.

The simulation can also be judged in terms of its ability to replicate price changes between 1770 and 1841. Here too, the picture is generally encouraging, especially in terms of cottons, "other traded manufactures," and agricul-

[22] Harley, "Cotton Textile Prices."

TABLE 3
OBERVED AND SIMULATED ECONOMIES, 1841 RELATIVE TO 1770
(percentage of 1841 British national income)

	Observed Values		Base Simulation	
	1841 (1)	1841/1770 (2)	1770 (3)	1841/1770 (4)
Outputs				
Cottons	10.3	125	0.1	98.4
Other textiles	12.7	2.3	3.9	3.3
Metal industries	4.2	14.3	0.4	11.2
Other traded manufactures	8.7	4	3.1	2.8
Other industry	8.7	4	2.3	3.8
Agriculture	22.1	2	9.6	2.3
Services	41.8	2.5	14.7	2.8
Exports				
Cottons	6.2	253	0	239
Other textiles	2.8	1.6	0.9	3.0
Metal industries	1.5	4.5	0	31.1
Other traded manufactures	2.9	2.1	1.2	2.3
Imports				
Temperate agriculture	7.1	6.8	0.5	15.3
Tropical raw materials	3.6	15.9	0	130
Tropical food	3.0	3.2	1.5	2.0
Modern industry	0.5	?	1	0.5
Other traded manufactures	0.4	?	0.2	1.8
Goods price relatives (1770/1841)				
Cottons		0.13		0.13
Other textiles		0.48		0.37
Metal industries		0.56		0.40
Other traded manufactures		1.00		0.91
Other industry		1.11		0.91
Agriculture		0.83		0.83
Factor price relatives (1770/1841)				
Labor		1.00		1.00
Capital		1.00		0.77
Land		1.67		3.33
Cost of living		0.83		0.71

Sources: Model solutions are from the computable equilibrium model. The benchmarks in Column 2 were estimated as follows. Outputs: Agriculture from Allen, "Agriculture," p. 101; services from Crafts, *British Economic Growth*, p. 37, extended using Deane and Cole, *British Economic Growth*, p. 166. All others based on Harley, "British Industrialization," p. 272. Exports: "Other Industry" calculated directly for 1830/1770 using U.K., *Finance Accounts*, and Davis, "English Foreign Trade," and extended to 1841 based on Schlote, *British Overseas Trade*, p. 152. All others from Mitchell, *British Historical Statistics*, pp. 469, 471, extended to 1841 using Davis, *Industrial Revolution*, pp. 98–100. Imports: "Temperate Agriculture"estimates for 1841 from Davis, *Industrial Revolution*, adopting the correction for Ireland proposed by Thomas, "Food Supply," p. 145, deflated by the agricultural price index in O'Brien, "Agriculture and the Home Market," and extended to 1841 using the Rousseaux agricultural prices index. All others from Davis, "English Foreign Trade," and Mitchell, *British Historical Statistics*, pp. 466–67. Goods Price Relatives: "Cottons" from Harley, "Cotton Textile Prices"; "Other Textiles," "Metal Industries," "Other Traded Manufactures" (represented by leather), and "Other Industry" (represented by construction) from O'Brien, "Agriculture and the Home Market," extended respectively using woolens export prices from Imlah, *Economic Elements*; bar iron from Mitchell, *British Historical Statistics*, p. 762, leather from Gayer, Rostow, and Schwartz, *Growth and Fluctuation*, pp. 143, 279, and building materials from Jones, *Increasing Returns*. Factor Price Relatives: these are nominal prices where capital is based on consols yields from Mitchell, *British Historical Statistics*, p. 678, capital goods prices from Feinstein, "Appendix," p. 441, and land from Turner, Beckett, and Afton, *Agricultural Rent*, p. 150; cost of living index from Feinstein, "Pessimism Perpetuated."

tural output, all of which are central to the external trade outcomes. At the same time, it should be remembered that some of the price comparisons are necessarily rather crude given the lack of adequate data from which to construct benchmarks (as is apparent from the source notes to Table 3). The model's most obvious weakness is its overestimate of the change in the price of agricultural land, which rises too much over the period. A possible reason for this is that technical change in agriculture may have had a land-saving bias, whereas we have specified it as neutral.[23]

A Simulation Without Diminishing Returns

A modified version of this simulation highlights the importance of diminishing agricultural returns in determining the economic structure and trade of the mid-nineteenth-century Britain. In our base simulation, the agricultural production function uses land, labor, and capital as inputs. Because land resources are allowed to increase by only 15 percent, diminishing returns to labor and capital ensue. In order to consider a situation without diminishing returns, the modified model's agricultural production function contains only capital and labor (the income previously going to land being distributed proportionately to capital and labor, such that capital's share rises to one-third, labor's to two-thirds).

Table 4 displays the results of the model without diminishing returns (Column 3), the historical benchmark estimates (Column 1), and the base simulation of the model of Table 3 (Column 2). The importance of population pressure on agricultural resources in determining the change in British economic structure and foreign trade between 1770 and 1841 emerges clearly. Absent the stimulus of diminishing returns in agriculture, Britain sells less to foreigners in every export category. To be sure, advancing cotton textile and iron technology would have generated substantial expansion of those industries' output and exports even without diminishing agricultural returns, but the model indicates that both industries owed about two-thirds of their actual growth to the export stimulus provided by the demand for agricultural imports. The simulation also confirms that population growth and diminishing returns in agriculture played an important role in expanding exports of "other traded manufactures."

Without diminishing returns in agriculture the model fails to replicate key aspects of economic development during the British Industrial Revolution. In particular, the simulation shows agricultural output expanding 4.8-fold between 1770 and 1841, compared with an estimated actual doubling of output, while simulated output of cottons and metals rises only 38.3-fold and

[23] This is suggested by a simulation in which technical change in agriculture is specified as relatively land-saving, such that 1770 factor inputs are 0.75 land, 0.25 capital, and 0.5 labor, rather than 0.6, 0.3, and 0.6 respectively. This replicates exactly the land-price change over 1770 to 1841, while leaving the other main outputs of the model little changed (with the one exception that cotton's growth was significantly reduced).

TABLE 4
EFFECTS OF DIMINISHING RETURNS IN AGRICULTURE AND VARYING DEMAND ELASTICITIES

	Observed Values (1)	Base Simulation (2)	Constant Returns in Agriculture (3)	Unitary Elasticities: Textiles (4)	Unitary Elasticities: Manufs. (5)
Outputs					
Cottons	125	98.4	38.3	49.9	124
Other textiles	2.3	3.3	2.8	3.7	4.1
Metal industries	14.3	11.2	5.2	10.3	11.4
Other traded manufactures	4.0	2.8	2.0	2.7	2.1
Other industry	4.0	3.8	3.8	3.8	2.8
Agriculture	2.0	2.3	4.8	2.2	2.3
Services	2.5	2.8	2.9	2.8	2.8
Exports					
Cottons	253	239	44.8	148	308
Other textiles	1.6	3.0	1.6	3.2	3.8
Metal industries	4.5	31.1	5.5	26.5	30.1
Other traded manufactures	2.1	2.3	1.2	2.1	2
Imports					
Temperate agriculture	6.8	15.3	1.8	†	16
Tropical raw materials	15.9	130	50.7	66	164
Tropical food	3.2	2.0	2.4	2.1	2.1
Modern industry	?	0.5	1.8	0.4	0.6
Other traded manufactures	?	1.8	4.0	2.0	1.3
Goods price relatives (1770/1841)					
Cottons	0.13	0.13	0.12	0.14	0.14
Other textiles	0.48	0.37	0.33	0.36	0.38
Metal industries	0.56	0.40	0.37	0.40	0.42
Other traded manufactures	1.00	0.91	0.83	0.91	0.91
Other industry	1.11	0.91	0.83	0.91	0.91
Agriculture	0.83	0.91	0.59	0.91	0.91
Factor price relatives (1770/1841)					
Labor	1.00	1.00	1.00	1.00	1
Capital	1.00	0.77	0.71	0.77	0.83
Land	1.67	3.33	n.a.!	3.33	3.33
Cost of living	0.83	0.71	0.63	0.71	0.77

† The simulation shows Britain with no temperate agricultural imports but small exports in 1770.
Sources: See the text.

5.2-fold respectively, compared with actual multiples of 125 and 14.3. Simulated exports of cottons and imports of temperate agricultural products also fail to match actual growth by large margins. In addition, agricultural prices (and thus the cost of living) fall far too rapidly. In other words, without diminishing returns in agriculture the key structural changes of the Industrial Revolution are seriously underestimated. The model shows that *both* diminishing returns in agriculture *and* technical change in modern industry played important roles in promoting the growth of modern industrial exports.

The simulated behavior of trade in "other traded manufactures" in the absence of diminishing agricultural returns is closer to Temin's deductions from the Crafts-Harley view. Exports of "other traded manufactures," while not actually lower, grow much more slowly than in historical fact, while imports of these goods expand considerably faster. Even in this modified simulation, however, it should be noted that exports by no means disappear, because domestic and foreign goods are imperfect substitutes.

Demand conditions greatly influence trading patterns. Columns 4 and 5 of Table 4 show this by exploring the role of demand elasticities in the growth of British manufactured exports. In Column 4 the elasticity of substitution among textiles is reduced from 2.0 to 1.0, thus making cotton a poorer substitute for other textiles, and in the process diminishing the export-demand elasticity for the premier Industrial-Revolution good. In Column 5, the elasticity of substitution used to aggregate manufactures is raised to 1.0, making cotton a better substitute for other manufactures. Relative to the other simulations, the higher (lower) elasticity of substitution among manufactures increases (decreases) exports of the goods—notably, cottons—whose prices have fallen most as a result of technical change.[24] With higher (lower) elasticities of demand for cotton textiles, Britain earns more (less) from exporting them, such that other exports play a lesser (greater) role in financing agricultural imports. The simulations underline the importance of demand conditions in cottons' extraordinary growth. With the lower demand elasticity the industry grows much more slowly.[25]

Simulations With Widespread TFP Growth

Temin's assertion that Britain could have exported "other manufactures" only if that sector had achieved substantial rates of productivity growth is not confirmed by these simulations, which impute to it no TFP growth whatsoever. It follows that we cannot rely on trade data to provide crucial information about technical change in industries about which our direct knowledge is deficient. It would, of course, be nice to know more about these industries. After all, one implication we draw from our work is that modern economic growth depended on change beyond the famous Industrial-Revolution industries. Unfortunately, we feel that the available evidence suggests little growth in per capita output or productivity in other industries before the 1830s. It is interesting, nonetheless, to examine what the impact of technical advance in "other traded manufactures" would be in our general-equilibrium context.

In Table 5 we explore two cases incorporating TFP growth in "other traded manufactures." In the first (Column 3), we suppose annual TFP

[24] The simulations generate very small 1770 outputs, in line with the historical record. As a result, small changes in resource allocation make a considerable difference to growth rates. The calculated 1770 value in the base case is 0.10, or 0.08 assuming the higher elasticity of substitution among manufactured goods.

[25] Two important points to note about both simulations (and others not reported here) are the following. First, most key results of the model are not very highly sensitive to the assumed Armington elasticities. Second, in each case the simulated growth in exports of other traded manufactures is robust to the changes.

TABLE 5
GENERAL-EQUILIBRIUM EFFECTS OF TECHNICAL PROGRESS IN "OTHER TRADED MANUFACTURES"

	Observed Values	Base Simulation	Manufactures σ = 1 OTM TFP = 0.2	OTM TFP = 0.5
Outputs				
Cottons	125	98.4	120.3	115.2
Other textiles	2.3	3.3	4.1	4.0
Metal industries	14.3	11.2	11.2	11.2
Other traded manufactures	4.0	2.8	2.5	3.3
Other industry	4.0	3.8	2.8	2.8
Agriculture	2.0	2.3	2.3	2.3
Services	2.5	2.8	2.8	2.8
Exports				
Cottons	253	239	295	277
Other textiles	1.6	3.0	3.8	3.7
Metal industries	4.5	31.1	29.6	29.3
Other traded manufactures	2.1	2.3	2.3	3.4
Imports				
Temperate agriculture	6.8	15.3	23.8	78.3
Tropical raw materials	15.9	130	159	152
Tropical food	3.2	2.0	2.1	2.1
Modern industry	?	0.5	0.6	0.6
Other traded manufactures	?	1.8	1.2	1.0
Goods price relatives (1770/1841)				
Cottons	0.13	0.13	0.14	0.14
Other textiles	0.48	0.37	0.38	0.38
Metal industries	0.56	0.40	0.42	0.40
Other traded manufactures	1.00	0.91	0.83	0.67
Other industry	1.11	0.91	0.91	0.91
Agriculture	0.83	0.91	0.91	0.91
Factor price relatives (1770/1841)				
Labor	1.00	1.00	1.00	1.00
Capital	1.00	0.77	0.83	0.83
Land	1.67	3.33	3.33	3.33
Cost of living	0.83	0.71	0.77	0.77

Sources: See the text.

growth of 0.2 percent; in the second (Column 4), 0.5 percent—that is, about the low end of the rates in the modernized sectors. In both cases we employ a demand function with the elasticity of substitution in manufacturing raised from 0.5 to 1.0, as in Column 5 of Table 4.

The main effect of TFP growth in "other traded manufactures" shows up in the growth rates of output and exports. A TFP growth rate of 0.5 percent seems to result in excessive export growth in that category. A simulation with 0.2 percent TFP growth, however, yields results that are a reasonable replication of the historical record. The only possible anomaly is the large increase in agricultural imports, which equilibrate the model by absorbing the greater export revenue generated by cheap manufactures. The simulations suggest that modest TFP growth in "other traded manufactures" might be accommodated within the CGE framework. It should be noted, however, that this conclusion in not very robust. If we use a 0.5 substitution elasticity in manufacturing (which we prefer and use in the base simulation) in the exercise, even 0.2 percent TFP growth produces excessive (2.9-fold) growth in exports of "other traded manufactures." TFP growth of 0.5 percent pushes the multiple up to 4.2—twice its historical growth.

Finally, in other CGE simulations not detailed here, we have considered the nearest equivalent to Temin's own implicit specification. In this case, diminishing returns are removed from agriculture and TFP growth is introduced into the "other traded manufactures" sector. Under these assumptions, Temin is correct that it would be necessary to have rapid TFP growth in that sector in order to replicate the historical export experience—indeed, the model suggests that this TFP growth would have to be well in excess of 0.5 percent per year. But as in Table 4, this specification generates agricultural output growth that is far too rapid, and growth rates of modern-sector output and exports and of agricultural imports that are much too slow. These simulations appear to be much less satisfactory than the base case reported in Table 3.

Upshot and Outlook

Our CGE simulations indicate that Temin's attempt to infer conclusions about the extent of technical change during the Industrial Revolution from foreign-trade data, while quite innovative, is based on an inadequate view of the factors shaping British trade. Our model illustrates the likely mechanisms maintaining exports even in industries where technical change was either modest or nonexistent. Clearly, diminishing returns in agriculture, an important feature of the early nineteenth century, played a key role. An effective demand for food imports required greatly expanded export earnings from industrial goods generally. The nature of demand facing the leading industries of the Industrial Revolution resulted in the price of these goods falling in response to technical advance. This in turn depressed export earnings from these products. Some of the expanded export earnings came from traditional exports whose production had not been transformed. To approximate historical reality as recorded in census and customs records, we needed models with less than perfect substitution between the imported and exported goods in the broad, somewhat heterogeneous, categories. This specification greatly increases the likelihood that exports of goods from sectors experiencing relative technical retardation will continue to be recorded in the trade data. While it is likely that some specific goods ceased to be exported, this would be hidden by the aggregation of historical data. When we extend Temin's basic Ricardian model to improve its realism, we can see why industrial goods that experienced no TFP growth continued to be exported.

It must be recognized, however, that we do not have enough information to use a CGE model of this type to go beyond general tendencies and make precise quantitative predictions about specific details. In particular, we lack firm estimates of the elasticities that are central to the specification of the demand side of the model and so affect the pattern of trade; thus we do not feel we can rule out modest TFP growth in "other manufactures." But we have shown clearly that the continued exportation of other manufactures certainly cannot be taken as convincing evidence that technology changed in these industries at a rate comparable to modern industry's, or even agriculture's.

The present model allows us to gain considerable insight into the way trade patterns were affected by the Industrial Revolution. Although we have disaggregated output to highlight key issues, the level of aggregation remains deliberately high. We feel that our results can indicate general tendencies within the economy, and that finer degrees of disaggregation would depend on increasingly idiosyncratic developments in particular industries and markets, which we cannot expect to model accurately.

There are, nonetheless, a number of ways in which the model might usefully be developed further. We have already noted that it may be appropriate to consider biased technical change in agriculture to explain the observed course of factor prices and factor input ratios. The model also seems deficient in its treatment of metallurgy, where it inadequately replicates actual trade performance. Effectively addressing this issue, and possibly others, would require considerable extension of the model. In the case of metallurgy it would be necessary to disaggregate the heterogeneous output. Two obvious issues are the imports of iron bars, which were inputs into later stages of metal production throughout the eighteenth century, and the intermediate demand for iron created by railroads in the nineteenth century. In addition, the model pays little attention to the complex pattern of protection—both tariffs and prohibitions—in the late eighteenth and early nineteenth centuries, which affected British iron, among other goods. Similar modifications might be useful elsewhere as well. For example, before independence Britain's American colonies were major markets; in the nineteenth century, though, British industry faced protective American tariffs.

CONCLUSIONS

The nature of the British Industrial Revolution continues to be debated. The Crafts-Harley view that aggregate TFP growth was moderate and concentrated in relatively few sectors has gained wide support, but doubts persist. In particular, critics have been concerned by apparent inconsistencies between this view of change and Britain's external trade experience. The question was posed originally by Jeffrey Williamson and now, in a new guise, by Peter Temin. We have addressed the issue with a general equilibrium model that embodies what we see as essential characteristics of the British economy. Simulations using this model support our position, and also provide valuable insights into the operation of the British economy in its international context during the Industrial Revolution.

The model indicates that the pattern of British trade in the mid-nineteenth century can fit easily into our view of technical change. To be sure, Britain's technical leadership in cottons and iron was a major source of export growth. But the pattern of trade evolved under other important influences as well. The rapid growth of British population was the first of these: inevitably it increased the demand for food and raw materials. British agriculture, with limited land resources, experienced diminishing returns and rising costs and prices despite impressive technical change. Since the world market offered a relatively elastic source of food and raw materials, imports increased. Exports by the leading sectors paid for much of this increase in imports, but revenue from these exports was limited by the imperfect elasticity of foreign demand: the rapid increase in cotton-textile and iron exports occurred in response to rapidly falling prices, such that foreign-exchange revenues increased much more slowly than export volumes. Old exports continued, despite the absence of technical improvement, for two reasons. First, they had a role to play in financing greatly expanded food imports. Second, many of the exported goods were of idiosyncratic character. Similar foreign goods differed from the British exports and were only poor substitutes in the eyes of foreign buyers.

Our investigation of the evolution of British trade during the Industrial Revolution shows that substantial productivity growth in the "other traded manufactures" sector is neither necessary, nor indeed likely. There remains the possibility of modest TFP growth in these industries, but that would not substantially change our view of aggregate British growth. "Other traded manufactures" amounted to less than 9 percent of national income in 1841, whereas services were over 41 percent. The trade data offer no reason to revise our view that TFP growth in the tertiary sector as a whole was very low. The low weight of "other traded manufactures" in the economy implies that modest TFP growth there could have little effect on the aggregate.

We continue to believe that the exceptional feature of the British Industrial Revolution was rapid structural change, culminating in a very low share of agricultural employment in the mid-nineteenth century, rather than fast growth. Britain's structural transformation needs to be understood in an open-economy context. The CGE model we have constructed here underlines that *both* substantial TFP growth in part of the manufacturing sector *and* diminishing returns in agriculture made important contributions to Britain's precocious industrialization. Our best estimates continue to suggest that growth during the Industrial Revolution was slower than was once thought, and modest by later standards. None of this detracts from the period's real accomplishments: unprecedented technical progress, and successful accommodation of population pressures that would have undermined living standards in earlier times.

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