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NECESSITY IS THE MOTHER OF INVENTION: INPUT SUPPLIES AND DIRECTED TECHNICAL CHANGE

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This study provides causal evidence that a shock to the relative supply of inputs to production can (1) affect the direction of technological progress and (2) lead to a rebound in the relative price of the input that became relatively more abundant (the strong induced-bias hypothesis). I exploit the impact of the U.S. Civil War on the British cotton textile industry, which reduced supplies of cotton from the Southern United States, forcing British producers to shift to lower-quality Indian cotton. Using detailed new data, I show that this shift induced the development of new technologies that augmented Indian cotton. As these new technologies became available, I show that the relative price of Indian/U.S. cotton rebounded to its pre-war level, despite the increased relative supply of Indian cotton. This is the first paper to establish both of these patterns empirically, lending support to the two key predictions of leading directed technical change theories.

KEYWORDS: Directed technical change, induced innovation, strong induced bias.

1. INTRODUCTION

DIRECTED TECHNICAL THEORIES SUGGEST that a shift in the relative supply of inputs to the production process can influence the direction of technological progress (Hicks (1932), Acemoglu (2002, 2007)). In some cases, a change in the relative supply of inputs can encourage innovation that augments the relatively more abundant input, generating a positive relationship between the relative quantity and relative price of inputs. For example, it has been suggested that the increase in skilled workers in the United States starting in the 1970s caused skill-biased directed technical change, and that this directed technical change allowed the skill premium to increase despite the increase in the relative abundance of skilled workers (Acemoglu (1998), Kiley (1999)).[2] Despite the interest in this theory, there has been relatively little documentation

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[2]Other applications include the impact of labor scarcity on development in economic history (Habakkuk (1962), Allen (2009)), the sources of cross-country productivity differences (Acemoglu and Zilibotti (2001), Caselli and Coleman (2006)), the impact of high energy prices on energy-saving innovation (Newell, Jaffe, and Stavins (1999), Popp (2002)), the effect of environmental regulation (e.g., Acemoglu, Aghion, Bursztyn, and Hemous (2012)), the impact of immigration on technology upgrading (Lewis (2011)), and agricultural productivity trends (Hayami and Ruttan (1970), Olmstead and Rhode (1993)).

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of the actual process of directed technical change and its impact on the market prices of inputs. This paper provides the first well-identified study of the impact of a shift in relative input supplies on both (1) the direction of technological progress and (2) relative input prices. To do so, it exploits a large exogenous shift in relative supplies to the British cotton textile industry caused by the U.S. Civil War (April 1861–April 1865). The war, which included a blockade on Southern shipping by the Union Navy, sharply increased the cost of supplying U.S. cotton from the South. The result was a sharp depression in the industry; output dropped by as much as 50% and hundreds of thousands of mill operatives found themselves out of work or working short-time. The shortage of U.S. cotton forced British producers to turn to raw cotton from alternative suppliers, chiefly India. However, the cotton available from India differed from American cotton in important ways; it was a low-quality variety that was difficult to clean and prepare for the spinning process. Thus, this event generated a sharp shift in the relative supplies of two similar, but not identical, inputs to the production process. Historians and contemporary observers have noted the important changes that took place as a result of this event. D. A. Farnie, in his authoritative history of the British cotton textile industry, wrote, "The shortage of American cotton compelled employers to re-equip their mills in order to spin Surat [Indian cotton], and especially to improve their preparatory processes... The reorganization of the preparatory processes entailed such an extensive investment of capital that it amounted almost to the creation of a new industry..."[3]

The first contribution of this paper is to document the pattern of directed technical change generated by the shock to input supplies. Using detailed new patent data, I show that the Civil War time period was characterized by a sharp increase in innovation in three types of cotton textile machinery—gins, openers/scutchers, and carding machines—that were particularly important for addressing the key bottlenecks in the use of Indian cotton. Comparing these three technology types to all other cotton spinning technologies, I document substantial increases in innovation in technologies related to the use of Indian cotton. Innovators reacted quickly, introducing simple improvements in technologies during the first year of the war, followed by more advanced machines in later years. Innovation in technologies related to Indian cotton peaked three years into the conflict, and remained high one to two years after the end of the war. Thus, the patent data reveal substantial directed technical change toward technologies that augmented Indian cotton.

To support these results, I draw on two additional indicators of technological progress. First, using data from one of the largest textile machine manufacturing firms of the period, Dobson & Barlow, I show the rapid evolution in technology over this period. This company cycled through four different gin designs in just four years, with the introduction of new designs often closely following

[3]Farnie (1979, pp. 152–153).

the filing of a patent for gin technology. This suggests both the speed at which technology was changing as well as the link between patents and machine production. Second, I present data on one aspect of aggregate productivity: the amount of waste generated in the cotton textile production process. A simple calculation suggests that the waste generated when using Indian cotton fell by 19–30 percent between 1862 and 1868, consistent with the impact we should expect from the new technologies, many of which were designed specifically to reduce waste.

The second contribution of this paper is to provide evidence describing the response of relative input prices to a change in relative input supplies in the presence of directed technical change. In the absence of directed technical change, we would expect the relative price of an input to fall as it becomes relatively more abundant. On the other hand, directed technical change may offset this, by shifting relative demand for the more abundant variety upward enough to offset the shift in relative supply. Acemoglu called this result the "strong induced-bias hypothesis." To look for this pattern, I collected new data on the prices of several cotton varieties from *The Economist* magazine. Graphing the relative price of Indian to U.S. cotton, I observe a sharp decrease following the onset of the war. By early 1862, the relative price of Indian cotton had reached its lowest point in the 1855–1876 period. However, starting in late 1862, the relative price of Indian/U.S. cotton rebounded, and it then remained close to, and often above, the pre-war average through 1874, despite the fact that it had become much more abundant relative to U.S. cotton. The timing of this rebound follows the introduction of many of the new technologies tailored to the use of Indian cotton.

To strengthen this result, I control for time-varying factors using the price of two smaller alternative cotton varieties from Brazil and Egypt. Contemporary reports indicate that these varieties were too small to warrant substantial new innovation during the Civil War. But, like Indian cotton, they became much more abundant relative to U.S. cotton during the war. Thus, these varieties provide an indicator of how relative price might have behaved in the absence of directed technical change. In contrast to the pattern observed for Indian cotton, the relative price of Brazilian/U.S. cotton and Egyptian/U.S. cotton remained low during the period in which the relative supply of these varieties was high, exactly as we would expect in the absence of directed technical change. This suggests that the pattern observed for Indian cotton was not the result of other shifts occurring during the Civil War. Overall, the relative price pattern that I document is consistent with the strong induced-bias hypothesis for the relative price of Indian cotton, but this result comes with the caveat that it is based on a small number of price series observed over time.

A relatively small number of existing empirical studies provide evidence on the relationship between input supplies (or prices) and the direction of technological progress.[4] The main focus of this research has been on the energy sector, where studies by Newell, Jaffe, and Stavins (1999), Popp (2002), and Aghion, Dechezlepretre, Hemous, Martin, and Van Reenen (2012) looked at the impact of high energy prices on energy-saving innovation.[5] The current study differs from previous work in two ways. First, my identification of the impact of shifting input supplies on innovation is arguably cleaner because I am able to take advantage of a large, exogenous, and surprising shock to input availability. This is aided by the fact that there was virtually no government intervention in this market due to the strong free-market ideology that was dominant in Britain during this period. Second, this is the first study to evaluate the strong induced-bias hypothesis. Previous researchers have used input prices as the key explanatory variable, so they were not able to look at the impact of technological change on input prices.

The next section provides a brief review of the theoretical motivation behind this study, while Section 3 introduces the empirical setting. The data are described in Section 4, followed by the empirical analysis in Section 5. Section 6 concludes.

2. MOTIVATING THEORETICAL FRAMEWORK

This project is motivated by directed technical change theories, and in particular the model offered by Acemoglu (2002). This section provides a brief review of the key predictions of this theory. The theory focuses on an industry with two inputs and delivers three main results. First, if the relative expenditure level on an input increases, the relative technology level of that input should also increase on the balanced growth path. Second, an increase in the relative supply of an input will increase the relative technology level of that input on the balanced growth path if the elasticity of substitution between inputs is sufficiently high (>1). Third, an increase in the relative supply of an input will increase the relative price of that input on the balanced growth path when the elasticity of substitution between inputs is sufficiently high (>2).

In the model, consumption is over a CES index of two final goods. For this study, we can think of these as textile goods made using U.S. cotton and textile

[4]This project is also related to work considering the impact of input supplies on the adoption of already-existing technologies, such as Lewis (2011) and Acemoglu and Finkelstein (2008).

[5]An alternative approach to directed technical change was taken by Blum (2010) who used cross-country trade data in an effort to find evidence of directed technical change at a macro level. While this study is focused on the impact of changes in input supplies on innovation, there are complementary studies that consider the influence of demand factors or competition. Finkelstein (2004) and Acemoglu and Linn (2004) considered the impact of shifting demand patterns on innovation rates in the context of the pharmaceutical industry. Both found that shifts in demand can be an important driver of new product development. For competition, Bloom, Draca, and Van Reenen (2011) used several measures of technical change, including patents and R&D expenditures, to show that an increase in competition from Chinese producers led European firms to upgrade their technology.

goods made using Indian cotton. These goods are produced using raw materials and machines by perfectly competitive final goods producers with the production function $y_i = (\frac{1}{1-\alpha})(\int_0^{N_i} x_i(k)^{1-\alpha}\, dk) Z_i^{\alpha}$, where y_i is output of textile goods of type $i \in$ (US, INDIA), $x_i(k)$ is the quantity of machine variety k used, N_i is the measure of machine designs of type i available, and Z_i is the quantity of raw materials. For this study, the relevant raw materials are cotton from the United States and cotton from India, each of which is used to produce the corresponding final good. I denote the price of raw materials from location i as c_i. The set of machine designs available for producing each type of output, N_i, represents the level of technology available for producers of the type i good. Both machines and raw materials are specific to the good that they are used to produce and production exhibits constant returns to scale when N_i is fixed. Machines fully depreciate after use.

The most important elements of the model are the machines and their makers. Machine making firms can invest in producing a new machine design. They then hold an infinite patent on this machine design, which allows them to produce and sell machines of that type. Once they have a design, machine makers produce machines of that type subject to a fixed marginal cost and then sell them at the monopoly price to final goods producers. The key to the model is the entry decision of new machine making firms. To enter, they must pay a fixed cost to generate a new machine design. Whether they pay this cost to expand the set of available technologies depends on the discounted present value of the new machine design, which in turn depends on the demand for machines from final goods producers.

In steady state, the discounted present value of producing a design for a machine of type i is $V_i = \alpha p_i^{1/\alpha} Z_i / r$, where p_i is the price of final good and r is the interest rate. This equation shows the two key effects at work in the model. First, the value of innovation of type i is increasing in the quantity of raw materials Z_i. This *market size effect* occurs because machines and raw materials are complements in production. Second, the value of innovations of type i is increasing in the price p_i. This *price effect* occurs because higher final goods prices act as a demand shifter for machines. Crucially, however, Z_i and p_i are not independent; an increase in Z_i implies greater output of the final good, which will decrease p_i. Thus, as Z_i changes, the price and market size effects will work against each other to determine the overall impact on the returns to innovation in machines using that input. The relative strength of the two effects depends on the extent to which an increase in Z_i reduces p_i. This in turn depends on the (derived) elasticity of substitution between inputs, which I label σ. The value of σ determines the extent to which an increase in Z_i reduces p_i, and thus the strength of the price effect relative to the market size effect.

Holding technology fixed, an increase in the relative supply of an input results in a decrease in the relative price of that input. When technology can adjust, the model makes three main predictions:

PREDICTION 1: Relative technology ($N_{\text{INDIA}}/N_{\text{US}}$) is increasing in relative expenditures ($c_{\text{INDIA}}Z_{\text{INDIA}}/c_{\text{US}}Z_{\text{US}}$) on the balanced growth path.

PREDICTION 2: If $\sigma > 1$, an increase in relative input quantity ($Z_{\text{INDIA}}/Z_{\text{US}}$) will cause an increase in relative technology ($N_{\text{INDIA}}/N_{\text{US}}$) on the balanced growth path.

PREDICTION 3—Strong Induced Bias: If $\sigma > 2$, an increase in relative input quantity ($Z_{\text{INDIA}}/Z_{\text{US}}$) will cause an increase in the relative price of Indian cotton ($c_{\text{INDIA}}/c_{\text{US}}$) on the balanced growth path.

There is some evidence that the relevant elasticity of substitution for this study is greater than 1, and potentially above 2, but the available estimates are not precise enough to provide a structural test of the theory. The main challenge here is the need to use annual data, which leaves me relatively few observations to work with. Existing work by Irwin (2003) finds an elasticity of substitution between Indian and U.S. cotton of 1.96, but his approach imposes strong assumptions.[6] I have generated alternative estimates under weaker assumptions using weather shocks as instruments for relative supply. These results (see Supplemental Material (Hanlon (2015))) suggest an elasticity of substitution above 5.5, but with few observations the IV estimates are imprecise.

Finally, note that these are long-run predictions. Following an exogenous change in relative inputs supplies, the theory predicts that along the transition path innovation will focus on technologies related to only one machine type until the new long-run relative technology level is reached.[7] Given the nature of the experiment in this paper, it is this transition toward the new balanced growth path that we will observe.

3. EMPIRICAL SETTING

3.1. *Cotton Textile Production*

In the second half of the 19th century, the cotton textile industry was the largest manufacturing sector in the world's leading industrialized economy. Cotton textiles were Britain's largest export and raw cotton was Britain's largest import.[8] In terms of employment, the 1861 Census of Population shows 456,646 people in England and Wales worked in cotton textile manufacturing, equal to 2.3% of the total population or 9.5% of manufacturing employment. The focus of this study is on effects occurring within the cotton textile industry,

[6]Specifically, he used an Almost Ideal Demand System approach that assumes that export supply is perfectly elastic, which will bias his results downward.

[7]See Acemoglu and Zilibotti (2001, Appendix 1), for further details.

[8]Of course, this was not the case during the U.S. Civil War.

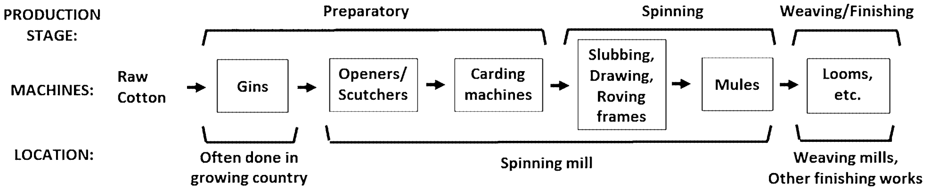

FIGURE 1.—The cotton textile production process.

so to keep things simple I do not discuss impacts of the Civil War outside of this industry unless it is necessary for the analysis.[9]

Figure 1 describes the production process for cotton textiles, which can be divided into three stages: Preparation, Spinning, and Weaving/Finishing. The middle row of the figure describes some of the key machines in each production stage, while the bottom row indicates where each process was usually carried out. Preparation, the most important stage for this paper, involved separating the cotton fibers from the seeds using gins, opening the cotton fibers using openers, and cleaning the cotton by removing leaves, dirt, and other matter using scutchers and carding machines.[10] Ginning generally took place in the cotton producing region, while later stages, such as opening and carding, took place in spinning mills in manufacturing centers such as Britain. In the spinning stage, the prepared raw cotton was spun into yarn. The yarn was then made into fabric, through weaving, after which the fabric could be finished through bleaching, dyeing, or printing.

All of these production stages relied heavily on machinery produced by Britain's large and innovative textile machinery sector. These British firms supplied machinery to British producers as well as most of the machinery used by producers outside of Britain.[11] Technologically, this was a fast-moving sector. Textile innovations made up over 11% of British patents from 1855 to 1883. Historians document numerous instances of cotton textile technologies responding to changes in the market within a one to two year period, a figure that is consistent with the innovation lag documented in this study.[12]

[9]Hanlon (2014) explored some of the impacts of the Civil War on other industries in Britain.

[10]Definitions of these and other textile-related terms are available in the Supplemental Material.

[11]The main exceptions were producers in the United States, who purchased much of their machinery from U.S. machine producers.

[12]For example, in her authoritative history of the development of the cotton gin, Lakwete (2003) detailed numerous instances in which inventors produced new innovations or patentable improvements on existing inventions within a one to three year period. Among these inventors is Eli Whitney, who had invented, patented, and introduced commercially his famous cotton gin within two years of first setting foot on a Southern cotton plantation. Two other good examples are Macarthy's roller gin and Whipple's cylinder gin, which were both invented in response to the panic of 1837 and patented in the United States in 1840. These examples suggest that, at least in

3.2. *Sources of Supply*

The British cotton textile industry depended entirely on imported raw cotton supplies, since growing cotton was infeasible in Britain. Just prior to the U.S. Civil War, roughly three-quarters of these supplies came from the Southern United States (77% in 1860). The other major supplier was India, which supplied 17% of imports in 1860. The remainder came from smaller suppliers, including Brazil and Egypt (both around 3% in 1860).

The focus of this study is on cotton from the two main suppliers, the United States and India. This focus is consistent with the assessment of most contemporary observers, before, during, and after the Civil War, who viewed India as the only viable alternative to American supplies. In 1859, *The Economist*, a leading commercial publication in the cotton districts, stated that, "practically speaking, we possess but two sources of supply…the United States and British India." This view was reiterated in an 1862 article titled "How is Cotton to be Got?" in which they wrote, "And at the outset, and to clear our ground, we may observe that India and America are practically the only two quarters which need occupy our attention…"[13] A similar view is offered in a retrospective piece on the efforts of the Cotton Supply Association, a group dedicated to encouraging new sources of cotton supply, by Watts (1871). In describing the failure of the Association to generate sufficient supplies from other locations to replace the shortage of U.S. cotton, he highlighted that, while many countries possessed the climate to grow cotton, the availability of labor was the key missing ingredient in most countries. However, "one of the few countries in which this great barrier to progress is but little known is India."

One consequence of the predominance of the two main varieties was that innovators focused their efforts on technologies related to either U.S. or Indian cotton. Thus, when investigating technological change, I concentrate my analysis on technologies related to these two varieties. However, the existence of smaller suppliers such as Brazil and Egypt is still helpful. While too small to be the focus of innovators, these varieties did have quoted market prices. As a result, they can be used to construct counterfactual relative price series in the absence of substantial innovations biased in their favor.

In order to identify technologies that were biased toward either American or Indian cotton, it is necessary to understand the key differences between these varieties. Here I discuss the most important differences, while further details

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the case of gins, it is reasonable to expect innovation to respond to changing conditions within a one to three year time frame. Another piece of evidence from the same time period comes from Lampe and Moser (2013). They found evidence that the introduction of a patent pool in the sewing machine industry led to an increase in patents of substitute inventions that spiked one to three years after the pool began.

[13] Later, the article stated, "Nor can the quantity furnished to us regularly from Brazil or Egypt be much increased, either immediately or ultimately, for reasons we have more than once explained."

are available in the Supplemental Material. Indian cotton was a low-quality variety that competed primarily with the low or middle grades of U.S. cotton, both of which were used to serve the large market for low- to medium-quality goods. The raw cotton supplied by the United States and India at the time of this study came from biologically distinct varieties.[14] The cotton available from India in the 1860s was widely considered to be inferior to U.S. cotton along several dimensions.

One difference between these varieties was that Indian cotton was more difficult to prepare for spinning. In particular, it was difficult to remove the seeds from the Indian cotton using the cotton gins that were available prior to 1861. This was a result of the unusually small size of the Indian cotton seeds, as well as their strong bond to the cotton plant (Wheeler (1862)). The primary machine used to remove seeds in India was the Churka, a very simple and inexpensive but inefficient and often ineffective hand-operated machine. The main alternative, prior to 1860, was the saw gin, which had been developed for processing American cotton and was also used for ginning high-quality cotton from Brazil and Egypt. However, American saw gins tended to cut up the Indian cotton fibers, reducing their length, and therefore their usefulness. As a result, the saw gin proved ill suited for India. In addition to the difficulty in removing seeds, Indian cotton fibers were also tightly compressed for shipping, making them difficult to open, a process which was done using openers.[15]

The United States also had a better developed cotton growing and processing industry than India, which influenced the cleanliness of the cotton. Indian cotton had a difficult journey from the interior to the ports, and passed through the hands of multiple middle-men, who habitually added dirt, salt water, or other substances in order to increase the weight of the cotton.[16] Compounding this problem, Indian cotton plants were leafier, which resulted in additional material being mixed in during picking. As a result, the Indian cotton required more cleaning than American cotton, a process that was done using gins, scutchers, and carding machines.

Indian and U.S. cotton also differed in their fiber length. Most of the raw cotton coming from the United States was of a medium-length variety, which was easier to spin than the short-fiber cotton supplied by India. The fact that Indian cotton was shorter likely compounded the difficulties involved in preparing the fibers, since ill-suited machinery could significantly shorten the fiber length.

[14]There had been some efforts to introduce U.S. cotton plants into India prior to the U.S. Civil War, but these were unsuccessful. During the war, there was a redoubling of effort and growers achieved some success in limited areas of India such as Dharwar. However, the vast majority of Indian cotton continued to come from native Indian plants.

[15]Compression for shipping was done using hydraulic presses. This process had some negative effects on cotton quality, but was still worth it when shipping from India, which faced much greater shipping distances and costs than the United States, Brazil, or Egypt, particularly before the opening of the Suez Canal in 1869. Patents filed in India show an increase in innovation related to these hydraulic press machines during the Civil War.

[16]See, for example, the description in Wheeler (1862, pp. 125–129) and Mackay (1853).

Of these differences, the most important bottleneck for the use of Indian cotton was the removal of seeds, dirt, and other matter without damaging the fibers. These steps were done by gins, openers/scutchers, and carding machines. Prior to the Civil War, these early-stage machines were well adapted for the use of U.S. cotton, as well as other high-quality varieties, but were poorly suited for dealing with Indian cotton. Thus, my analysis focuses on how innovation in these machine types reacted as the relative importance of Indian cotton increased during the Civil War.

3.3. *The Impact of the U.S. Civil War*

After the beginning of the U.S. Civil War in April of 1861, the North immediately declared a naval blockade of Southern ports. While initially ineffective, the blockade became increasingly disruptive to Southern commerce, including the export of raw cotton, as the war continued and the Union Navy expanded.[17] The resulting increase in transport costs and other disruptions caused by the war had a significant effect on British imports. Other suppliers, particularly India, but also Brazil and Egypt, substantially increased supplies in response to the shortage of U.S. cotton. Yet they were not able to increase their production rapidly enough to replace the flows from the United States. This pattern is visible in the left-hand panel of Figure 2. The right-hand panel of Figure 2

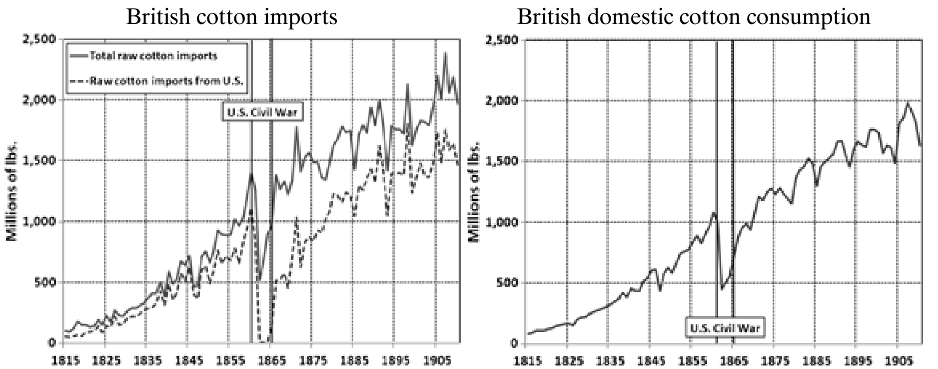


FIGURE 2.—British cotton imports and domestic consumption 1815–1910. Data from Mitchell and Deane (1962).

[17]A graph showing transport costs during the early part of the Civil War is available in the Supplemental Material. In addition to the Northern blockade, there were also efforts by the Confederate government to restrict cotton exports at the Southern ports in an effort to force Britain to intervene.

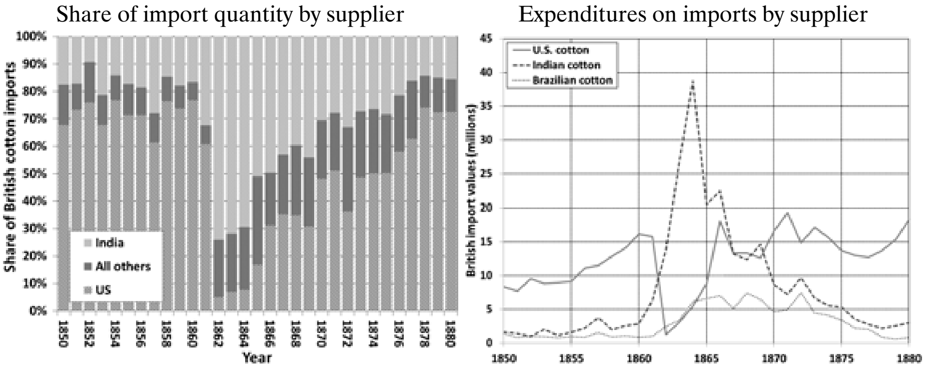


FIGURE 3.—British cotton import shares and expenditures, by supplier, 1850–1880. Data from Ellison (1886).

shows that there was a significant drop in British domestic cotton consumption from 1861 to 1865, a good indicator of production in the industry.[18]

Figure 3 shows the impact on the share of total import quantity from the United States, India, and other suppliers (left panel), and the value of imports from each location (right panel).[19] It is clear that the shock caused a sharp drop in the import share of U.S. cotton and an increase in the share of imports from India and other suppliers. While imports from the United States dropped sharply during the war, significant supplies remained on the market, allowing me to obtain reliable price data for U.S. cotton throughout the shock period.[20] Overall expenditure on cotton inputs shifted toward Indian cotton, as shown in the right-hand panel of Figure 3.

These figures make it clear that the war caused large changes during the 1861–1865 period. Following the end of the war, conditions began returning to their original equilibrium. The overall level of imports and production rebounded almost immediately, but the re-adjustment of relative input supplies took time. Imports of American cotton remained low through 1870, while im-

[18]The fall in production led to massive unemployment in the cotton textile districts, resulting in the "Lancashire Cotton Famine." Brady (1963) argued that in fact the drop in production was driven by an oversupply of cotton textile goods on the market in 1860–1861, rather than a drop in the availability of inputs. His argument is based on the fact that the ratio of cotton stocks to imports remained high during the war. However, when one considers the size of the reduction in imports and the drawdown in stocks over the 1861–1865 period, rather than comparing ratios, it is clear that his argument cannot be correct.

[19]Note that the import data shown in Figures 2 and 3 come from two different sources. The Mitchell and Deane (1962) data used in Figure 2 provide the longest time coverage but do not distinguish between imports from different sources.

[20]Imports from the United States never drop below 70,000 bales per year. For comparison, there were only 100,000 bales of Brazilian cotton imports in 1861. See the Supplemental Material for more details.

ports of Indian, Brazilian, and Egyptian cotton remained high through the mid-1870s. Also, while the share of Indian cotton in British imports fell back to pre-war levels by the late 1870s, overall Indian exports remained high through the 1870s, at least until the drought and famine of 1876–1878, because of a diversion of Indian exports to the Continent following the opening of the Suez Canal in 1869.[21]

The expectations of British producers played an important role in their response to the onset of the war. The most important part of this calculation was agents' expectations about the potential end of slavery and how it would affect the productive capacity of the U.S. South. Many believed that the United States could not maintain the production levels achieved in the 1850s without slavery. By 1862, we observe reports suggesting that at least some believed that the war, though temporary, would cause a long-term shift in relative supplies.[22] It is therefore reasonable to think of the war as shifting, for at least some time, agents' expectations of the long-run growth path of the economy. This shift played an important role in innovation investment decisions.

4. DATA

Most of the data used in this study were collected from original source material. In this section, I briefly describe how each of the main data sets were constructed, beginning with the patent data. Further details are available in the Supplemental Material.

Patent data, while imperfect, are often the best available measure of innovation patterns and are widely used. The patent data used in this study are drawn from a large new set of British patent data which I have collected from around 1,500 pages of original printed documents. The novel feature of these data is that each patent is classified into one or more of 146 technology categories by the British Patent Office (BPO).[23] These classifications allow me to identify the type of technology underlying each patent. They also contain other useful information, including the patent title and the name of the inventor. The analysis is conducted on data for 1855–1876, a period in which no significant changes to British patent law occurred. The dates given in the data represent the date of the patent application, rather than the date at which the patent was ultimately granted. Thus, the data identify patents at the earliest stage of the

[21] See Figure A.11 in the Supplemental Material.

[22] To cite one example, *The Economist* (August 23, 1862) wrote, "We admit, further, that, however and whenever this wretched and ruinous war may terminate, the ordinary routine of agricultural labor and the ordinary channels of transmission will have been so grievously disturbed that, for some time to come and perhaps for ever, the production of cotton in the Southern States will be smaller and costlier than it has been..."

[23] The purpose of this categorization was to aid inventors in identifying previously patented technologies.

patenting process and we can dismiss concerns regarding delays in the granting of patents in the analysis.

This paper focuses on patents falling into the BPO's "Preparation & Spinning" technology category, which includes technologies used in the preparation of raw cotton, such as cotton gins and carding machines, as well as machines used in the spinning process, such as mules, yarn types, and other related technologies. Within the BPO "Preparation & Spinning" technology category, patents are listed in various technology subcategories which represent specific types of textile machinery. In the main analysis, I include the three "Preparation & Spinning" technologies that were most relevant for Indian cotton as well as any other technology subcategory that was important enough to receive at least one patent in each of the years from 1855 to 1876.[24] I also exclude four technologies which were not applicable to the use of cotton, since my focus is on changes occurring within the cotton textile industry.[25]

Three of these subcategories—Gins, Openers/Scutchers, and Carding machines—represented the primary bottleneck in the use of Indian cotton. To learn more about these machines, I reviewed hundreds of abstracts describing each patented technology.[26] This review allowed me to better identify patents related to Indian cotton. Within the "Openers/Scutchers" subcategory, I further divide the patents into those machines applicable for cotton, which I label "Openers/Scutchers—for cotton," and those machines focused instead on other inputs (e.g., flax, rags, etc.), which I label "Openers/Scutchers—other." Within the Carding technology subcategory, the relevant technologies for using Indian cotton are those related to removing dirt and other debris from the fibers. The BPO classifications identify two sub-subcategories related to dirt removal. Thus, I divide the Carding machine subcategory into "Carding—dirt removal" technologies, which are relevant for using Indian cotton, and the remainder, "Carding—other."

This leaves me with three technology series which were the most important for the use of Indian cotton: (1) Gins, (2) Openers/Scutchers—for cotton, and (3) Carding machines—dirt removal.[27] In the main analysis, I compare these

[24]The subcategories used in the analysis are described in Table A.II in the Supplemental Material. Confining the analysis to subcategories with at least one patent in each year ensures that the control technologies represent substantially important technology categories. Also, from a practical perspective this allows me to avoid some issues related to the presence of zeros in the data when analyzing the time-path of patents. I also provide robustness results that include a number of smaller technology subcategories.

[25] Most of these excluded technology subcategories were related to the preparation of flax. In the Supplemental Material, I check the robustness of the main results to including these non-cotton subcategories.

[26]These abstracts function somewhat like abstracts for academic papers. They are generally one or a few paragraphs describing the new technology, and often include a diagram.

[27]Some additional Indian-related patents, having escaped my review, may remain outside of these three categories. These will act to bias my results against finding evidence of directed technical change toward Indian cotton.

to the 19 other large "Preparation & Spinning" technologies. In terms of the theory, we can think of changes in the ratio of Indian-related patents to the remaining "Preparation & Spinning" patents as reflecting shifts in $N_{\text{INDIA}}/N_{\text{US}}$.

Adjusting for quality is important when using patent data because raw patent counts mask the quality of the new technology represented by individual patents, which may vary widely. For this study, I collected new data providing two measures of patent quality. The first measure is based on the payment of patent renewal fees, which patent holders were required to pay at the end of the third and seventh years of the patent term in order to keep the patent in force.[28] Since just under 18% of patents were renewed at three years, the payment of these renewal fees represents a substantial investment which would only have been worth it for the most successful technologies.[29] The second quality measure is based on mentions of the patent in a contemporary periodical, *Newton's London Journal*.[30] This monthly journal, devoted to covering new patents and other technology-related topics, was published by William Newton & Sons, one of the preeminent London patent agents.

In addition to the patent data, I draw on two sources of additional evidence reflecting technical change. One source of data comes from the surviving records of one of the leading machine producers at the time, Dobson & Barlow of Bolton. These data were gathered from original hand-written order books, available in the Lancashire Archives. They describe the number of gins ordered during the Civil War period, and more importantly, they specify the type of gin ordered. Thus, they allow me to track the evolution of the designs of gins produced.[31] A second source is based on data from Forwood (1870) showing the percentage of cotton wasted in aggregate British production. The amount of waste is calculated by taking the total weight of raw cotton consumed by British mills in a year and subtracting the weight of yarn they produced. These data provide insight into the impact of new technologies on one important aspect of industry productivity.

Finally, I look at the impact of these machines on market outcomes using new price data that I gathered from market reports printed in *The Economist* magazine. The data cover 1852–1875. While the data were collected on a monthly basis, I average by quarter to reduce short-term volatility and measurement error. These data are available for the following benchmark cotton

[28] Renewal fee data have been used as an indicator of patent quality in previous studies (Pakes (1986), Schankerman and Pakes (1986), Lanjouw, Pakes, and Putnam (1998)), including some using historical British patent data (Sullivan (1994), Brunt, Lerner, and Nicholas (2012)).

[29] Because so few observations of patents renewed at year seven are available, I use only the renewals filed at year three.

[30] Contemporary periodicals have previously been used to value historical British patents by Nuvolari and Tartari (2011).

[31] Similar order data are available for other machine types, including carding machines and openers/scutchers, but it is not possible to track the pattern of technological progress in these orders because new technologies were embedded as parts in larger machines, rather than completely different machine types.

varieties: Upland Middling and Upland Ordinary from the United States, Surat Fair from India, Pernambuco Fair from Brazil, and Egyptian Fair. Of the two U.S. varieties, the Upland Middling was a higher-quality variety that was more comparable to the high-quality cotton from Brazil and Egypt, while the Upland Ordinary was a lower-quality variety that was more comparable to Indian cotton. Thus, I generally compare Indian cotton prices to those of Upland Ordinary, the most comparable U.S. price series.

A key feature of the price data is that they are for specific quality grades. Quality grading was a serious business at this time, undertaken by trained professionals. Quality changes that might occur as a result of the introduction of new techniques in the producer country would be reflected in shifts across the quality bins, with only a limited scope for quality changes within a grade. As a result, the prices we observe can be thought of as representing a fixed quality level.

5. EMPIRICAL ANALYSIS

The empirical analysis begins by using patent data to uncover the innovation response to the change in relative input supplies. These innovation patterns are then tied to investments in new or improved machinery using machine production data. Data on the waste generated in the production process are used to calculate the impact of these new technologies on one aspect of aggregate productivity. Finally, price data are used to investigate the impact on overall market outcomes.

5.1. *The Direction of Innovation*

To investigate the direction of the technical change, I use data on patents in 22 technology subcategories within the BPO Preparatory & Spinning technology category. Patents of technologies in the Preparatory & Spinning technology category show a substantial increase during the Civil War period. In contrast, patents in the other major textile-related technology category, Weaving & Finishing, do not increase, nor do patents across all other technology categories.[32] This motivates my focus on these early-stage textile technologies.

The left-hand panel of Figure 4 graphs the count of patents in the three technology types that were most important for using Indian cotton and the average count of patents in the other 19 Preparatory & Spinning technology subcategories. We can see that all three of the crucial technologies for using Indian cotton experienced a sharp increase during the Civil War period, while

[32]See Figure A.12 in the Supplemental Material. The reason that we see no effect on Weaving & Finishing technologies is that this category includes only machines used in the later stages of the production process. By the time the cotton reached these later stages, either the major quality issues had been dealt with or the cotton had been rejected as waste.

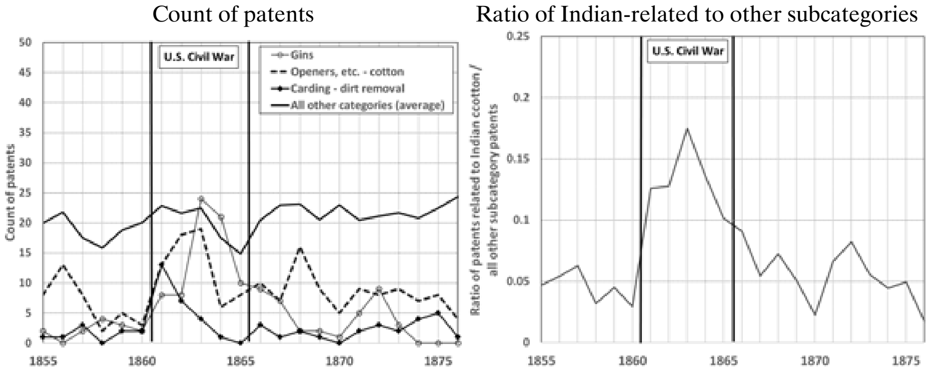


FIGURE 4.—Comparing Indian-related patents to other Preparatory & Spinning patents. These panels use data from 22 technology subcategories within the Preparatory & Spinning technology category. The three categories related to Indian cotton are Gins, Openers/Scutchers—for cotton, and Carding technologies—for dirt removal.

other technologies show no positive response.[33] The right-hand panel of the figure describes the ratio of patents of technologies related to Indian cotton to all other subcategory patents. Prior to the war, the technologies important for using Indian cotton made up only around 4–6% of subcategory patents. This ratio rose above 15% during the 1861–1865 period, with the peak in 1863, but had fallen back to 6% by 1867.

The results in Figure 4 provide evidence of directed technical change toward technologies that augment Indian cotton. In the context of the theory, this would mean an increase in $N_{\mathrm{INDIA}}/N_{\mathrm{US}}$, and given that we have observed an increase in expenditures on Indian cotton relative to U.S. cotton during this period, this is consistent with the predictions of the theory. These results also foreshadow the differences-in-differences approach taken in the econometric analysis.

Note that the timing of these patterns differs across gins, openers/scutchers, and carding machines. The increase occurs earliest in patents for carding machines related to dirt removal, while patents for openers/scutchers peak in 1862–1863 and gins do not reach a peak until 1863–1864. A review of the historical record, and the patents themselves, offers two explanations for this pattern. The first has to do with the nature of the technologies being invented. Gin patents often represented entirely new machines, and sometimes entirely new ginning concepts. In contrast, many of the patents in the openers/scutchers and carding categories were modifications of parts of machines or adjustments to otherwise well-developed production systems. Many of these carding and opener/scutcher technologies could be adopted quickly by modifying existing

[33]Graphs showing patent counts for all subcategories are available in the Supplemental Material.

machines; as an example, the Dobson & Barlow data show that the firm received 53 orders to alter existing carding machines during the U.S. Civil War, covering at least 1,085 individual machines.[34] Thus, technological complexity helps explain why innovations in carding machines and openers/scutchers appeared so rapidly, while there was a longer lag before the peak of innovation in gins.

A second explanation for the timing patterns in Figure 4 is that British machine producers had less experience in producing gins, and in creating new gin designs, than they had for openers/scutchers or carding machines. Carding machines, openers, and scutchers were an important part of the output of diversified textile machinery firms. In contrast, prior to the Civil War, most American cotton was ginned using American-made gins, while Indian cotton was ginned using crude locally produced equipment. This left little room for British engineering firms to produce gins. This is illustrated in the Dobson & Barlow production data, which show no evidence that firm produced gins prior to the Civil War. Thus, British producers had more to learn about gin production and design than about other technology types.

Next, I analyze these patterns econometrically using a panel data approach. The primary data set spans 22 years (1855–1876) and 22 technology groups, three of which are related to Indian cotton. Analyzing these data econometrically requires that I deal with a number of issues, some of which are the subject of ongoing research and debate. One issue is truncation in the data, since some of the data series show zero patents in some years. This is a particular problem with the three technology types related to Indian cotton, since there was little interest in these types of technologies in the pre-war period. A second issue is serial correlation, which Bertrand, Duflo, and Mullainathan (2004) have shown can lead to underestimated standard errors in panel data regressions. A third issue is that I am conducting panel data analysis with a small number of cross-sectional units.

To deal with these issues, I begin by aggregating the data into pre-shock, shock, and post-shock periods.[35] One advantage of aggregation is that it avoids the need for count data models, which are often required when using patent

[34]Pre-war data, available only for Nov. 1860–March 1861, show zero orders for the alteration of carding machines, suggesting that this surge in alterations was driven by the Civil War.

[35]This follows the suggestion by Bertrand, Duflo, and Mullainathan (2004), who showed that aggregation can help deal with serial correlation issues and performs well in small samples. Aggregating appears to be an effective solution to serial correlation issues in my data. Applying the panel-data serial correlation test from Wooldridge (2002) to the annual data with the three treatment groups pooled together as in Equation (1) yields an F-statistic of 8.148 and a p-value of 0.0095. After aggregation, the same test yields an F-statistic of 2.87 and a p-value of 0.1049. It is worth keeping in mind here that the small-sample properties of these tests are not well studied. There are two promising alternatives to aggregation for dealing with serial correlation. One is to cluster by technology category, allowing errors to be correlated over time, and then make a small-sample adjustment. A second alternative, which I apply later, is to exploit the time-series nature of the data and calculate Newey–West standard errors. The current literature does not provide

data, and eliminates all zeros in the data. At the same time, it addresses serial correlation issues. However, aggregating this way also reduces the available data, making it less likely that I find statistically significant results.

After collapsing the data for each subcategory into pre-shock, shock, and post-shock periods, the regressions specification is

$$\log(\mathrm{PAT}_{jt}) = \alpha + \beta(S_t \times \mathrm{INDIATECH}_j) + \Psi_j + \xi_t + e_{jt}, \tag{1}$$

where PAT_{jt} is the average count of patents in subcategory j and period t, Ψ_j is a full set of subcategory-specific fixed effects, ξ_t is a set of period indicator variables, and e_{jt} is an error term. The key explanatory variable is the interaction between an indicator variable for the shock period, S_t, and an indicator variable, $\mathrm{INDIATECH}_j$, for the "gins," "openers/scutchers applicable to cotton," and "carding machines for dirt removal" subcategories.

The regression results are displayed in Table I. Column 1 presents results including the pre-shock, shock, and post-shock periods, while Column 2 presents

TABLE I

RESPONSE OF TECHNOLOGIES RELATED TO INDIAN COTTON DURING THE CIVIL WAR[a]

	Dependent Variable: Log Patents	
	Comparing Shock Period to Pre- and Post-Periods	Comparing Shock to Pre-Period Only
India-related × Shock period	1.127 (0.276) [0.001] [[0.044]]	1.254 (0.302) [0.001] [[0.049]]
Subcategory effects	Yes	Yes
Time period effects	Yes	Yes
Observations	66	44
Number of panels	22	22

[a] The pre-shock, shock, and post-shock periods are, respectively, 1855–1860, 1861–1865, and 1866–1876. *Parentheses* contain robust standard errors. *Single brackets* contain p-values from a test in which I select every combination of three technologies out of the 22 technology categories (22 choose 3 = 1,540) and estimate the impact on these three during the shock period. The distribution of these "placebo" coefficients is then used to construct the p-value of the treatment coefficient. Histograms of these coefficients are available in the Supplemental Material. *Double brackets* contain p-values from a test based on HC2 standard errors tested against a t-distribution with a degrees of freedom determined using Welch's (1947) formula. For the specification in Column 1, Welch's approach gives a degrees of freedom of 2.35. For the specification in Column 2, Welch's formula gives 2.55. Regressions with only the shock and post-shock periods generate similar results but with slightly smaller coefficients, suggesting that some effects may have spilled over into the post-war period.

clear guidance on which of these alternatives is preferred. My preference for aggregation is based on the fact that aggregation also eliminates zeros in the data, which allows me to run regressions in logs and avoid the use of count data models. The data show no evidence of substantial cross-sectional dependence, passing Pesaran's test for cross-sectional dependence in panel data with a p-value of 0.2835. See Hoyos and Sarafidis (2006) for a discussion.

a more standard differences-in-differences approach with only the pre-shock and shock periods. Robust standard errors are in parentheses. We can tell from the standard errors in Table I that the coefficients are statistically significant under standard inference procedures based on asymptotic results.

Conducting inference using standard approaches may lead to underestimated confidence intervals in this setting because of the small number of panels (22) in the data.[36] To address this concern, I present the results of two small-sample corrections. In the single brackets, I offer p-values from a permutation-based approach where I take every permutation of three technology groups, out of the 22 groups in the analysis, and treat them as if they were the treated technologies. This generates 22 choose 3 = 1,540 coefficient estimates. Under the null hypothesis of no effect, these coefficients will have the same distribution as the estimated coefficient from Equation (1). Thus, they can be used for inference with exact size.[37] Alternatively, I follow the advice of Imbens and Kolesar (2012) by calculating heteroskedasticity-robust HC2 standard errors (MacKinnon and White (1985)) and then conducting inference using a t-distribution with a data-determined degrees of freedom based on the formula from Welch (1947).[38] The p-values obtained from this procedure are in double brackets.[39]

These results confirm the patterns from Figure 4: there was a substantial increase in patents related to Indian cotton during the Civil War period, relative to all other types of Preparatory & Spinning technologies. These patterns are statistically significant even under a very conservative approach. Further results, available in the Supplemental Material, show that these findings are

[36]A number of approaches have been offered for dealing with this issue. These include bias corrections (MacKinnon and White (1985), Bell and McCaffrey (2002)), bootstrap-based approaches (Cameron, Glelbach, and Miller (2008)), the use of t-distributions for inference (Donald and Lang (2007), Imbens and Kolesar (2012)), and using permutations reassigning treatment to control groups to estimate the distribution of the test statistic (Conley and Taber (2011), Ibragimov and Muller (2010)). I have explored a variety of alternatives to the approach presented and they all confirm the pattern documented here.

[37]This approach has been used by Bloom, Eifert, Mahajan, McKenzie, and Roberts (2013) and is similar to the approach of Conley and Taber (2011). Histograms of the permutation coefficients are available in the Supplemental Material.

[38]Imbens and Kolesar (2012) suggested using a data-determined degrees of freedom based on Bell and McCaffrey (2002), but that approach requires an assumption of homoskedasticity that does not appear to be a good fit for my data. Nevertheless, the two approaches deliver very similar results.

[39]It may seem somewhat surprising here that the permutation-based approach delivers results that are much stronger than those from the Imbens and Kolesar (2012) approach. The cause of this is not the HC2 standard errors. The difference comes almost entirely from conducting inference with a t-distribution with very few degrees of freedom. This is a very conservative distribution, with confidence intervals more than twice as wide as under normal standard errors. Thus, the p-values in double brackets should be viewed as very conservative.

robust to variation in the underlying data, such as the inclusion of small technology subcategories or considering only patents with "cotton" in the title.[40]

One feature of the approach taken in Table I is that it does not allow me to explore the pattern of these effects over time. Investigating the timing of these impacts in more detail requires that I use annual data and a slightly different econometric approach. I begin by summing patents from the three treated categories into one treated technology category, called INDIATECH2_j, which eliminates all zeros in the data. I then run the following regression specification:

$$\log(\text{PAT}_{jt}) = \alpha + \left[\sum_{k=1858}^{1876} \beta_k \times \text{YR}_k \times \text{INDIATECH2}_j\right] + \Psi_j + \phi_t + \varepsilon_{jt}, \tag{2}$$

where YR_k is an indicator variable for year k and ϕ_t is a set of year indicator variables. To assess pre-trends, I begin estimating coefficients several years before the onset of the conflict. To deal with heteroskedasticity and serial correlation, I calculate Newey–West standard errors.[41] There is no evidence of time-trends in the series, so I do not include time-trends in the regression.[42]

The results are presented in Figure 5. There is no evidence of an increase in Indian-related technology patents prior to 1861, and in fact patents in these categories were unusually low, perhaps due to the disruptions in Indian cotton supplies following the Indian Rebellion of 1857–1858. This is consistent with the historical record, which indicates that people were surprised by the magnitude of the conflict. Starting in 1861, patents in categories related to Indian cotton increased substantially, peaking in 1863, and declining thereafter. There is some evidence that the high level of patents in these categories extended beyond the end of the war to 1867. This pattern is consistent with some

[40]There is also evidence that all three Indian-related technology categories experienced significant increases during the Civil War period. Results are presented in Table A.V in the Supplemental Material. However, for reasons discussed in the Supplemental Material, the small-sample corrections do not perform well in that specification, so those results must be interpreted with caution.

[41]Hansen (2007) showed that HAC estimators of this type provide valid inference either as N and T go to infinity jointly, or as T goes to infinity with N held fixed. His Monte Carlo simulations also suggest that these estimators perform well in samples comparable in size to mine. In the Supplemental Material, I explore two alternative approaches to generating the confidence intervals. The first uses clustered standard errors, while the second follows Angrist and Lavy (2009) in using the Bias Reduced Linearization approach introduced by Bell and McCaffrey (2002). These approaches generate similar results.

[42]Because of the relatively short and volatile pre-period, results generated with time-trends are highly sensitive to the number of pre-periods included in the summation in Equation (2). This feature, plus the lack of clear time-trend in the data, suggests that including time-trends in the regressions is likely to reduce the accuracy of the estimated results.

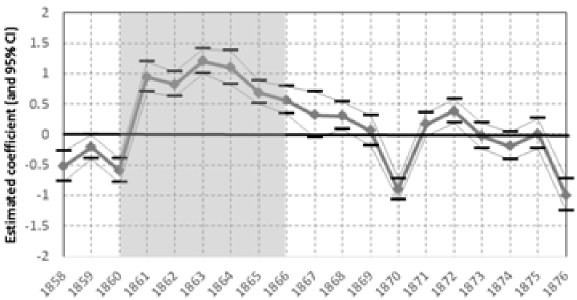


FIGURE 5.—Pattern of patents related to Indian cotton over time. This chart shows estimated coefficients and 95% confidence intervals for the interaction between technologies related to Indian cotton and each year from 1858 to 1876. The dependent variable is the log of patents in each subcategory-year. The Indian-cotton-related technology category is formed by aggregating the Gins, Openers for Cotton, and Carding for Dirt Removal technology categories. Thus, the data include 20 technology categories over 22 years (1855–1876) with one treated category. Confidence intervals are based on Newey–West standard errors with a lag length of 3 (based on Greene's rule-of-thumb lag length of $T^{1/4}$ rounded upwards).

path dependence in innovation, such as that hypothesized by Acemoglu et al. (2012), and may also lead to a slight downward bias in the results presented in the first column of Table I.

When using patent data, it is always important to account for the quality of inventions, which may be obscured when only raw patent counts are used. To investigate the behavior of high-quality patents during the Civil War, I use the approach from Equation (1), but with the count of high-quality patents PAT_{jt}^{H} used in place of the count of all patents PAT_{jt} in a technology and period.

To identify high-quality patents I use two approaches. First, I look at those patents for which the renewal fee was paid at year three to keep the patent in force. Renewal fee data are available for 1856–1869, so I can compare pre-shock, shock, and post-shock periods. The second quality measure is based on abstracts included in a contemporary periodical, *Newton's London Journal*. Those data are available from 1854 to 1864, so I compare the pre-shock period to the shock period. Graphs of both series are available in the Supplemental Material.

Results are presented in Table II. There is evidence of an increase in high-quality patents related to the use of Indian cotton during the Civil War. The results are statistically significant at or very close to the 95% level under the permutation-based approach, but are not statistically significant at the 95% level under the more conservative Imbens and Kolesar (2012) approach. Graphs, available in the Supplemental Material, show that this increase in renewed patents was present even for patents which would have been renewed after the end of the Civil War.

Next, I turn to two non-patent measures of technological progress. The first is drawn from the order books of Dobson & Barlow, a textile machine pro-

TABLE II

HIGH-QUALITY PATENTS RELATED TO INDIAN COTTON DURING THE CIVIL WAR[a]

	Dependent Variable: Log Patents		
	Patents Paying Renewal Fee After Three Years		Patents Mentioned in *Newton's London Journal*
	(1)	(2)	(3)
India-related × Shock period	1.343 (0.482) [0.002] [[0.125]]	1.805 (0.554) [0.001] [[0.086]]	0.887 (0.475) [0.052] [[0.204]]
Subcategory effects	Yes	Yes	Yes
Time period effects	Yes	Yes	Yes
Included time periods	Pre-shock, shock, post-shock	Pre-shock, shock	Pre-shock, shock
Observations	66	44	40
Number of panels	22	22	20

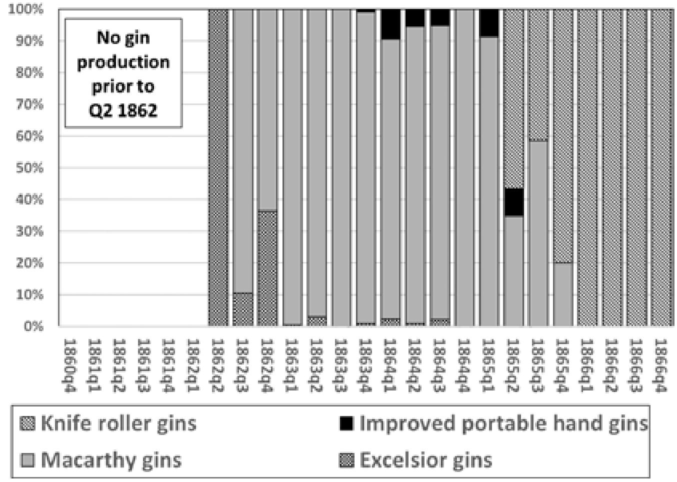
[a]The renewal fee data used in Columns 1 and 2 cover 1856–1869 and the shock period is 1861–1865. The data used in Column 3 cover 1855–1864 and the shock period is 1861–1864. Patents are classified by the application date. The "Bobbins" and "Winding-on" technology subcategories are omitted from the data used in Column 3 because they have zero mentions in Newton's London Journal in at least one of the periods. *Parentheses* contain robust standard errors. *Single brackets* contain p-values from a test in which I select every combination of three technologies out of the available technology categories and estimate the impact on these three during the shock period. The distribution of these "placebo" coefficients is then used to construct the p-value of the treatment coefficient. Histograms of these coefficients are available in the Supplemental Material. *Double brackets* contain p-values from a test based on HC2 standard errors tested against a t-distribution with a degrees of freedom determined using Welch's (1947) formula. For the specification in Column 1, Welch's approach gives a degrees of freedom of 2.31. For Column 2, it gives 2.45. For Column 3, it gives 2.90.

ducing firm. This was an important firm, employing 1,600 workers in 1860 and supplying a full line of textile-related machinery. The firm was also active in innovation, particularly in gins and carding machines. The firm produced no cotton gins in the pre-war period, but this changed dramatically starting in 1862, and gins made up an important part of overall machine sales during much of the Civil War period.[43]

These data allow us to observe the evolution of the different gin types that Dobson & Barlow produced over the Civil War period and compare this pattern to their gin patents. Figure 6 shows the share of gin orders made up of each of the four gin types produced by Dobson & Barlow from 1860 to 1866. The data show a rapid evolution, starting with Excelsior gins, moving to Macarthy gins, followed by the less-successful Improved Portable Hand Gin, and finally

[43]American cotton was generally ginned using American-made gins, while prior to the war Indian cotton was ginned using simple locally produced hand-gins. Thus, it is not surprising that Dobson & Barlow were not active in gin production in the pre-war period.

Share of gin sales by gin type



Gin patents

Year	Month	Patent No.	Applicant	Patent title
1862	Oct.	2765	Barlow, E	"Certain improvements in machinery for driving cotton gins and for preparing and combing cotton and other fibrous substances."
1863	Nov.	2915	Dobson, B & Barlow, E	"Machinery for ginning cotton and for opening cotton and other fibrous substances."
1865	Jan.	44	Dobson, B	"Machinery for ginning cotton."
1865	Jan.	248	Dobson, B	"Cotton gins."

FIGURE 6.—Dobson & Barlow share of gin sales by type and gin patents. Sales data from Dobson & Barlow contract books accessed at the Lancashire County Archives. Gin contracts were reviewed from October 1860 to December 1866. The date is based on when the contract was received. Patent titles from the *Cradle of Invention* database.

the Knife Roller Gin. At the bottom of the figure is a list of Dobson & Barlow patents of gin technology over the period. Excluding the first patent, which was for a driving apparatus, we can see that the patent applications tended to correspond to the introduction of new gin types.[44] The introduction of the Improved Portable Hand Gin in December of 1863 closely follows a patent filing in November of 1863. Similarly, two gin patents were filed in January of 1865 and the firm begins switching production to the new Knife Roller Gin soon after. These patterns suggest a close link between patenting and production.[45]

[44]Note that a patent application granted provisional protection with the application date as the priority data. Thus, once a patent application is filed, the patent applicant can begin using the patented technology.

[45]Because the patents are given as a set of technical specifications, and I do not have the technical specifications for the gins sold by Dobson & Barlow under each name, I cannot definitively link the patents to the new machines that were introduced.

Next, I present evidence suggesting that these new technologies had an impact on aggregate productivity in cotton textile production. To do so, I focus on one important and observable element of productivity: the waste produced as part of the production process. The level of waste is simply the difference between the weight of raw cotton consumed by spinning mills and the weight of yarn produced. Waste was generated in two primary ways. First, raw cotton going into the mills may be weighed down with dirt and other debris. When this is removed as part of the production process, it will show up as waste in these calculations. Second, cotton may be damaged during the preparatory process in the mills, making it useless for spinning. Improved preparatory stage technologies could thus reduce waste in two ways: by reducing the amount of materials contaminating the raw cotton entering the mills, or by reducing damage to the raw cotton done through the production process.

Data from Forwood (1870) describe the percentage of raw cotton wasted in the production process from 1860 to 1868. This waste percentage is shown in the solid line in Figure 7. The sharp increase in waste in 1862 is an indicator of the difficulties faced by British producers as they shifted toward using Indian cotton. This increase is particularly striking given that prices had increased substantially by 1862 (see next section) and producers must have been working to minimize wastage at that time.

To assess the impact of new machinery and techniques on cotton waste, I conduct a simple calculation. Suppose that the increase in cotton waste from 1860 to 1862 is due to the increase in the share of Indian cotton consumed by British mills, which rose from 7% in 1860 to 59% in 1862.[46] This suggests a

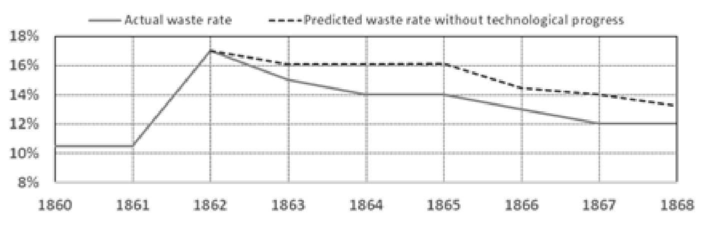


FIGURE 7.—Percentage of cotton wasted in production. *Solid line* describes the actual percentage of raw cotton weight that is lost in the production process. *Dotted line* is constructed by comparing the increase in waste from 1860 to 1862 to the increase in the share of Indian cotton in cotton consumption by British mills over that period in order to calculate the waste rates for Indian and non-Indian cotton. Holding the waste rates constant, I then project aggregate waste shares for years after 1862 based on the share of Indian cotton in total consumption. Data from Forwood (1870). The predicted waste level for 1864 is interpolated because Forwood did not report cotton consumption data for that year.

[46]Note that the increase in consumption of Indian cotton was small in 1861, reaching just 15% of consumption, despite a larger increase in imports. This is most likely because the jump in imports occurred late in the year and producers put off using the less attractive Indian cotton as long as possible.

waste rate of 22% for Indian cotton compared to 9.6% for non-Indian (mostly American) cotton. If these percentages remained the same after 1862, then the overall waste share we would expect is given by the dotted line in Figure 7. This line is declining slowly due to the declining share of Indian cotton imports after 1862, but does not decline as fast as the actual waste share. The difference between the solid and dotted lines can be thought of as a rough estimate of the impact of improved technology on waste in the production process. This simple calculation suggests a fall in the waste generated from spinning with Indian cotton to 15.5–17.9% by 1866–1868, a 19–30% improvement over the original level.[47] These results are consistent with the timing of the introduction of new machines and suggest that these machines had a substantial impact on aggregate productivity.

5.2. *Price Responses: Strong Induced Bias*

This section explores the impact of the change in relative input supplies on relative input prices in the presence of directed technical change. Of particular interest is the strong induced-bias hypothesis: the idea that, if technical change is strongly biased toward an input that has become relatively more abundant, the relative price of that input can rebound, and may actually increase, despite the increase in relative supply.

Figure 8 plots the price data used in this analysis. I use prices for the two large varieties, U.S. and Indian cotton, as well as two smaller varieties, Brazil-

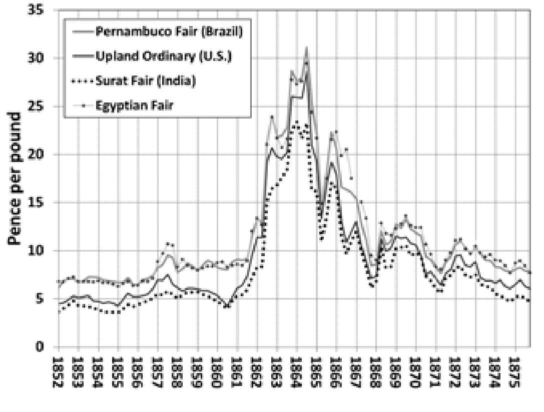


FIGURE 8.—Raw cotton prices on the Liverpool market for key varieties 1852–1875. Quarterly price data from *The Economist*. Upland Ordinary is the benchmark lower-quality U.S. cotton variety. Surat is the benchmark Indian cotton variety. Pernambuco is the benchmark Brazilian cotton variety.

[47]The estimated waste share for non-Indian cotton for the 1866–1868 period ranges from 9.9% to 10.1%, suggesting that for cotton other than from India there was little improvement in the waste rate over that period.

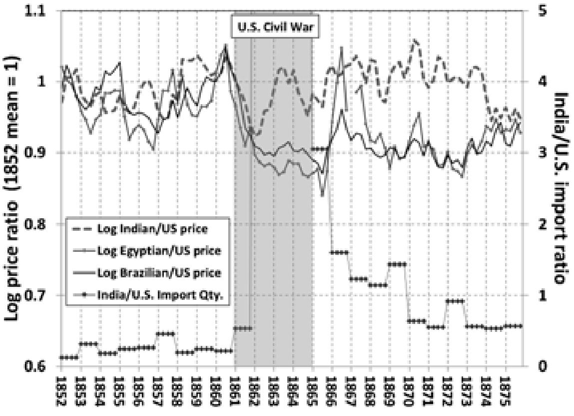


FIGURE 9.—Comparing relative cotton price movements. Price data from *The Economist* magazine. Import data from Ellison (1886).

ian (Pernambuco) and Egyptian cotton. In all periods, these prices are roughly ordered according to quality, with Brazilian and Egyptian fetching the highest prices, and Indian cotton the lowest. We can see that the onset of the Civil War was followed, with some lag, by a sharp increase in the price of all cotton varieties. Prices remained high through 1865 and began to decline in 1866.

What we cannot see in Figure 8 is the behavior of relative prices, which is our primary interest. In Figure 9, I graph the relative prices of Indian/U.S. cotton, Brazilian/U.S. cotton, and Egyptian/U.S. cotton for 1852–1875, as well as the relative import quantity of Indian to U.S. cotton.[48] To make things easier to compare, I have put each relative price line in logs and set the average price in 1852 to equal 1 for each series. Relative quantities are not shown for 1862–1864, when the low levels of U.S. imports led to very high ratios.

Focusing first on the relative import series, we can see that the ratio of Indian/U.S. imports was at least double the pre-war level from 1862 through 1870 and remained above the pre-war level through 1875. Next, looking at the relative price of Indian to U.S. cotton, we see a drop at the beginning of the war, as relative quantity shot upwards. However, the relative price rebounded after 1862 and remained near the pre-war level through the mid-1870s, despite the fact that the relative quantity of Indian/U.S. cotton had substantially increased. The rebound occurred despite the fact that the share of imports made up of Indian cotton increased from 17% in 1860 to 34% in 1861, more than doubled to 74% in 1862, and then remained high through 1876. The timing of this rebound also fits the pattern of innovation well; by late 1862, many new technologies had entered the market, and others would follow soon after.

[48] Additional price graphs are available in the Supplemental Material. I end the graph in 1875 because 1876 marked the beginning of the Great Indian Famine, which sharply reduced Indian cotton exports and marked the end of the period of relative abundance of Indian cotton.

Finally, consider the relative prices of Brazilian and Egyptian cotton, varieties where I did not observe evidence of substantial directed technical change. These series suggest the counterfactual relative price pattern obtained in the absence of directed technical change. Prior to the war, all three of the relative prices moved within a similar range, though they did not move together.[49] They all fell sharply at the beginning of the war and followed a fairly similar pattern through early 1862. After 1862, in contrast to the rebound in the relative price of Indian cotton, the relative prices of the Brazilian and Egyptian varieties remained low throughout the period in which they remained relatively more abundant.[50] The divergence between the relative price of Indian cotton and the relative prices of the other varieties after 1862 is consistent with the expected impact of directed technical change focused primarily on Indian cotton.

There is evidence in Figure 9 of a high relative price of Indian cotton in 1858, prior to the Civil War. This increase was due to the short-term effect of the Indian Rebellion of 1857, which caused a sharp short-term reduction in the availability of Indian cotton (from 680,500 bales in 1857 to 361,000 in 1858). This temporary reduction in supply had the expected positive effect on relative prices. It is interesting that the relative price of Indian cotton during this period of shortage is similar to that reached in the late Civil War period even though the quantity of Indian cotton on the market was much higher, reaching 1,866,610 bales in 1866 compared to 361,000 in 1858. Given the shortage of U.S. cotton, the increase in the relative quantity of Indian cotton was even greater. In the absence of directed technical change, it would be puzzling to observe similar relative prices in 1858, when there was a severe shortage of Indian cotton, and in 1866, when the relative availability of Indian cotton was at a historic high.

To analyze these patterns econometrically, I consider two separate questions. First, is there evidence that the relative price of Indian cotton behaved differently than that of the smaller alternative varieties that did not benefit from substantial directed technical change? Second, is there evidence that during and after the Civil War the relative price of Indian/U.S. cotton rebounded to the pre-war level despite the increase in relative supply? Answering each of these questions requires a slightly different approach.

Answering the first question involves comparing price patterns across varieties, so it can be addressed using a panel-data approach with data on the

[49]Given the importance of idiosyncratic shocks such as bad weather, this is not surprising.

[50]The main exception to the pattern of low relative prices for Egyptian and Brazilian cotton is the increase in the relative price of Egyptian cotton in 1865–1867. This was the result of a decrease in the quantity of Egyptian cotton on the market due to poor agricultural conditions.

relative prices of Indian/U.S., Brazilian/U.S., and Egyptian/U.S. cotton.[51] The specification is

$$\text{(3)} \qquad \mathrm{RP}_{jt} = \alpha + \left[\sum_{k=1859}^{1875} \gamma_k \times \mathrm{YR}_k \times \mathrm{INDIA}_j\right] + \eta_j + \phi_t + Q_t + \varepsilon_{jt},$$

where j designates a variety (Indian, Brazilian, or Egyptian cotton), RP_{jt} is the price of the variety relative to the comparable U.S. variety, INDIA_j is an indicator variable for Indian cotton, η_j is a set of variety fixed effects, and ϕ_t and Q_t are, respectively, sets of year and quarter effects.[52] Treatment coefficients are estimated for two pre-war years in order to look at pre-trends. In some specifications I also control for the impact of the Indian Rebellion in 1858–1859 by including an indicator variable for India in those years. Estimation is done using Newey–West standard errors.[53]

The coefficient estimates and 95% confidence intervals are presented graphically in Figure 10.[54] These results show no evidence of pre-trends. The relative price of Indian/U.S. cotton began diverging from the pattern shown by the comparison varieties in 1862. This difference widened in 1863 and persisted through the mid-1870s. These patterns are consistent with the impact we would expect from new technologies tailored to the use of Indian cotton.

The second question posed above involves comparing the response of the relative price of Indian/U.S. cotton during the Civil War to the pattern in the pre-war period. This naturally begs a time-series approach. The specification is

$$\text{(4)} \qquad \mathrm{RP}_t^{\mathrm{INDIA/US}} = \alpha + \left[\sum_{k=1859}^{1875} \gamma_k \times \mathrm{YR}_k\right] + \varepsilon_t.$$

[51] In this analysis, I compare Indian cotton to lower-quality U.S. cotton and Brazilian or Egyptian cotton to higher-quality U.S. cotton. One advantage of this is that these results are more robust to shifts in demand toward the lower- or higher-quality market segments, an important concern since some such shifts may have occurred during the Civil War period. If I instead compare all of the alternative cotton varieties to the same type of U.S. cotton, the results are essentially unchanged.

[52] It is possible to include variety-specific time-trends in this specification. However, there is no evidence of such trends in the pre-war period in Figure 9, suggesting that including these terms is not necessary. Moreover, with a somewhat short and volatile set of pre-war observations, including such time-trends has the potential to substantially reduce the quality of the estimates.

[53] The asymptotic properties of estimators of this type with fixed N and large T, or with both N and T growing, were studied by Hansen (2007). A lag length of 8 is used to allow correlation across two harvest seasons. This is larger than what Green's rule of thumb lag length $= T^{1/4}$ would suggest. I have experimented with using alternative lag lengths for these regressions and found that this does not substantially affect the statistical significance of the coefficients.

[54] Full regression results are available in the Supplemental Material.

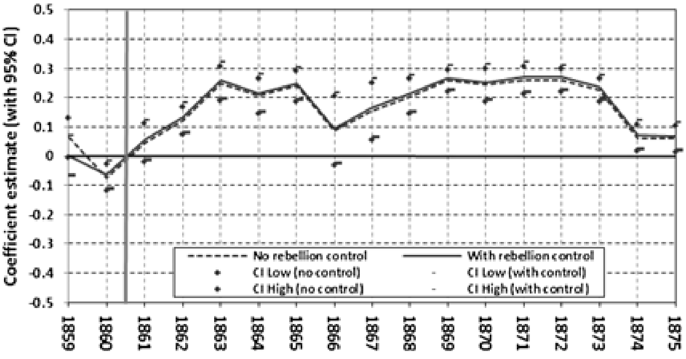


FIGURE 10.—Pattern of India/U.S. cotton price relative to control varieties. Regressions compare the price response of Indian/U.S. cotton to two alternative varieties, Brazilian/U.S., and Egyptian/U.S. cotton using the specification in Equation (3). The data are quarterly and cover 1852–1875. The figure presents the estimated coefficient and 95% confidence intervals for variables interacting an indicator for each year starting in 1859 with an indicator variable for Indian cotton. Regressions use Newey–West standard errors with a lag length of 8. Regressions are done with and without controlling for the Indian Rebellion of 1858 using an indicator variable for Indian cotton in 1858–1859.

There is no evidence of a time-trend in Figure 9, so a time-trend term is not included here. As before, I use quarterly data from 1852 to 1875 and calculate Newey–West standard errors with a lag length of 8 (to cover two growing seasons). The results are presented in Figure 11. Compared to the pre-war period, we see a statistically significant drop in the relative price of Indian/U.S.

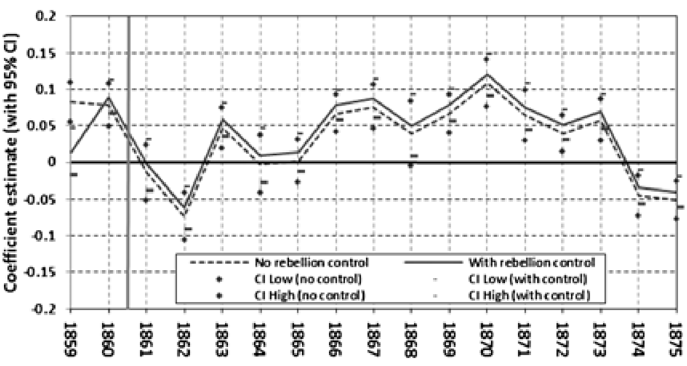


FIGURE 11.—Behavior of the Indian/U.S. cotton price relative to the pre-war period. Regression is run on a single time-series of the relative price of Indian/U.S. cotton using quarterly data from 1852 to 1875 and the specification in Equation (4). The figure describes the coefficient and 95% confidence intervals for indicator variables for each year starting in 1859. Regressions use Newey–West standard errors with a lag length of 8. Regressions are done with and without controlling for the Indian Rebellion of 1858 using an indicator variable for 1858–1859.

cotton in 1862, followed by a rebound to the pre-war level in 1863. The relative price then remained at or above the pre-war level through the mid-1870s, with evidence of a statistically significant increase in several years in the late 1860s.

These results raise several potential issues that must be addressed. First, we may be concerned that the timing of the rebound in the relative price of Indian cotton occurs too rapidly, before the new innovations could have substantially affected the market. Yet, by the time the rebound began in October of 1862, many new technologies had already been patented, particularly in the carding and openers/scutchers categories, and gin patents had also reached a historic high. Market participants likely knew that further innovations were being developed. Given that information, and the fact that cotton was storable for up to a year, it is not surprising that market prices began reacting in 1862.

Another concern is that other time-varying shifts in the market, such as a shift in demand toward low-quality products, might have affected higher- and lower-quality textile products differently. We may be worried that such a shift could cause the relative price of Indian cotton to behave differently than that of Brazilian or Egyptian cotton. However, recall that we are comparing the price of Indian cotton to the price of lower-quality U.S. cotton. A shift in demand toward lower-quality textile products would affect both of these varieties. The same argument applies to Brazilian and Egyptian cotton, higher-quality varieties that are compared to higher-quality U.S. cotton. Thus, it is unlikely that such a shift could be generating the patterns we observe, since it would be reflected in both the numerator and denominator of the relative price series.

Finally, we may be concerned that these results are generated by an upward shift in the quality of Indian cotton. However, recall that the prices of each cotton variety are reported *for a specific quality level*. Thus, shifts in cotton quality would be reflected in a reallocation of quantities across the fixed quality bins, but the quoted prices would continue to reflect the value of cotton at a fixed quality level. Moreover, rather than improving during the Civil War, the historical evidence suggests that the quality of Indian cotton actually declined during this period.[55] Thus, shifts in quality can be discarded as a likely explanation for the patterns we observe.

[55] For example, the *Bombay Saturday Review* (April 12, 1862, quoted from Logan (1965)), wrote, “the quality of Bombay cotton has notoriously become worse instead of better. The rise in prices has no other effect than of stimulating the practice of adulteration. Every trick... is used to swell the bulk and lower the intrinsic value of cotton. Sometimes the bales are wetted in the sea, sometimes their weight is increased by keeping seed in the cotton and loading it besides with stones and dirt, sometimes there is a systematic substitution of an inferior for a better kind of cotton, or a mixture of two kinds.”

6. CONCLUSIONS

The study provides evidence that the temporary reduction in the supply of American cotton during the U.S. Civil War caused directed technical change focused on the main alternative input, Indian cotton. While similar, American and Indian cotton differed in important ways, and innovators focused their efforts on technology types that addressed these differences. Moreover, as these new technologies were introduced, the relative price of Indian to U.S. cotton rebounded to (and in some years above) the average level observed during the pre-war period, despite a substantial increase in the relative supply of Indian to U.S. cotton.

Directed technical change theories, such as Acemoglu (2002), can potentially explain the innovation and relative price movements of Indian cotton if the elasticity of substitution between U.S. and Indian cotton is sufficiently high (near 2), as is suggested by Irwin (2003). Alternative theories may also have the potential to explain the patterns I identify. For example, perhaps innovators simply focused on reducing waste and this was more easily accomplished for Indian cotton than for other varieties. However, we do not observe increased innovation in other major waste-producing technologies, such as combing machines, so this explanation seems unlikely. A more compelling alternative is that innovation may have been a result of learning-by-doing and the switch to production of machines more suited to Indian cotton. Differentiating between directed technical change and learning-by-doing is an interesting direction for future research.

My findings raise a historical question: what were the long-term impacts of these new innovations? Given that textile spinning firms the world over were supplied by British machine makers, it may be that the primary beneficiaries of the new technologies developed during the U.S. Civil War were not British cotton spinners, but rather cotton textile producers in locations ranging from Japan and China to Continental Europe, and in India itself. The long-term impact of the new technologies on these producers, and on Indian cotton farmers, is another avenue for future work.

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