Econometrica Supplementary Material

SUPPLEMENT TO "NECESSITY IS THE MOTHER OF INVENTION: INPUT SUPPLIES AND DIRECTED TECHNICAL CHANGE": ONLINE APPENDIX

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APPENDIX A: FURTHER DETAILS ON THE EMPIRICAL SETTING

A.1. *Increase in Transport Costs Caused by the Civil War*

FIGURE A.1 SHOWS AN INDEX OF TRANSPORT COSTS during the early part of the war constructed using the wedge between the cotton price in New Orleans, which was within the blockaded region until April of 1862, and the price in Liverpool.

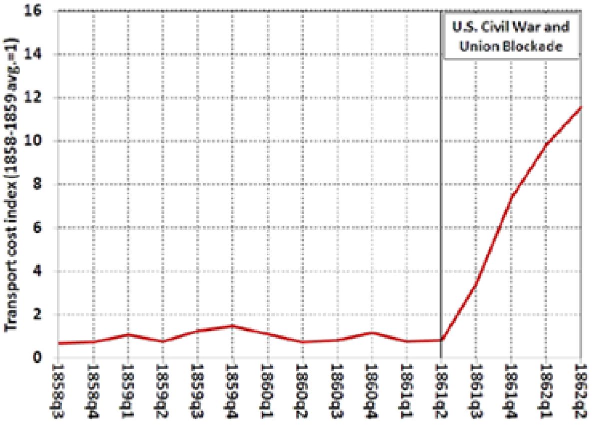

FIGURE A.1.—Effect of the Union blockade on the transport cost of cotton. Index constructed using price of Middling Orleans cotton from Liverpool and New Orleans. Liverpool prices collected from *The Economist*. New Orleans prices collected from the *New Orleans Price Current and Commercial Intelligencer* and converted to Sterling using the price of Sterling 60 day notes reported in the same. A similar pattern holds if New York prices are used in place of Liverpool prices.

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A.2. *Additional Details on Cotton Supplies*

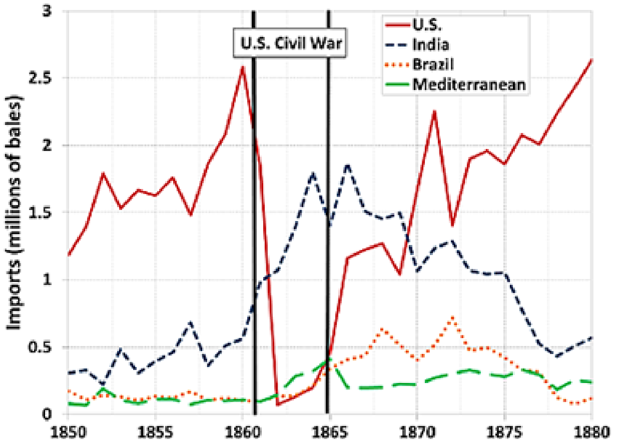


FIGURE A.2.—Cotton imports by supplier 1850–1880. Data from Ellison (1886). Most of the imports from the Mediterranean would have come from Egypt.

A.3. *Most Innovative Technology Categories by Patent Count*

TABLE A.I

TOP TEN BRITISH PATENT OFFICE TECHNOLOGY CATEGORIES 1855–1883[a]

Rank	Technology Category	Patents	Rank	Technology Category	Patents
1	Metals, Cutting, etc.	7,017	6	Railway etc. vehicles	4,184
2	Furnaces	6,157	7	Steam generators	4,065
3	Preparatory & Spinning	6,009	8	Furniture	3,216
4	Steam engines	4,809	9	Mechanisms	3,120
5	Weaving & Finishing	4,807	10	Ships, Div. I	3,051

[a]Top ten technology categories, by patent count, out of the 146 total British Patent Office technology categories. “Preparatory & Spinning” includes machinery used in the preparatory and spinning stages of production. “Weaving & Finishing” includes machinery used in the weaving and finishing stages.

A.4. *Definitions of Important Textile Terms*

The following definitions were constructed with the aid of *The “Mercury” Dictionary of Textile Terms*. 1950. Textile Mercury Limited: Manchester, England.

Carding—A very thorough opening-out and separating of the fibers of cotton, together with an effective cleaning. This machine is the last where cleaning the cotton takes place (unless the cotton has to be combed).

Combing—This term is used literally and denotes the combing of fibrous materials in sliver form by mechanically actuated combs or by hand-operated combs. In general, the objectives in combing are two, namely (1) to obtain the maximum parallelization of the fibers and (2) to remove impurities and undesired short fibers.

Gin—A cotton cleaning machine with the primary purpose of separating the cotton seeds from the cotton fibers.

Opening cotton—This is done on machines (openers) which beat the cotton into a more fleecy condition and also remove a good proportion of the dirt and heavier impurities.

Scutching—An operation in preparing cotton for spinning that has three objects, to reduce the cotton to a loose open condition by beating it, removal of impurities remaining in the cotton after opening, and the formation of a continuous lap or web of cotton wound on to a rod—which laps go forward to the carding engine.

A.5. *Cotton Textile Machinery*

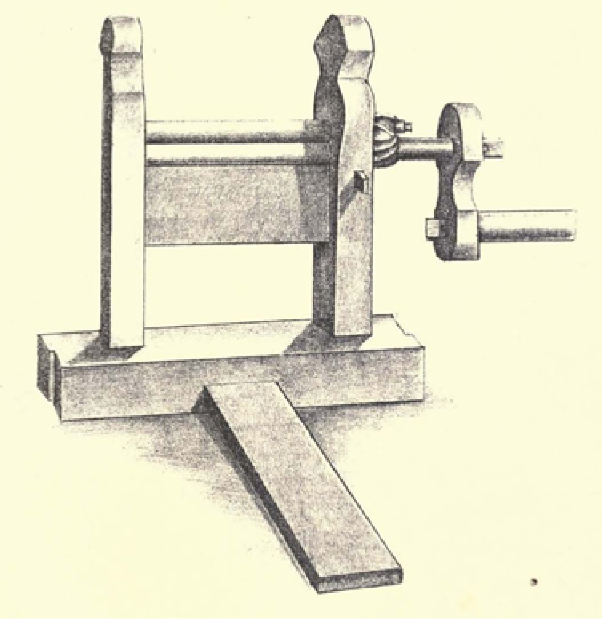


FIGURE A.3.—Indian Churka for removing cotton seeds. Reproduced from Wheeler (1862).

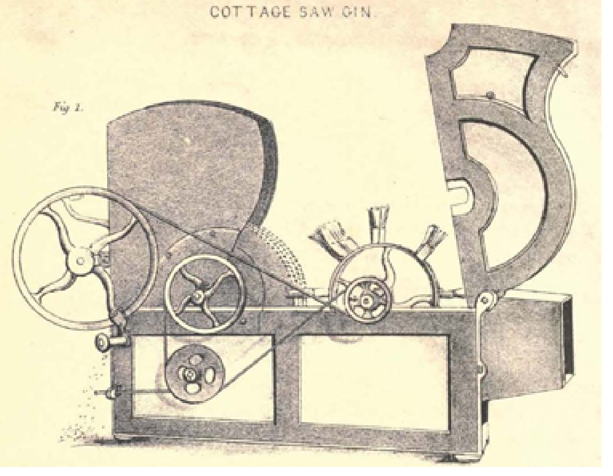


FIGURE A.4.—Cottage saw gin. Reproduced from Wheeler (1862).

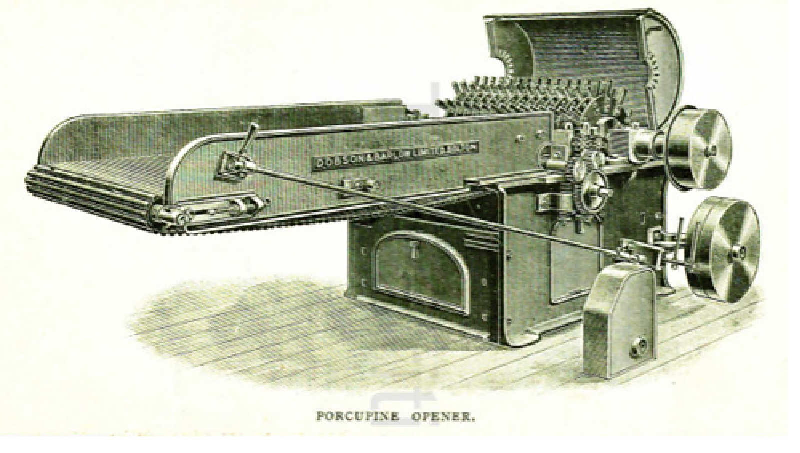


FIGURE A.5.—Dobson & Barlow opener circa 1920.

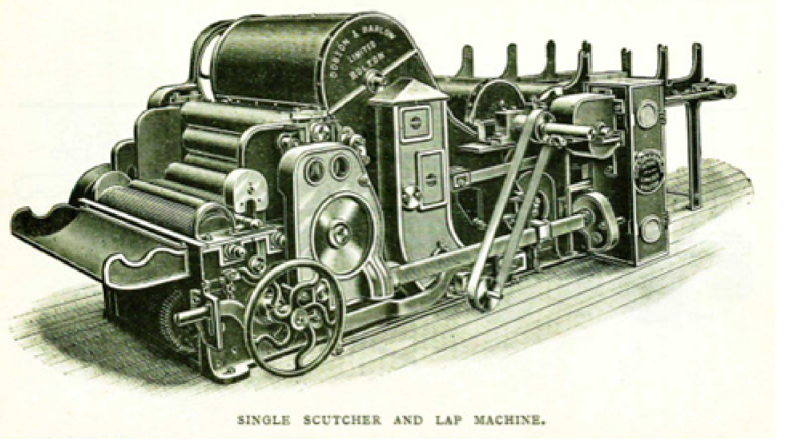


FIGURE A.6.—Dobson & Barlow scutcher circa 1920.

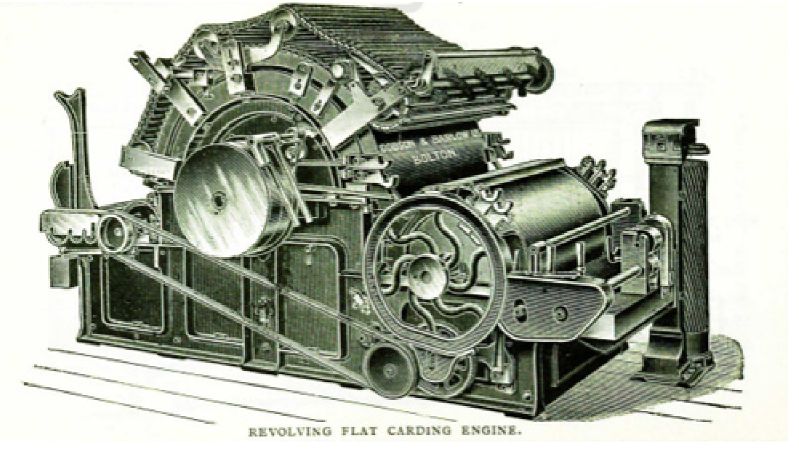


FIGURE A.7.—Dobson & Barlow carding machine circa 1920.

A.6. *Details on the Differences Between Cotton Types*

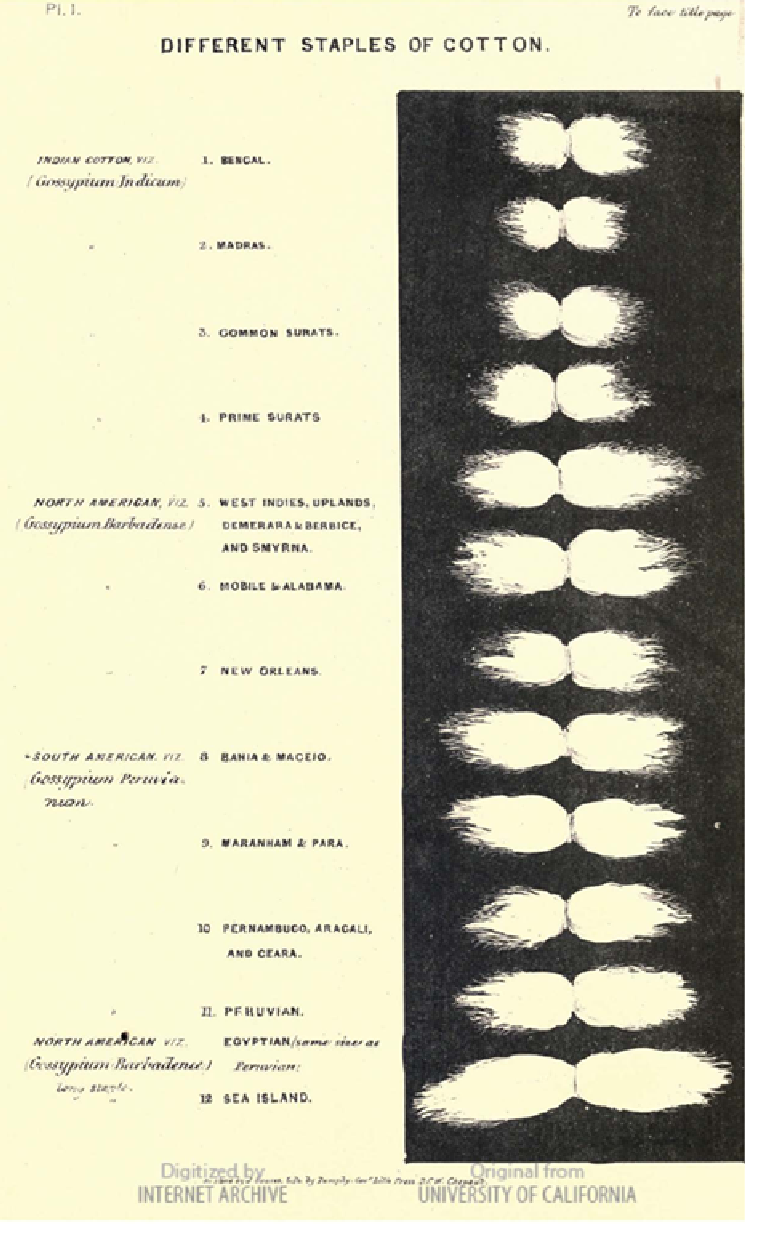


FIGURE A.8.—Length of cotton staples for various cotton types. Reproduced from Wheeler (1862).

A.7. *Impact of Ginning on Cotton Fiber Length*

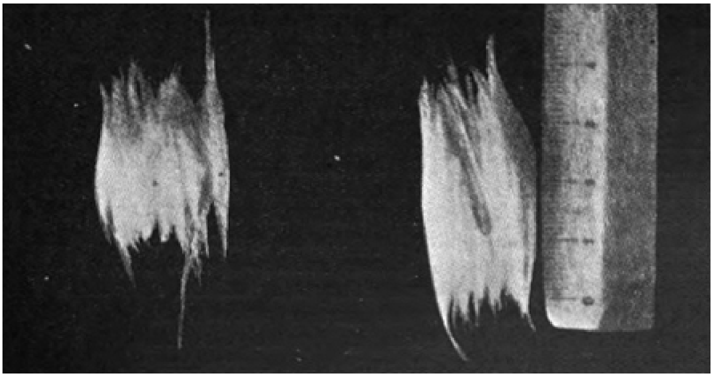


FIGURE A.9.—A comparison of ginned (left) and hand-cleaned cotton (right) fiber length. Reproduced from Pearse (1921).

A.8. *Example Patent Specifically Mentioning Indian Cotton*

2162. Wanklyn, W. July 30.

Steaming fibres ; openers, cleaners, &c.—Relates to apparatus for opening and conditioning East Indian and other tightly-compressed cotton, sheep's wool, &c. by steaming. The cotton is transferred from the bale to a vessel *a*, which is mounted on trunnions, and is provided with a perforated false bottom *d* and a tightly-fitting lid *e* balanced by the counterweight *f*. Steam under pressure is admitted to the space below the perforated false bottom, and after the material has been submitted to the action of the steam for about a minute, the steam is shut off, the lid *e* removed and the vessel *a* tilted so that the cotton may be raked into a truck &c. and taken to the opening-machine. A suitable prop is provided for holding the vessel *a* in the tilted position, and the act of tilting the vessel opens by means of a chain *p* an escape valve *m* for condensed water. In order that condensed water may be excluded as much as possible from the vessel *a*, the steam pipe *h* is connected with a horizontal pipe *j* in which is a valve connected by rods *l* with a crosshead *k* on the end of the pipe. So long as the pipe *j* is sufficiently heated by the steam, the valve is closed, but when the pipe is cooled by the accumulated condensed water, the valve is opened and the water escapes.

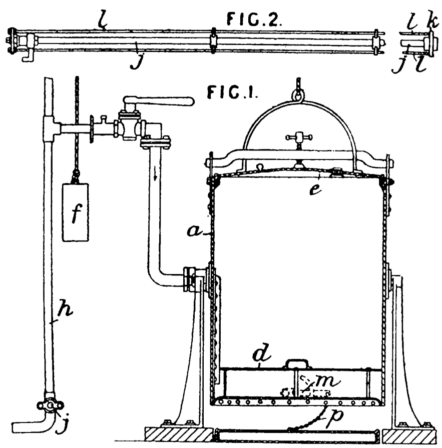


FIGURE A.10.—An example: Patent no. 2162 from 1862. From *British Patent Abstracts, Class 120, 1855–1866*. Available from the British Library.

A.9. *Indian Cotton Exports*

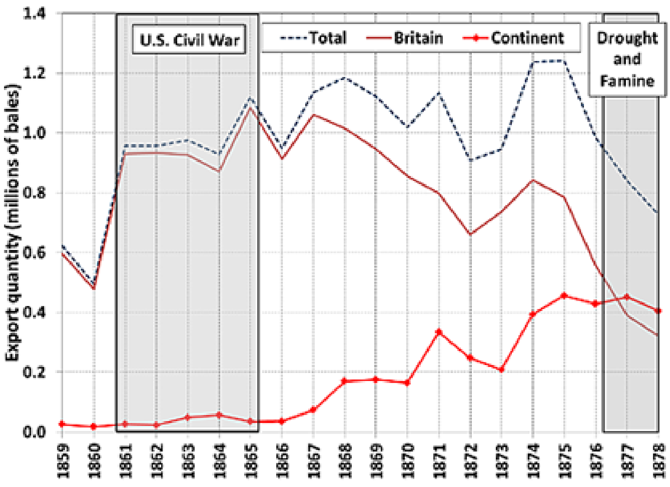


FIGURE A.11.—Indian cotton exports, showing Britain and the Continent. Data collected from *Statistical Abstracts of British India*.

APPENDIX B: DATA APPENDIX

B.1. *Overview of the Patent Data*

Modern patent data have been widely used in recent studies of innovation, building on seminal work by Schmookler (1966), Scherer (1982), Griliches (1984), and Jaffe, Trajtenberg, and Henderson (1993). Hall, Jaffe, and Trajtenberg (2001) provided a helpful review of the advantages of using patent data, including that (1) patents contain highly detailed information, (2) there are a large number of patents available to study, and (3) patents are provided on a voluntary basis under a clearly defined set of incentives. This study is able to take advantage of thousands of patents and draws heavily on the detailed information available in the patent descriptions.

One disadvantage of using patent data is that they do not capture all types of innovation. Evidence from Moser (2012) shows that a significant fraction of new inventions went unpatented during the period I study. However, her results also suggest that, among all categories, inventions of manufacturing machinery—the primary focus of this study—were the most likely to be patented. Moser (2012) found that of those innovations exhibited in the Crystal Palace exhibition in 1851, 29.8% of manufacturing machinery exhibits were patented compared to an average of 11.1% over all exhibit types. Of the exhibits receiving prizes, 47.1% of manufacturing machinery exhibits were patented compared to an average of 15.6% across all exhibit types. Note that a significant patent reform was undertaken in 1852 which simplified the process for obtaining patent protection while greatly reducing cost of patenting. The result was a sharp increase in patents from hundreds to thousands. Thus, these percentages are likely to have been significantly higher during the period I study. The incentive to patent appears to have been particularly strong for textile machinery, which was relatively easy to reverse-engineer. Thus, this concern appears to be less important in the context studied here. A second concern is that patent counts may not reflect the underlying quality of the new inventions, which can vary widely. This concern is addressed using several measures of patent quality.

Much of the data used in this study was collected for the purpose of this project from around 1,500 pages of printed British patent records. To begin, I constructed a database covering all of the patents granted in Britain between 1855 and 1883, 118,863 in all. Each patent is classified into one or more of 146 technology categories by the British Patent Office (BPO). These classifications allow me to identify the type of technology underlying each patent. The purpose of this categorization was to aid inventors in identifying previously patented technologies. My focus is on the two BPO categories related to textile production, "Preparation & Spinning" and "Weaving & Finishing." The British Patent Office calls these categories Spinning and Weaving, but I use these names to make it clear that the preparatory machines are included in the spinning technology category.

These data include both granted patents and those which received provisional protection but where a patent was not ultimately granted. However, because the British patent system did not include a patent examination at this time, substantially all of the patents applied for appear to have been granted. The validity of the patent could then be challenged ex post in the courts.

These data are supplemented with information from the *A Cradle of Invention* database, which has been used in previous research (e.g., Brunt, Lerner, and Nicholas (2012)).[1] This database provides the titles of the patents, which are not available in the patent data I collected.

B.2. *Data on Spinning Technology Subcategories*

To track innovation patterns in specific textile spinning technologies, I use BPO subcategories within the BPO Spinning technology category. Within this

[1]I thank Tom Nicholas for suggesting this data source. These data are available through MFIS LTD (http://finishingpublications.com/books-and-cd-roms/cd-roms/patents.html). These data match the primary database well, with over 98% of patents in the two databases matching.

category, the BPO classifies patents into one or more technology subcategories and often into sub-subcategories. I have collected data on all substantial technology subcategories within the Spinning technology category.

An important concern in these data is that some of these subcategories (and sub-subcategories) are so detailed that they contain few patents. This requires a decision about how small a control technology subcategory can be and still be useful. For the data used in the main analysis, I include only control technology types that were important enough to receive at least one patent in each year. This bar is low enough to obtain a reasonable number of control technology groups. At the same time, not having zero patents in any year in the control technology groups allows me to use the same set of groups for the analysis of the time-path of patents in Figure 5 in the main text as were used in the main results in Table I (main text) without having to worry about losing observations when taking logs. Patents fitting into the smaller technology categories are included in the main analysis in a residual technology category, "Uncategorized spinning patents." In the robustness exercises, I explore how the results change when I break out these smaller technology categories. I find that breaking out these smaller technology subcategories does not substantially affect the results.

A second issue with the data is that some of the technology subcategories are explicitly for textiles other than cotton. The most common example are technologies related to the preparation of flax for use in producing linen. Since my primary focus is on shifts occurring within the cotton textile industry, I omit these technologies from the main analysis, though I also assess the impact of including these in the robustness exercises.

B.3. *Identifying Patents Related to Indian Cotton*

Historical accounts of the use of Indian cotton during the study period indicate that the major challenges faced by users were removing the seeds from the Indian cotton, opening the fibers which had been tightly compressed for their journey, and removing sand, dirt, leaves, and other debris from the cotton. These processes were done using gins, openers, scutchers, and carding machines. Gins focused on removing the seeds, openers opened the compressed fibers so that they could be handled by later machines, and scutchers and carding machines helped clean the fibers.

While openers and scutchers were important for the use of cotton, variations of these machines also had applications to other textile inputs. In particular, different versions of these machines were used to prepare flax and to tear up waste rags for re-spinning. Some patents were for even more exotic inputs, such as oakum, silk rags, reed grass, and piassave (also known as monkey grass). Some patented technologies within this category were specialized for

TABLE A.II

PREPARATORY & SPINNING TECHNOLOGY SUBCATEGORIES[a]

	Patents		Patents
Major Preparatory & Spinning technologies (used in main analysis)			
Preparatory machines		Spinning machines	
Gins*	122	Mules and twiners	446
Openers/Scutchers	331	Spinning/twisting machines	1013
– *Applicable to cotton**	195	Winding machines	341
– *Others*	135	Drawing frames	153
Carding	696	Lap forming machines	73
– *Dirt/debris removal**	53	General spinning technologies	
– *Others*	643	Bobbins	265
Combing machines	354	Spindles (includes bearings)	720
Gill boxes	187	Processes	536
Motions		Rollers for spinning	462
Building motions	257	Yarn and finishing	
Stop motions	267	Yarns	218
Winding-on motions	190	Finishing of yarn	332
Uncategorized			
Uncategorized spinning patents	770		
Smaller categories (used only in robustness analysis)			
Carbonizing fibers	72	Cards (wire)	89
Lubricating fibers	86	Reeling machines	90
Feeding carding machines	73	Fiber treatments	72
Twist tubes	97		
Categories for non-cotton textiles (used only in robustness analysis)			
Retting machines	128	Heckling machines	157
Flax breaking machines	223	Flax feeding machines	86
Obtaining fibers (special materials)	168	Fibers for special articles	62

[a]Categories marked with a * were the most important for using Indian cotton. Patent counts for BPO Preparatory & Spinning technology subcategories, 1855–1876.

cotton or were applicable to all types of machines, while others were specialized for other uses. It is important to separate these out, since only patents related to cotton or generally applicable should be included in the treated technology category. To do this, I reviewed the abstract of all 331 patents of openers/scutchers. These abstracts, similar to an abstract for an academic paper, contain a brief overview of the patent, usually in one to three paragraphs. Patents that mentioned another input and did not mention cotton were classified as "Openers/Scutchers—non-cotton." Patents that specifically mentioned cotton, and patents that did not mention any specific type of input, were treated as being applicable to cotton and classified into the "Openers/Scutchers—cotton" category.

Carding machines formed an important part of spinning mill machinery during the study period. While carding machines could be improved in many ways, the most relevant improvement for the use of Indian cotton would have been technologies related to removing dirt and other debris from the raw fibers. These were large and complex machines and, as a result, patents in the carding machine subcategory were divided by the British Patent Office into a number of technology sub-subcategories. Among these subcategories, the BPO identifies two that are specifically related to dirt removal. Their titles are "dirt, waste and the like, collecting and removing" and "dirt-knife arrangements." The classification of patents into "Carding—dirt removal" is based on these two sub-subcategories, while all other carding patents are included in the "Carding—other" category.

B.4. *Details of the British Patent System Between 1852 and 1883*

There were no major changes in the British patent system between 1852 and 1883. During this period, patent applications cost £25, which was considered a substantial sum at the time. This amount was roughly equal to £1,840 2009 pounds, when deflating by the retail price index, or £16,300, when deflating by average earnings (calculator available from the Measuring Worth project at www.measuringworth.com). For comparison, the fee was reduced to only £4 as a result of the 1883 patent law. Applications were also a lengthy and complicated process.

This study focuses on the filing of preliminary patent applications. These preliminary applications were easier to submit; they could be made using only basic information on the invention. The application provided the applicant with provisional protection and could aid them in establishing the seniority of their invention. The applicant was then responsible for supplying full patent specifications within six months or the patent became void. Patents lasted for 14 years, but renewal fees had to be paid at years three and seven in order to keep the patent in force. These fees were even more onerous than the initial application fee; applicants had to pay £50 after three years and another £100 after seven years to keep their patents in force.

At this time, the British patent system did not include an official examination, such as the one we are familiar with today. Instead, the validity of patents was mainly established through ex post litigation. As a result, substantially all of the patent applications in the data would have been sealed (i.e., granted) unless the applicant failed to provide a final specification or to undertake the necessary bureaucratic steps. For more information on the British patenting system during this period, see Van Dulken (1999) and Khan (2005).

B.5. *Details on Inventors in the Patent Database*

TABLE A.III

DETAILS OF INDIVIDUAL SPINNING AND COTTON TECHNOLOGY INVENTORS

Number of Inventors	Number of Inventor × Patent Obs.	Median Patents/Inventor	Mean Patents/Inventor
	Spinning technology inventors, 1855–1883		
5,038	9,744	1	1.934101
	Cotton technology inventors, 1855–1870		
1,384	2,144	1	1.549133

B.6. *Further Details on the Patent Quality Measure Data*

This section describes the three measures of patent quality used to evaluate whether the 1861–1865 period was also characterized by an increase in the number of high-quality cotton-textile-related patents.

B.6.1. *Valuing Patents Using Renewal Data*

During the period covered by this study, British patents lasted for 14 years, but in order to keep them in force patent holders were required to pay renewal fees of £50 before the end of three years and an additional £100 before the end of seven years.[2] These were substantial sums at the time and the result was that the vast majority of patents were allowed to expire before their full term. My data show that just under 18% of patents were renewed at three years, while just over 6% were renewed at seven years. Thus, paying a renewal fee represents a substantial investment which would only have been worth it for a small set of the most successful technologies.

Renewal fee data were gathered from listings in *Mechanics' Magazine*, a weekly periodical focusing on patents and related topics. The magazine is available from the end of 1858 to the end of 1872, so that data on renewals at year three are available for patents filed from 1856 to 1869 and data on renewals at year seven are available from 1853 to 1865. By merging the renewal data with the primary patent data set, it is possible to track renewal patterns for textile-related patents.

B.6.2. *Valuing Patents Using Contemporary Publications*

A contemporary periodical can be used to highlight the interest or excitement generated by a new patent upon its publication. The data I use were

[2]For comparison, £100 in 1860 is equivalent to £7,020 2010 pounds using a retail price index deflator, or £65,200 when deflating by average earnings (calculator available through the Measuring Worth project at www.measuringworth.com).

collected from *Newton's London Journal*, a monthly publication devoted to covering new patents and other technology-related topics. This journal was published by William Newton & Sons, one of the preeminent patent agents in London. Among the *Journal*'s stated goals was making more easily available the information contained in patent filings, and to this end, each issue included abstracts from a selection of recently sealed (i.e., granted) patents, some of which were accompanied by detailed drawings. It is worth noting that patent abstracts were only included after the patent had been sealed, so publication was often as long as a year after the initial patent application was filed. This means that the editor would have had some perspective from which to judge the influence of a patent before including it in the journal. Though the publishers provide little information about the criteria used to select these patents, presumably they included those patents which were deemed by the editors to be the most important inventions, or those which would be of greatest interest to the readers. Thus, inclusion of a patent abstract in the journal is treated as an indication of the initial novelty of each patent, based on the judgment of a knowledgeable contemporary opinion.

The *Journal* is available from January 1855 to February 1866, meaning that any patent applied for from 1854 to 1864 should have been a candidate for inclusion. Matching these patents to the primary patent database allows me to identify patents of textile- and cotton-related technologies. The analysis is based on the date the patent was filed, rather than the publication date, so, for example, I look at all patents which were filed in 1861 and then subsequently published, and analyze the share composed of textile-related patents.

APPENDIX C: APPENDIX TO THE EMPIRICAL ANALYSIS SECTION

C.1. *Analysis of Patent Data*

To begin, I motivate the focus on innovations occurring in the Preparation & Spinning technology category by showing that it was these early-stage production technologies that responded strongly during the Civil War period. Figure A.12 illustrates that impact of the Civil War on the two key textile technology categories, Preparatory & Spinning and Weaving & Finishing in the top panel, and on all of the other 144 BPO technology categories, in the bottom panel, using annual data from 1855 to 1883.

Next, I provide individual graphs for each of the technology subcategories in the Preparatory & Spinning technology category that are used in the main analysis.

The results in the main text based on the permutation approach are strong. To help us understand these results, the next graph provides a histogram of the distribution of the estimated placebo coefficients based on the control technology groups compared to the estimated coefficient from the India-related technologies.

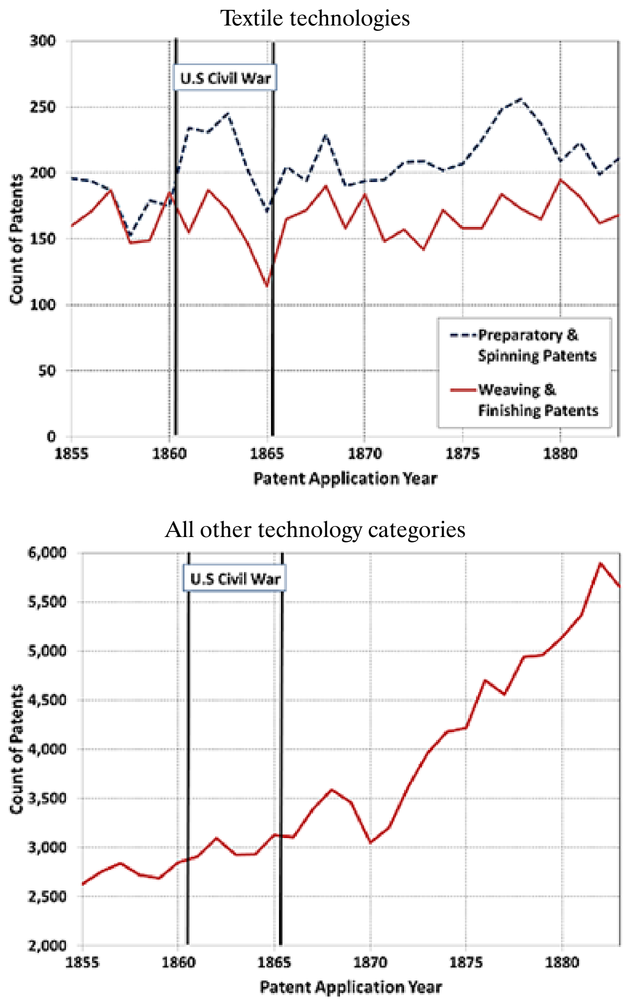


FIGURE A.12.—Patenting behavior over the study period. Annual data for 1855–1883 collected from British patent subject abstracts.

Next, I conduct some exercises exploring the robustness of the results to the inclusion of different control technologies. In the data set used in the main analysis, a number of small technology subcategories are aggregated into a single residual category. Also, four larger technology subcategories were excluded because those technologies were not applicable to cotton. In Columns 1–3 of Table A.IV, I add back in just the small technology subcategories (Column 1), just the larger non-cotton technology subcategories (Column 2), and both (Column 3) and show that the results are essentially unchanged. Another

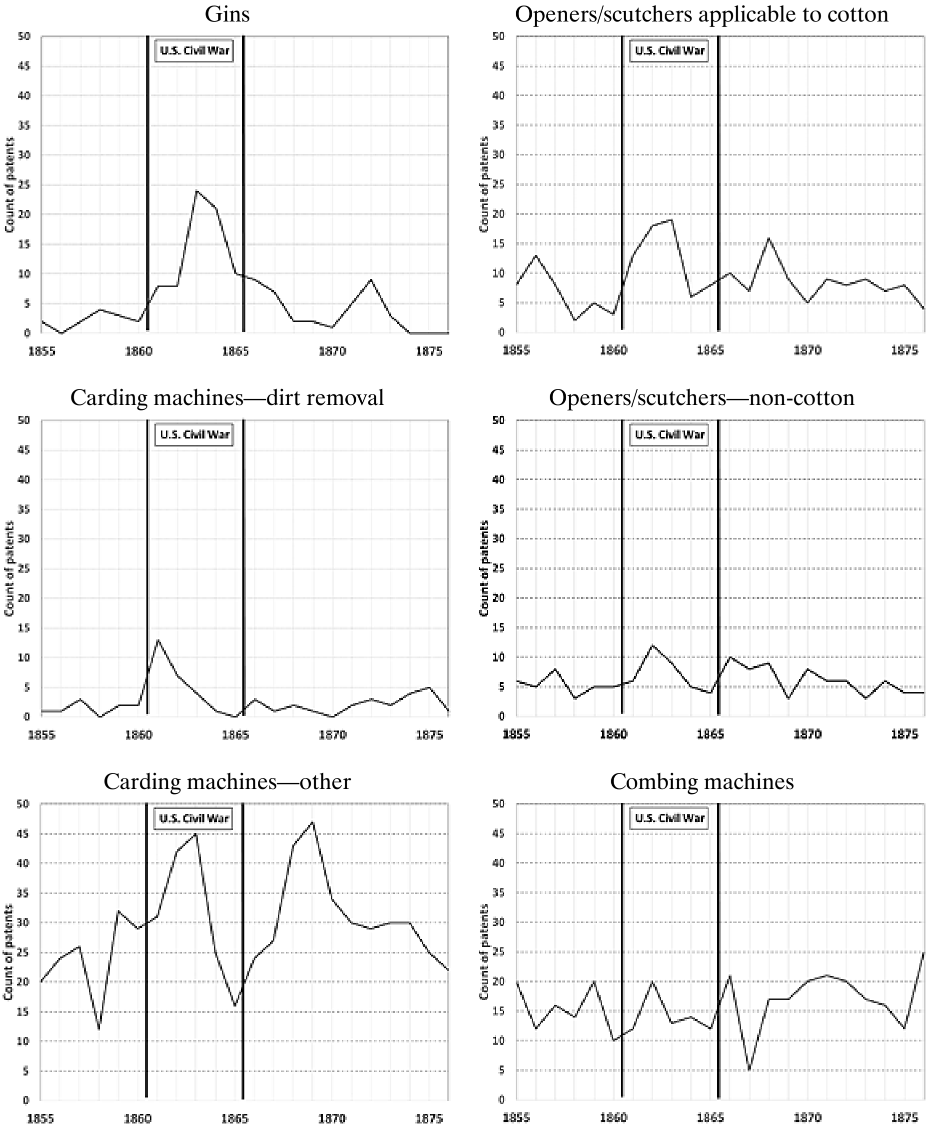


FIGURE A.13.—Patents in Preparatory & Spinning technology subcategories. The uncategorized spinning patents technology category excludes technologies explicitly for textiles other than cotton (*Continues*).

potential issue with the data is that some patents are listed in more than one technology subcategory. Of the 4,174 patents included in the main analysis, 1,832 of them are cross-listed into multiple technology subcategories. Dropping these leaves us with a database of 2,342 remaining patents. The results in

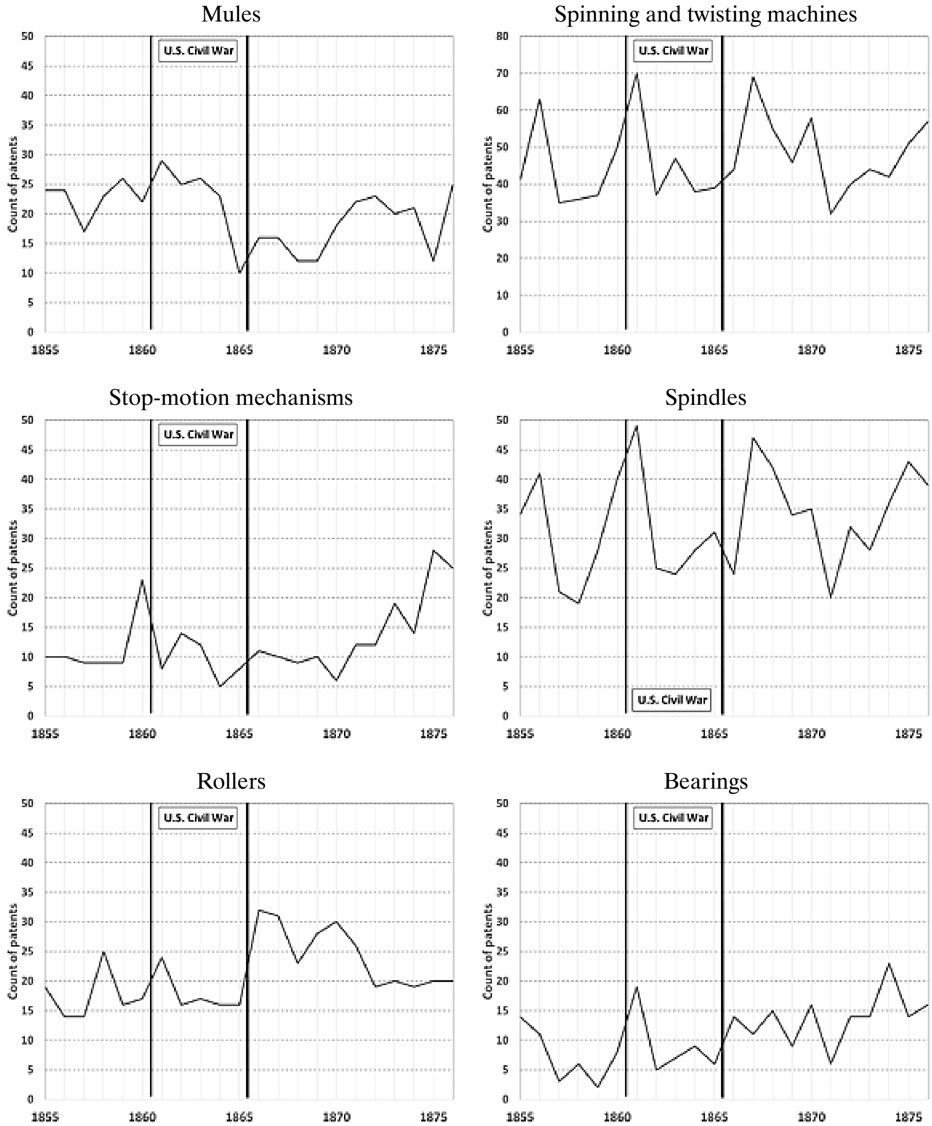


FIGURE A.13.—*Continued*.

Column 4 show that excluding these cross-listed patents weakens the results, but that in general they continue to be statistically significant. Note that one technology, "Winding-on Motions" does not have any patents that were not cross-listed and therefore has been dropped from the analysis. The last col-

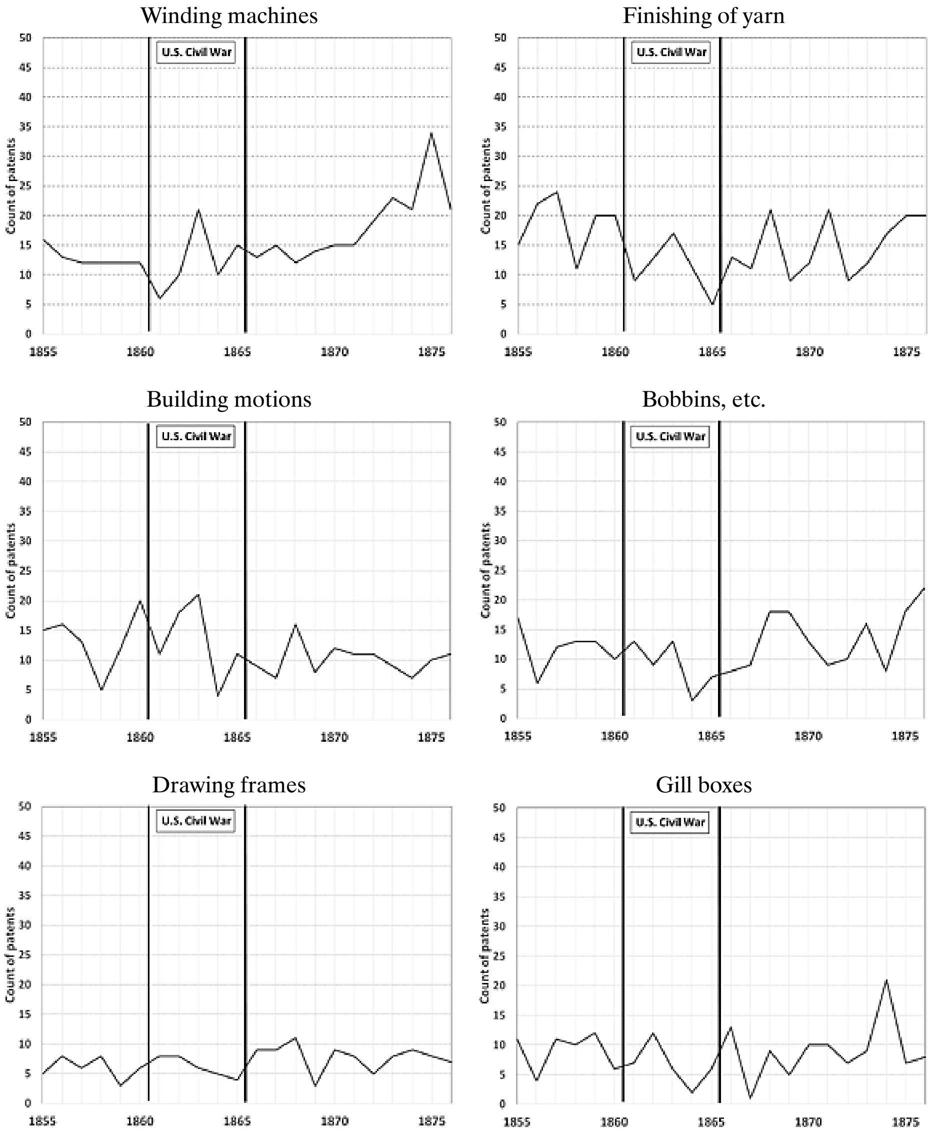


FIGURE A.13.—*Continued*.

umn presents results obtained when I include only patents with “cotton” in the title in the estimation data.

We may be interested in separating out the effects on the different technologies related to Indian cotton. The regressions presented below do this by estimating a separate coefficient for each of these technology subcategories.

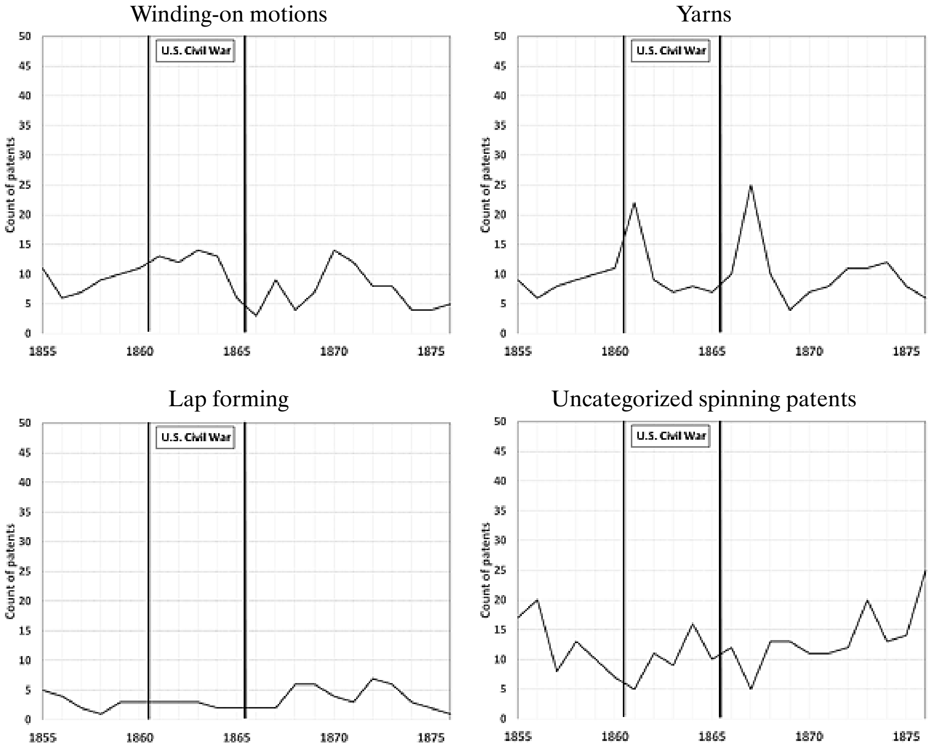


FIGURE A.13.—*Continued*.

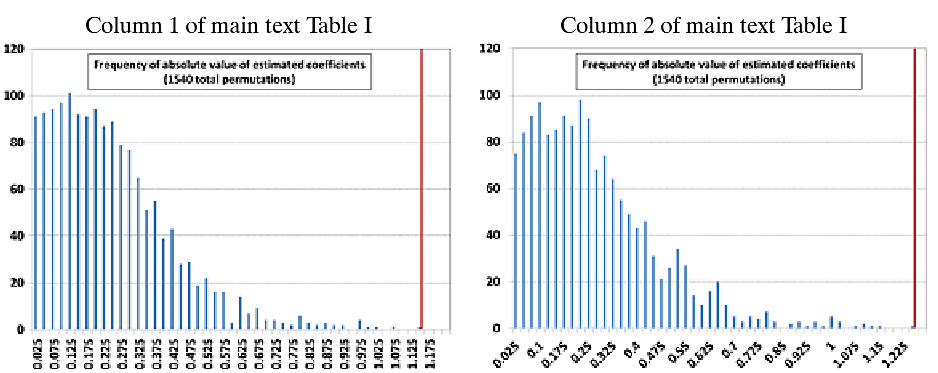


FIGURE A.14.—Histogram of coefficient estimates related to main text Table I. This figure compares the distribution of the absolute value of the coefficient estimates from regressions run with every combination of 3 out of the 22 technology categories treated as the three treatment categories. There are 22 technologies so there are 22 choose 3 = 1,540 placebo coefficients. The line on the right indicates the coefficient estimate from the actual India-related technology groups.

TABLE A.IV
ROBUSTNESS TO VARIATION IN UNDERLYING DATA[a]

	Dependent Variable: Log Patents				
	With 8 Smaller Subcategories (1)	With 4 Non-Cotton Subcategories (2)	With Smaller and Non-Cotton Subcategories (3)	Dropping Cross-Listed Patents (4)	Patents With Cotton in the Title (5)
India-related × Shock period	1.204 (0.275) [0.000] [[0.038]]	1.080 (0.275) [0.000] [[0.051]]	1.143 (0.273) [0.000] [[0.044]]	1.098 (0.313) [0.002] [[0.048]]	1.139 (0.344) [0.003] [[0.089]]
Subcategory effects	Yes	Yes	Yes	Yes	Yes
Time period effects	Yes	Yes	Yes	Yes	Yes
Observations	90	78	105	63	66
Number of panels	30	26	35	21	22

[a]All regressions include the pre-shock, shock, and post-shock periods. Column 1 includes data from 8 smaller technology subcategories. Column 2 includes data from 4 non-cotton technology subcategories. Column 3 contains both smaller subcategories and non-cotton subcategories (including smaller non-cotton subcategories not included in columns 1 and 2). *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. *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.

The regression specification is

$$\log(\mathrm{PAT}_{jt}) = \alpha + \beta^{\mathrm{Gins}}(S_t \times \mathrm{GINS}_j) + \beta^{\mathrm{Open}}(S_t \times \mathrm{OPENERS}_j) + \beta^{\mathrm{Card}}(S_t \times \mathrm{CARDING}_j) + \Psi_j + \xi_t + e_{jt},$$

where GINS_j is an indicator variable for gin technologies, $\mathrm{OPENERS}_j$ is an indicator variable for openers/scutchers related to cotton, and $\mathrm{CARDING}_j$ is an indicator variable for carding innovations for dirt removal. An important constraint in conducting this exercise after aggregating to pre-shock, shock, and post-shock periods is that we have three explanatory indicator variables that take a value of 1 only once, and are zero otherwise. This raises an issue with the small-sample adjustments that I have used. In this context, the permutation-based approach has only 19 estimated coefficients, one for each control group, to work with. With such a small number, it is not clear we can get a reasonable estimate of the distribution of the coefficient estimates. The alternative approach, based on Imbens and Kolesar (2012), is also inapplicable in this setting because it cannot accommodate these indicator variables. See Angrist and Pischke (2009, p. 320, footnote 17) for a discussion of this point. Thus, I present in Table A.V these results without accompanying small-sample

TABLE A.V

REGRESSIONS WITH SEPARATE COEFFICIENTS FOR EACH INDIAN-RELATED TECHNOLOGY[a]

	Dependent Variable: Log Patents	
	Comparing Shock Period to Pre- and Post-Periods (1)	Comparing Shock to Pre-Period Only (2)
Gins × Shock period	1.703 (0.052)	1.880 (0.054)
Openers for cotton × Shock period	0.607 (0.052)	0.678 (0.054)
Carding dirt removal × Shock period	1.072 (0.052)	1.204 (0.054)
Subcategory effects	Yes	Yes
Time period effects	Yes	Yes
Observations	66	44
Number of panels	22	22

[a]Column 1 uses data from the pre-shock, shock, and post-shock periods which are, respectively, 1855–1860, 1861–1865, and 1866–1876. Column 2 uses only data from the pre-shock and shock period. *Parentheses* contain robust standard errors.

adjustments. They should be taken as merely suggestive since we cannot be sure how precise these estimates are.

Next, I turn to some robustness checks on the timing regressions presented in Figure 5 in the main text. Here serial correlation is potentially a substantial concern. In addition to the Newey–West approach used in the main text, there are several other candidate approaches for dealing with serial correlation. One potential approach in the literature is to cluster standard errors by technology category. A concern with that approach is that there are only 20 clusters, so the standard errors may be understated. Another approach that aims to deal with the small number of groups is the Bias Reduced Linearization from Bell and McCaffrey (2002), which has previously been implemented by Angrist and Lavy (2009). Figure A.15 presents the resulting coefficients and confidence intervals. It is clear that these alternative methods all deliver nearly identical results.

C.2. *Analysis of High-Quality Patents*

This section presents some additional information related to the analysis of high-quality patents. The first two graphs (Figures A.16 and A.17) describe the patenting patterns for high-quality patents.

The next set of graphs (Figure A.18) present the distribution of coefficients used in the permutation-based inference exercises with high-quality patents.

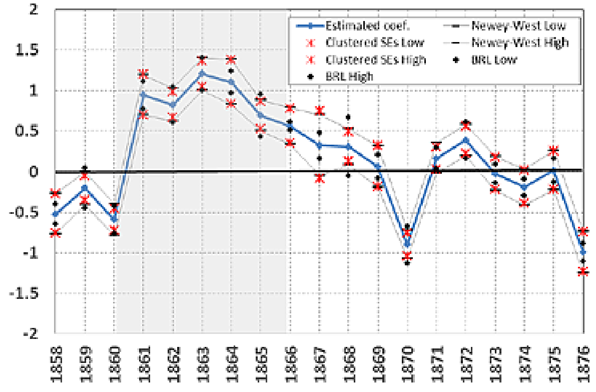


FIGURE A.15.—Comparing various methods for annual regressions. This figure presents coefficient estimates and standard errors based on the specification in Equation (2) in the main text, where patents from the three India-related technologies have been aggregated within each year. Standard errors are based on (1) Newey–West with a lag length of 3, (2) clustering by technology category, and (3) the Bias Reduced Linearization approach as in Angrist and Lavy (2009).

C.3. *Dobson & Barlow Graphs*

The graphs in this section show the level of orders for gins, openers/scutchers, and carding machines from the Dobson & Barlow order books. As Dobson & Barlow's experience with each machine type is slightly different, I discuss each in turn.

For gins, Dobson & Barlow was not active in the market prior to the Civil War (at least in the available data). The shift to alternative suppliers during the Civil War period generated enormous demand for gins, since the available gins in all locations were too few to gin the rapidly expanding crops, while existing gins were stuck in the American South. Thus, gins became an important

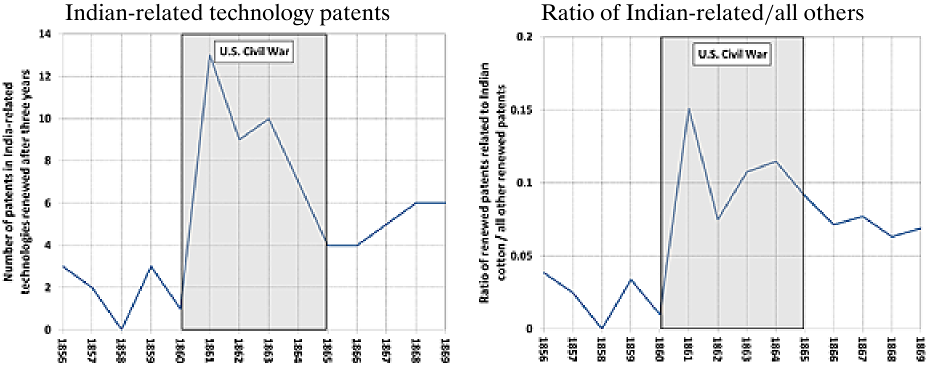


FIGURE A.16.—Patents renewed after three years.

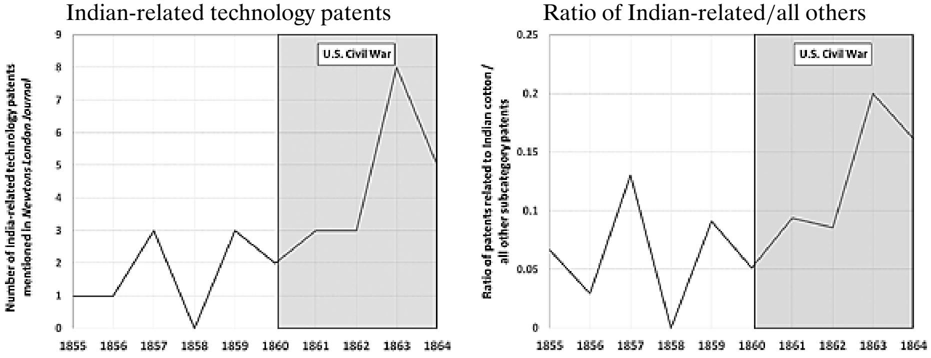


FIGURE A.17.—Patents mentioned in *Newton's London Journal.*

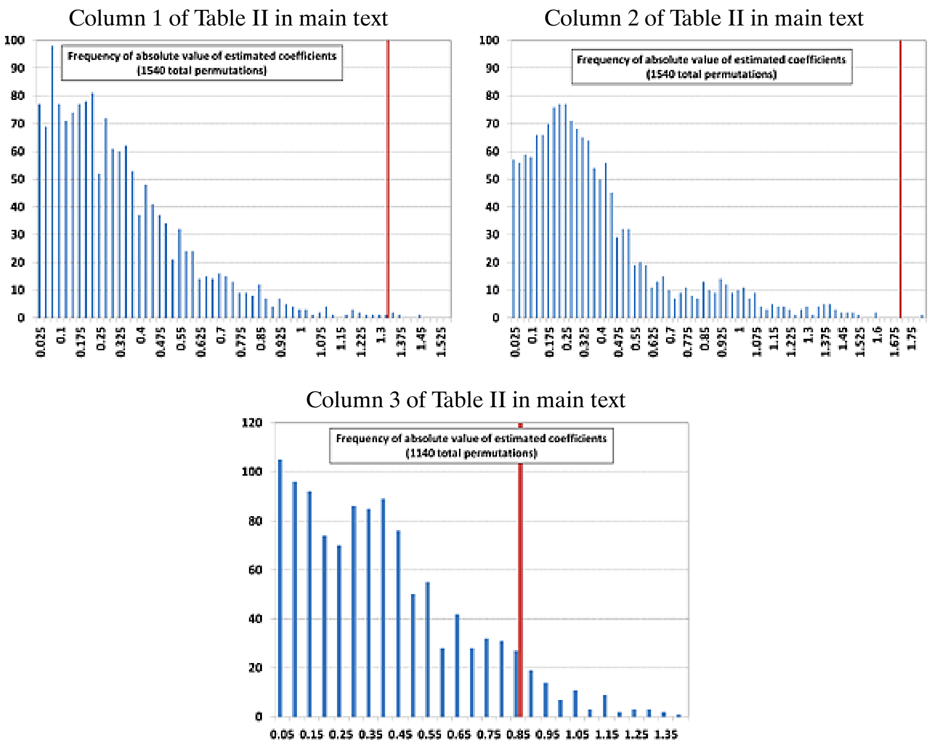


FIGURE A.18.—Histogram of placebo coefficients for high-quality patent results in Table II in main text. These figures compare the distribution of the absolute value of the coefficient estimates from regressions in which every combination of 3 out of the available technology categories are treated as the three treatment categories. For Columns 1 and 2, there are 22 technologies so there are 22 choose 3 = 1,540 placebo coefficients. For column 3, there are 20 technology categories and therefore 1,140 coefficients. The lines on the right indicate the coefficient estimate from the actual India-related technology groups.

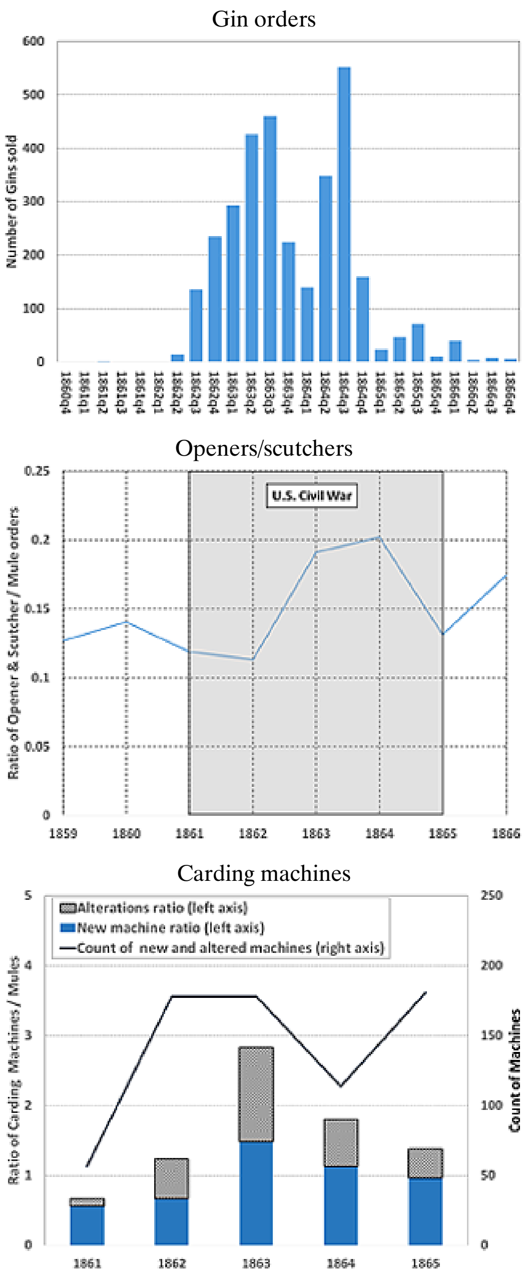


FIGURE A.19.—Dobson & Barlow orders for Indian-cotton related machinery types. Data from Dobson & Barlow contract books accessed at the Lancashire County Archives. Openers/scutchers includes lap machines. Carding includes both finishing cards and breaking cards. The date is based on when the contract was received.

product for Dobson & Barlow during the Civil War period. At first this appears to have been done using publicly available designs, though by 1863 Dobson & Barlow began patenting their own designs. These gins were shipped to a variety of buyers. Many were British firms, which presumably acted as traders, shipping the gins to third markets such as India. Dobson & Barlow also sold to the Cotton Supply Association, which shipped gins to a variety of locations for experimentation. Other orders went directly to places including Egypt, Turkey, Syria, and Brazil.

For openers/scutchers (which also includes related lap machines), the number of orders is presented relative to the number of mule orders. This is done to control for the general fall in sales of most spinning machines during the Civil War period. In normal times, openers/scutchers would be installed in mills alongside other spinning machinery in roughly similar proportions. Thus, the high relative level of openers/scutchers sales we observe is consistent with additional investment in these machines during the Civil War period.

The pattern for carding machine sales is particularly interesting. As with openers/scutchers, I divide carding machine sales by the number of mules sold to account for the overall drop in investment during the Civil War. The interesting feature for carding machines is that we observe a large number of orders for alterations of existing machines to incorporate cutting edge carding technology. These are shown in the top fraction of the stacked bars. In contrast, the sales of new machines shown in the bottom part of the stacked bars was modest.

APPENDIX D: APPENDIX TO THE RELATIVE PRICE ANALYSIS

Figure A.20 provides some additional graphs describing the movements of the actual and relative prices and actual and relative quantities of the various cotton varieties.

Figure 9 in the main text describes the movement of the relative price of Indian to lower-quality U.S. cotton (Upland Ordinary). Figure A.21 shows that essentially the same pattern holds when Indian cotton is compared instead to a higher-quality grade of U.S. cotton, Upland Middling.

To explore the timing of these patterns in greater depth, I turn to monthly data over the 1860–1865 period. The upper panel of Figure A.22 shows the prices of U.S. and Indian cotton, in levels. The lower panel shows relative prices. Key events have been marked on both charts. We can see that price rose slowly following the onset of the Civil War, while relative prices experienced a consistent decline throughout 1861 and into 1862. This was followed by a period of market panic lasting from May to September of 1862, characterized by an extraordinarily rapid rise in prices.[3] During this period, the relative

[3]This panic sparked, in part, by a speech by Lord John Russell in June of 1862 confirming Britain's intention to stay out of the conflict and was ended by Napoleon III's offer to mediate between the sides in October of 1862.

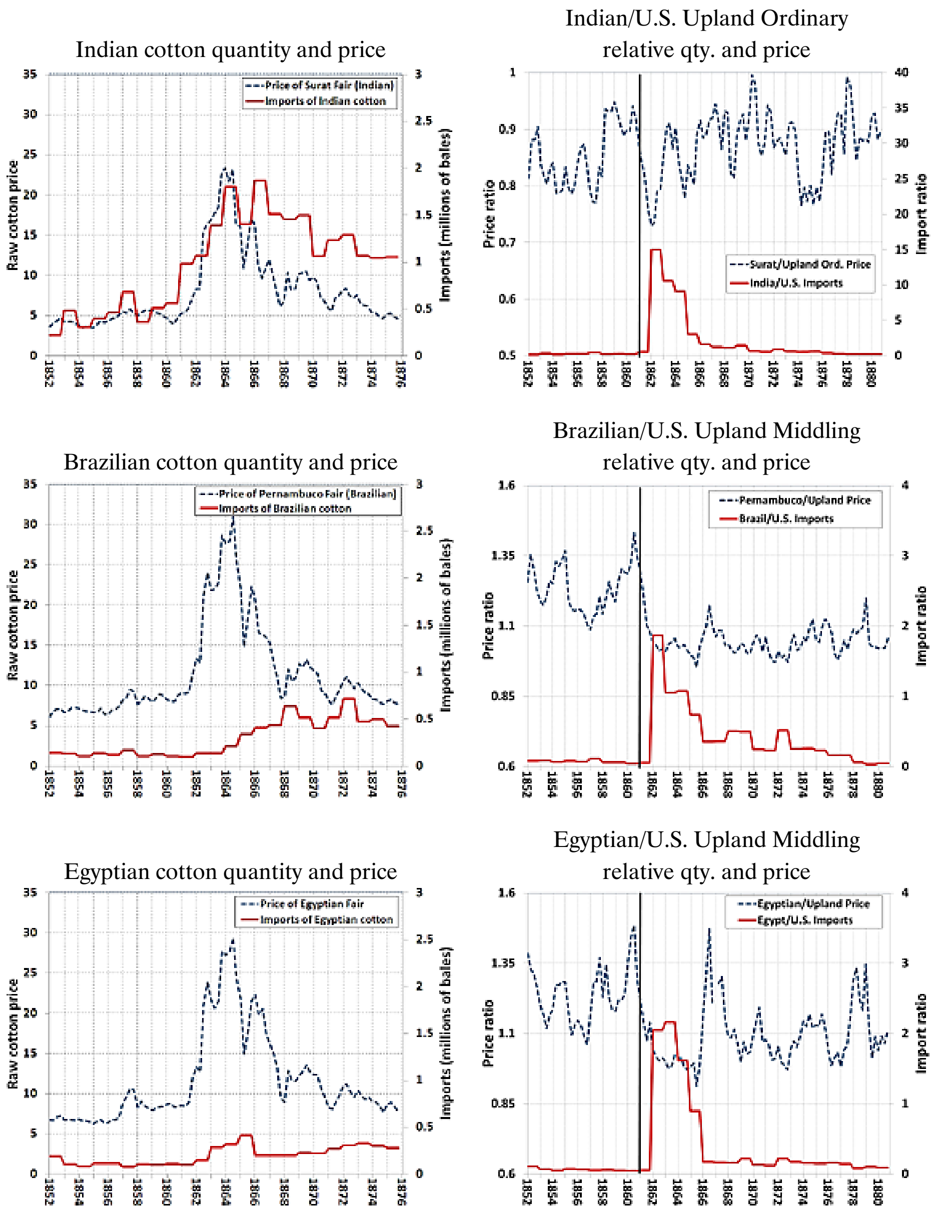


FIGURE A.20.—Prices and quantities for Indian, Brazilian, and Egyptian cotton. Price data gathered from *The Economist* magazine. Quantity data from Ellison (1886). For prices the denominator is the closest U.S. variety, while for quantities the denominator is total imports of cotton from the United States.

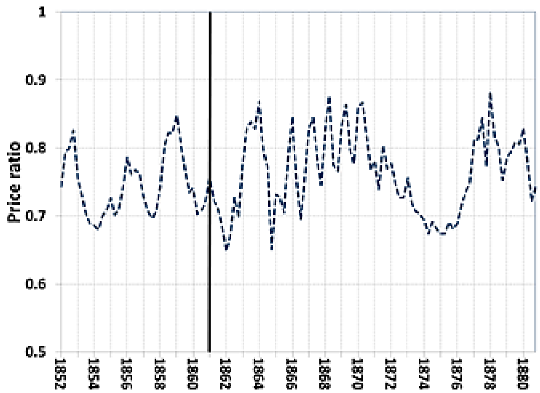


FIGURE A.21.—Ratio of Indian/higher-quality U.S. cotton (Upland Middling). Data from *The Economist*.

price experienced a sharp rise and fall, as the price of Indian cotton followed U.S. cotton prices upward with some delay. We can see from the bottom panel that it was not until the end of 1862, over a year and a half into the war, that relative prices began a sustained increase. By mid-1863, relative prices had returned to the historically high levels of 1860. A downward adjustment followed the Northern victories in July 1863, which ensured that the war would drag on, but relative prices remained near their pre-war average through the end of 1865, with the exception of the short-lived drop during the financial panic of September–November of 1864. Finally, the last months of the war in the Spring of 1865 saw a sharp drop in prices, but notably, relative prices moved very little during this period.

D.1. *Full Price Regression Results*

Tables A.VI and A.VII present the full set of regression results (excluding fixed effects) corresponding to Figures 10 and 11 in the main text, respectively. For the results in Table A.VI, the specification is

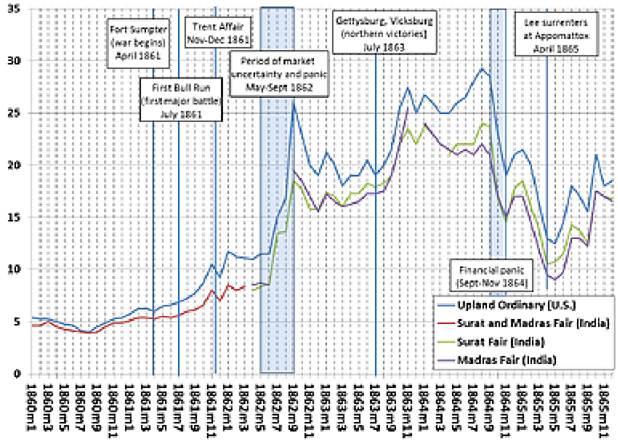
$$\mathrm{RP}_{jt} = \alpha + \left[\sum_{k=1859}^{1875} \gamma_k \times \mathrm{YR}_k \times \mathrm{INDIA}_j \right] + \Psi_j + \xi_t + Q_t + \varepsilon_{jt}.$$

These results correspond to Figure 10 in the main text.

For the results in Table A.VII, which correspond to Figure 11 in the main text, the specification is

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

Prices of U.S. and Indian cotton



Ratio of Indian/U.S. cotton prices

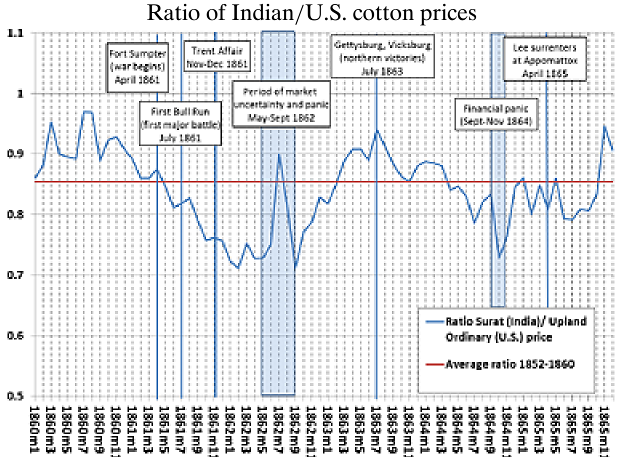


FIGURE A.22.—Monthly prices during the 1860–1865 period. Price data gathered from *The Economist* magazine.

D.2. *Using the Same Denominator for All Relative Price Series*

In the results in Figure 10 in the main text, I compared cotton from India, Brazil, and Egypt to the closest quality U.S. variety for each. The motivation is that each variety should be compared to the most similar U.S. variety. However, we may be worried that using a different denominator in these relative prices is influencing the results. To address this concern, I have generated additional results where each alternative variety is compared to the same U.S. benchmark price (Upland Middling), which was the most important benchmark out of all cotton prices during this period. The results are shown in

TABLE A.VI

FULL REGRESSION RESULTS FOR FIGURE 10 IN THE MAIN TEXT[a]

	Without Controlling for the Indian Rebellion of 1858	With a Dummy Control for the Indian Rebellion of 1858
india_1859	0.0623*	0.00164
	(0.0336)	(0.0339)
india_1860	−0.0731***	−0.0630***
	(0.0236)	(0.0242)
india_1861	0.0451	0.0552
	(0.0337)	(0.0346)
india_1862	0.121***	0.131***
	(0.0244)	(0.0256)
india_1863	0.248***	0.258***
	(0.0302)	(0.0312)
india_1864	0.206***	0.216***
	(0.0306)	(0.0316)
india_1865	0.239***	0.249***
	(0.0264)	(0.0275)
india_1866	0.0851	0.0953
	(0.0601)	(0.0607)
india_1867	0.154***	0.164***
	(0.0498)	(0.0504)
india_1868	0.203***	0.213***
	(0.0306)	(0.0315)
india_1869	0.258***	0.269***
	(0.0192)	(0.0207)
india_1870	0.243***	0.253***
	(0.0292)	(0.0302)
india_1871	0.260***	0.271***
	(0.0238)	(0.0250)
india_1872	0.260***	0.270***
	(0.0197)	(0.0211)
india_1873	0.225***	0.235***
	(0.0198)	(0.0212)
india_1874	0.0619***	0.0720***
	(0.0234)	(0.0247)
india_1875	0.0587**	0.0688***
	(0.0230)	(0.0243)
rebellion		0.0708**
		(0.0274)
Constant	1.271***	1.275***
	(0.0206)	(0.0188)
Observations	288	288

[a]This table presents regression specifications generated using the specification in Equation (3) in the main text. Newey–West standard errors calculated using a lag length of 8 are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

TABLE A.VII

FULL REGRESSION RESULTS FOR FIGURE 11 IN THE MAIN TEXT[a]

	Without Controlling for the Indian Rebellion of 1858	With a Dummy Control for the Indian Rebellion of 1858
india_1859	0.0825***	0.0143
	(0.0136)	(0.0161)
india_1860	0.0779***	0.0893***
	(0.0149)	(0.0112)
india_1861	−0.0146	−0.00325
	(0.0189)	(0.0173)
india_1862	−0.0733***	−0.0619***
	(0.0161)	(0.0142)
india_1863	0.0467***	0.0581***
	(0.0137)	(0.0112)
india_1864	−0.00246	0.00891
	(0.0198)	(0.0182)
india_1865	0.00164	0.0130
	(0.0148)	(0.0126)
india_1866	0.0666***	0.0780***
	(0.0130)	(0.0104)
india_1867	0.0756***	0.0870***
	(0.0152)	(0.0131)
india_1868	0.0389*	0.0503**
	(0.0223)	(0.0210)
india_1869	0.0668***	0.0782***
	(0.0132)	(0.0107)
india_1870	0.109***	0.120***
	(0.0162)	(0.0142)
india_1871	0.0642***	0.0756***
	(0.0175)	(0.0157)
india_1872	0.0392***	0.0506***
	(0.0128)	(0.0101)
india_1873	0.0578***	0.0691***
	(0.0140)	(0.0117)
india_1874	−0.0456***	−0.0342***
	(0.0137)	(0.0113)
india_1875	−0.0515***	−0.0402***
	(0.0130)	(0.0104)
rebellion		0.0796***
		(0.0170)
Constant	0.835***	0.824***
	(0.0127)	(0.0101)
Observations	96	96

[a]This table presents regression specifications generated using the specification in Equation (4) in the main text. Newey–West standard errors calculated using a lag length of 8 are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

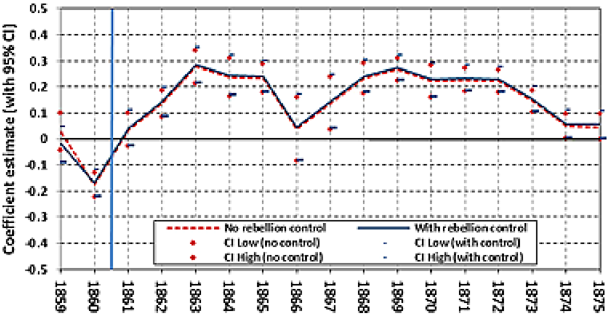


FIGURE A.23.—Behavior of the Indian/U.S. cotton price relative to the pre-war period comparing each alternative variety to the U.S. Upland Middling price. Estimated coefficients and 95% confidence intervals generated using quarterly data from 1852 to 1875. Regressions use Newey–West standard errors with 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.

Figure A.23. Comparing this to the results in the main text, it is clear that this change makes little difference to the results.

APPENDIX E: SOME EVIDENCE ON THE ELASTICITY OF SUBSTITUTION BETWEEN COTTON TYPES

This appendix provides some estimates of the elasticity of substitution between Indian and U.S. cotton in the context of the motivating theory. In this context, the elasticity of substitution can be estimated by looking at the impact of short-run changes in relative supplies on relative prices. The estimation equation is

$$\log(c_{I,t}/c_{\text{US},t}) = \beta_0 + \beta_1 \log(Z_{I,t}/Z_{\text{US},t}) + \beta_2 \text{TT}_t + \varepsilon_t,$$

and the elasticity of substitution is $\sigma_l = -1/\beta_1$. In any regression of relative prices on relative quantities, we must be worried about bias due to reverse causality, though this is less of a concern in the current agricultural setting, where any response of quantities to prices would likely have been lagged by at least one year. However, I still address this concern by using an instrumental variable that directly affects relative input supplies in period t but is not otherwise related to relative prices. To satisfy the exclusion restriction, the instrumental variable must be exogenous and vary only in the short run, so that it does not affect relative technology levels.[4] This approach allows me to estimate

[4]That is, fluctuations in the instrument should not affect the balanced growth path, which could generate directed technical change which would bias the resulting elasticity estimates.

the elasticity of substitution between Indian and U.S. cotton, but unfortunately it is not possible to do the same for Brazilian or Egyptian cotton.[5]

The instrument that I exploit is variation in the length of the cotton growing season in the United States. These data were collected from *The New York Times* (Oct. 8, 1866) and cover 1837–1860.[6] The first bloom and first frost dates played an important role in determining the size of the U.S. cotton crop, which in turn had a large effect on world prices.[7] The growing season length is the number of days between first bloom and first frost. Because these weather events represent exogenous short-run fluctuations, they should satisfy the exclusion restrictions. The length of the growing season does not exhibit a trend over time nor is there any evidence of autocorrelation. The two first-stage regressions are

$$\log(Z_{I,t}/Z_{\text{US},t}) = \alpha_0 + \alpha_1 \text{GROWINGDAYS}_t + \alpha_2 \text{TT}_t + e_t,$$
$$\log(Z_{I,t}/Z_{\text{US},t}) = \alpha_0 + \alpha_1 \text{BLOOM}_t + \alpha_2 \text{FROST}_t + \alpha_3 \text{TT}_t + e_t,$$

where GROWINGDAYS_t is the length of the growing season, BLOOM_t is the number of days in the year before the first bloom, and FROST_t is the number of days in the year before the first killing frost.

Regression results are shown in Table A.VIII for Indian/U.S. cotton. Because these are time-series regressions, I use Newey–West standard errors with a lag length of 2 in order to allow for some serial correlation across observations. Column 1 shows the relationship between relative quantities and relative prices estimated using OLS. In Columns 2 and 3, the length of the growing season (bloom to frost) is used as an instrument for relative quantities, while in columns 4 and 5 I use the bloom date and frost date separately.

The first-stage regression results in Table A.VIII indicate that the weather variables are providing a strong instrument for the relative supply of Indian to U.S. cotton. These variables take the expected sign; a longer growing season, an earlier bloom date, or a later frost date in the United States decrease the ratio of Indian to U.S. cotton. In the top panel of Table A.VIII we see that there is always a negative relationship between relative quantities and relative prices, as expected between two inputs which are imperfect substitutes. However, the point estimates are also small, suggesting that relative prices did not respond strongly to changes in relative quantities, consistent with inputs that were reasonably substitutable. The resulting elasticity estimates derived from these re-

[5]The instruments do not perform well for the relative quantity of Brazilian to U.S. cotton, most likely because the Southern United State and Northern Brazil were subject to correlated weather shocks. For Egypt, sufficient price and quantity data are not available.

[6]I am grateful to Claudia Steinwender for making me aware of these data.

[7]Writing in a somewhat later period, Garside (1935, p. 15) noted that “It has been calculated that climatic conditions, which of course are uncontrollable, account for about 50 percent of the total factors affecting yield per acre.”

TABLE A.VIII

ESTIMATED ELASTICITY OF SUBSTITUTION BETWEEN INDIAN AND U.S. COTTON[a]

	Dependent Variable: Relative Cotton Prices				
	OLS (1)	IV (2)	IV (3)	IV (4)	IV (5)
Relative quantity	−0.0124	−0.0779	−0.0731	−0.0182	−0.0555
	(0.0235)	(0.0500)	(0.0478)	(0.0438)	(0.0467)
Time-trend			0.00363*		0.00320*
			(0.00187)		(0.00181)
Constant	−0.315***	−0.423***	−0.461***	−0.325***	−0.426***
	(0.0355)	(0.0783)	(0.0894)	(0.0668)	(0.0860)
Observations	24	24	24	24	24
	First-stage regression results				
Growing days		−0.011**	−0.011**		
		(0.003)	(0.002)		
Bloom date				0.021***	0.0156***
				(0.005)	(0.005)
Frost date				−0.006	−0.009**
				(0.004)	(0.004)
Time trend			0.026***		0.021**
			(0.007)		(0.008)
Constant		−0.077	−0.346	−3.009**	−1.657
		(0.452)	(0.359)	(1.352)	(1.452)
F-statistic		12.70	25.09	10.99	12.40
	Implied elasticity of substitution				
Main estimate	80.65	12.84	13.69	54.97	18.02
95% C.I.	(16.37, +∞)	(5.51, +∞)	(5.80, +∞)	(9.18, +∞)	(6.55, +∞)

[a]Regressions use annual data from 1837 to 1860. Data from Ellison (1886). Standard errors are Newey–West with a lag length of 2, include a small-sample correction, and are robust to arbitrary heteroskedasticity. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

sults are shown at the bottom of the table. In all cases, these estimates suggest that the elasticity of substitution between Indian and U.S. cotton was above 2.

An alternative approach to estimating the elasticity of substitution, taken by Irwin (2003), is to use the Almost Ideal Demand System (AIDS) introduced by Deaton and Muellbauer (1980). The advantage of the AIDS approach is that it allows for a more flexible demand system than the CES model I use, with cross-price effects. One disadvantage is that it requires strong assumptions about the elasticity of supply of inputs, which will bias the AIDS estimates downward. Another potential issue with this approach is that it does not attempt to control for the influence of directed technical change, which will bias the AIDS estimates upward. The estimating equation for the AIDS approach is

$$w_{it} = \alpha_i + \sum_{j=1}^{n} \gamma_{ij} \ln(c_{jt}) + \beta_i \ln(D_t/C_t) + u_t,$$

where w_{it} is the expenditure share of input type i, c_{jt} is the price of input j, D_t is total expenditure on all inputs, C_t is a price index over all inputs, and u_t is a disturbance term. For empirical applications, the input price index is generally approximated by

$$\ln(C_t) = \sum_{k=1}^{n} w_{kt} \ln(c_{kt}).$$

Given the estimated coefficients from these equations, the elasticity of substitution between any two input types can be calculated according to $\sigma_{ij} = 1 + \gamma_{ij}/(w_i w_j)$, where the corresponding standard error is the estimated standard error for γ_{ij} divided by $w_i w_j$.

Estimating these equations requires the prices and import quantities for each input variety on the British market. Separate import quantity data are not available for higher- and lower-quality U.S. cotton, so I am able to calculate only an overall elasticity of substitution between each alternative variety and all U.S. cotton. Following Irwin (2003), I estimate these equations using seemingly unrelated regressions while imposing symmetry ($\gamma_{ij} = \gamma_{ji}$). In estimating these equations it is necessary to drop one, so I drop the equation for Egyptian cotton, the fourth largest variety.

Table A.IX presents a summary of the elasticity of substitution estimates generated using the AIDS approach for a variety of data sources and time periods. The first column of Table A.IX reproduces results found in Irwin (2003) using data from Mann (1860). The remaining columns present new estimates generated using data from Ellison (1886) for a variety of time periods. The

TABLE A.IX

ELASTICITY OF SUBSTITUTION ESTIMATES GENERATED USING THE AIDS APPROACH[a]

	Irwin (2001)	Additional Estimates			
Data Source:	Mann	Ellison	Ellison	Ellison	Ellison
Years:	1820–1859	1840–1859	1865–1884	1820–1859	1820–1884
U.S.–India	1.96	2.19	2.38	1.58	1.32
	(0.80)	(1.26)	(0.97)	(1.28)	(1.14)
U.S.–Brazil	3.88	2.95	1.66	4.16	5.39
	(0.70)	(0.73)	(3.06)	(0.70)	(1.27)
India–Brazil		−0.97	0.24	−0.01	−0.79
		(4.02)	(4.83)	(3.85)	(4.50)

[a]Standard errors in parentheses. Symmetry is imposed in all regressions, so for example, the coefficient on U.S. cotton in the Brazilian cotton regression must equal the coefficient on Brazilian cotton in the U.S. cotton regression. Durbin–Watson tests do not show evidence of serial correlation in the Indian cotton regressions using either the Mann data or the Ellison data from before the war (Columns 1–2 and 4). There is evidence of serial correlation in the Indian cotton regressions that include post-1860 data (Columns 3 and 5), which may be related to the persistent effects of the shock.

most relevant are in Columns 2 and 3, which present results for the twenty-year period just before the war, and the twenty years after the war, respectively. Both of these suggest that the elasticity of substitution between U.S. and Indian cotton was above 1 and likely also above 2. The elasticity of substitution between U.S. and Brazilian cotton also appears to be above 1, and some specifications generate point estimates that are above 2. There is little evidence of substitution between Indian and Brazilian cotton.

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