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Steam power, establishment size, and labor productivity growth in nineteenth century American manufacturing ☆

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Abstract

We use establishment-level data from the 1850–1880 censuses of manufacturing to study the relationships among establishment size, steam power use, and labor productivity. Large establishments, measured here by employment, were much more likely to use steam power than smaller establishments. By 1880, slightly more than half of all manufacturing workers were employed in establishments using steam power, compared with 17 percent in 1850 and we show that, after controlling for various establishment characteristics, steam-powered establishments had higher labor productivity than establishments using other sources of power. Moreover, this productivity differential was increasing in establishment size.

Keywords: Manufacturing; Steam power; Productivity growth; Firm size

1. Introduction

The vast majority of manufacturing establishments in early nineteenth century America were what Sokoloff (1984) has called "artisan shops". These were very small establishments, usually consisting of the entrepreneur and perhaps an assistant or two who fashioned the final product from start-to-finish using only their skill and a few hand tools. There were other establishments that still relied on hand tools and had no inanimate sources of power but which employed more workers who were less skilled than those in the artisan shops. However, their productivity was higher by virtue of the division of labor.

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Labor productivity could also be increased through the use of powered machinery such as lathes, power looms, and drill presses. Power had long been supplied by falling water but steam technology increasingly caught the attention of contemporaries. The diffusion of light, simple, and cheap high pressure engines along the lines pioneered by Oliver Evans fit well with relative factor prices in America (Habakkuk, 1967). These had a voracious appetite for fuel and a relatively short-life expectancy but were relatively cheap and easy to manufacture, ship and set-up (Atack, 1979; Hunter, 1985). Consequently, establishments using steam power could be much more ‘‘footloose’’ than those relying upon water especially after fuel prices fell. The wide variety of applications and scales to which these engines could be adapted also qualifies them as a ‘‘general purpose technology’’—that is, a technology that is adaptable to a wide range of uses and for which there may be external economies.[1] Manufacturing establishments using water power, on the other hand, had to locate at one of the limited suitable sites and their potential power was limited by the stream flow and the height of the water's fall.[2]

Although economic historians have written extensively about the diffusion of steam (Temin, 1966; Atack, 1979; Atack et al., 1980; Hunter, 1985) surprisingly little attention has been paid to the role played by establishment size and attendant productivity effects.[3] To this end, we use data for individual manufacturing establishments to examine the use of steam power and its impact on labor productivity in American manufacturing between 1850 and 1880, paying particularly close attention to differences by establishment size. We focus on the period from 1850 to 1880 because it is during this period that steam power began to diffuse in earnest, whereas, after 1880, electrical power increasingly became an alternative (Atack et al., 1980; Devine, 1983). Furthermore, excellent data are available at the establishment level for this period unlike for later in the nineteenth or early in the twentieth century.

We have three principal findings. First, the likelihood of adopting steam power was increasing in establishment size. This is consistent with the hypothesis that the availability of steam power was a factor behind the growth of large-scale enterprises which played a central role in the United States' ascendancy as the leading industrial nation by World War One (Wright, 1994; Broadberry, 1994, 1997; Broadberry and Irwin, 2006). Second, plants using machinery that was powered by steam or water had higher labor productivity than non-powered establishments, although most of these differences were due to higher capital intensity in powered establishments rather than the source of power itself. Third, even after controlling for capital intensity, steam-powered ‘‘factories’’—a label which we apply to establishments with 16 or more employees (see Sokoloff, 1984, 1986)—had significantly higher total factor productivity than steam-powered plants with fewer than 16 employees.[4]

2. The economics of the diffusion of steam power: the role of establishment size

There is an extensive literature on the choice of power (Temin, 1966; Atack, 1979; Halsey, 1981; Hunter, 1979, 1985) but none of these directly address whether the diffusion of steam varied with establishment size. Our explanation of why this should be the case has two parts. The first emphasizes the division of labor associated with mechanized production and is not (theoretically at least) specific to steam. The second part argues that the cost advantages of steam relative to water were increasing in establishment size. Taken together, the two parts imply that the diffusion of steam should have been positively related to establishment size.

[1] Rosenberg and Trajtenberg (2004) suggest that diffusion of steam may have promoted urbanization in the United States, which is assumed to have promoted external economies. See, however, Kim (2005) who argues that any such effect of the diffusion of steam was small in magnitude. For a general discussion, see David, 1990; Crafts, 2004; van Ark and Smits, 2004.

[2] These sites were quickly appropriated by first settlers who restricted and controlled entry to manage the scarce resource. For example, the Proprietors of the Locks and Canals at Lowell controlled the waterpower resources there while the Essex Company controlled the rights at Lawrence. See U.S. Census Office, 1991.

[3] A recent paper by Crafts (2004) examines the impact of the diffusion of stationary steam engines, steam-powered railways, and steamships on aggregate total factor productivity growth in the British economy during the nineteenth century. He finds that steam's impact was much larger after 1850 than before but overall the contribution to productivity growth was modest. The scope of our paper is narrower and different; it is narrower because we examine the use of steam and its impact on labor productivity by establishment size solely in manufacturing (and not the other sectors considered by Crafts) and it is different because it derives from econometric estimation of production functions in which we directly compare differences in labor productivity between steam, water, and hand (or animal) powered establishments.

[4] Here, the idea is that steam might have enhanced the division of labor. We elaborate on this point in Section 2.

Ever since Adam Smith, economists have been aware that the pure division of labor alone was sufficient to generate productivity gains. By dividing tasks among different workers according to their comparative advantage (possibly reinforced by learning-by-doing), output per unit of labor could be increased. However, these productivity gains were exhausted at relatively low levels of output and, according to estimates by Sokoloff (1984, 1986), were confined to certain industries such as boot and shoes, clothing, and wagons and carriages.

Because the use of powered machinery was associated with an increase in capital per worker, establishments with powered machinery would have higher labor productivity than non-powered establishments for this reason alone (Atack et al., 2005). If higher capital intensity were the *sole* reason why mechanization raised productivity, and if the associated increase in capital intensity did not vary with establishment size, then it is conceivable that the distribution of establishment sizes would remain unchanged after mechanization. However, there are good theoretical reasons and much empirical evidence to suggest that mechanization enhanced the division of labor so that, overall, mechanized establishments, as measured by employment, were larger.

One reason involves the installation and maintenance of power equipment, including the steam engine and boilers as well as the millwork—the shafts, belts and pulleys used to distribute the power throughout the plant (Hunter, 1979, 1985)—which required skilled, specialized labor. Consequently, establishments purchasing steam engines or waterwheels would have good reason to hire (or otherwise allocate) labor to these specific tasks even if the total amount of capital in production were held fixed. At the same time, steam engines required fuel which had to be delivered, stored on the premises, and then fed continuously to the boilers, all by unskilled labor while other unskilled workers served as haulers moving raw materials and semi-finished goods from one part of the factory to another, depending on where and how the machines were situated.

Independent of this internal specialization of labor associated with the power source, powered machinery could alter the degree of specialization within production itself, especially when certain tasks were particularly amenable to mechanization and others were not. Consider a product produced in, say, four steps. Assume that one group of workers specializes in steps #1 and #2, while a second group of workers performs steps #3 and #4. If, now, mechanized power can be applied to one of these steps (for example, step #2), thereby greatly increasing the amount of output from this stage of production per unit of time, the establishment might respond by separating step #2 from the step #1—that is, creating a third group of workers who specialized in this task alone. Depending on the size of the productivity gains from the inanimate powering of step #2 and on the nature of the complementarities across the other steps in production, the firm might also expand employment in steps #1, #3, and #4 so that the total number of workers overall increases.[5]

In the case of steam power, there is considerable late nineteenth century evidence collected by the U.S. Department of Labor (1899) that powered machinery was positively associated with an elaborate division of labor and, as a result, with much larger establishment sizes in terms of the number of workers. Consider, for example, the production of plows, a basic capital good in agriculture commonly produced using artisan methods by blacksmith shops and the like prior to mechanization. In one artisan shop two men, age 22 and 45, used hammers, anvils, chisels, hatchets, axes, mallets, shaves and augers and their muscles in 11 distinct operations to produce a plow in 118 man-hours. By contrast, a mechanized plow factory employed 52 workers performing 97 distinct tasks to produce a plow in just 3.75 man-hours. Seventy-two of these operations were assisted by steam power, including tasks such as grinding, shaping, bending, polishing, machining, forging, cutting, and tapping. These same activities were also performed in the artisan shop but—and this is the important distinction—*not* by workers who specialized in these tasks but rather as part of the many operations performed by the two workers in the course of their hand manufacture (U.S. Department of Labor, 1899, I, pp. 24–25; II, pp. 476–479). The degree of specialization was even greater in the switch between hand and machine production of men's white muslin shirts. In hand production, one worker (a 38-year old woman) performed 25 different tasks, producing 144 shirts in 1439 hours. Machine production took 188 man-hours to produce the same quantity but it engaged 230 different workers performing 39 different tasks. Specific jobs in the mechanized plant included cutters, turners and trimmers, as well as foremen and forewomen, inspectors, errand boys, an engineer, a fireman, and a watchman. More than half of the tasks were steam–powered (U.S. Department of Labor, 1899, I, pp. 46–47; II, pp. 1094–1097).

[5] This is not necessarily true because the mechanization of step #2 might also release labor that can be allocated to other steps. However, the establishment might still find it optimal to increase the total number of workers employed at the other steps.

On cost grounds, there were good reasons for larger mechanized establishments to choose steam over water. Expanding the potential water power at a specific site was difficult and expensive (Hunter, 1979, especially Chapter 6). Consequently, marginal user costs could never be constant beyond a certain level of output and so, even if average costs per horsepower favored waterpower for smaller producers in a particular location, larger establishments could easily prefer steam. Not only was steam ‘‘scalable’’ but it was also subject to increasing returns: larger steam engines generated more horsepower per unit of input than smaller engines, especially when pared with multiple boilers fueled by coal (Atack 1979, p. 16 also Devine, 1983). With multiple boilers, one or more boilers (depending upon the amount of steam and, hence, power required) could be kept operating while other(s) were being cleaned or repaired. However, the (quasi)-fixed costs of a larger engine-*cum*-multiple boilers would make it a profitable choice only for establishments with a sufficiently high level of output—and in all likelihood, therefore, more workers.[6] Steam was simply more reliable than water power which depended on nature (Hunter, 1979). Early on, many establishments were ‘‘part-year’’—that is, they did not operate for the entire year, often shutting down for months at time. For them, the seasonal nature of waterpower was of less consequence. By 1870, however, a substantial majority of establishments operated year round (Atack et al., 2002) and, while such establishments did shut down production routinely—for example, at night and on Sundays, unexpected shutdowns could be very costly. Despite steam's need for constant supervision by specialized workers and despite the daily start-up costs associated with raising steam, it offered reliable power all year long. Because larger establishments were more likely than smaller establishments to operate on a full-year basis, it is plausible that such establishments would have a stronger preference for a consistent power supply, and hence would prefer steam over water.[7]

3. Powered machinery and establishment size in American manufacturing, 1850–1880

Our empirical analyses draw upon establishment level samples from the manuscript censuses of manufacturing for the census years 1850 through 1880 (Atack and Bateman, 1999). Fortuitously, these years coincide with much of the diffusion of steam power in U.S. manufacturing during the nineteenth century (Fenichel, 1966; Temin, 1966; Atack et al., 1980).[8] For each establishment canvassed, the censuses reported the value of ‘‘real and personal’’ capital invested, numbers of persons employed and information about outputs and inputs although some of the specifics varied from census to census (see Atack and Bateman, 1999).[9] The censuses also gathered infor-

[6] The 1880 sample provides evidence on whether engine size and number of boilers varied with establishment size. For the sample analyzed in this paper (see Section 3; we have re-weighted to take account of the under-sampling of special agent establishments), 41 percent of steam-powered establishments with sixteen or more workers (which we call ‘‘factories’’, see Section 3) had more than one boiler in service and the average engine size was 47.8 hp. Among steam powered establishments with less than sixteen workers, only 11 percent had multiple boilers in service, and average engine size was 24.7 hp. Thee mean differences in engine size and frequency of multiple boilers by factory status were virtually the same if estimated in a regression controlling for the gender and age composition of the workforce (percent women and children), location (state and urban status), and three-digit SIC (standard industrial classification) industry codes; details available from the authors on request.

[7] Exploring this issue is difficult because the census did not report detailed information on operating times until 1880, well after steam had diffused. Using the 1880 sample of establishments analyzed in this paper (see Section 3) steam powered establishments operated for about 0.25 of a full-time equivalent month, or one week, longer than water powered establishments, controlling for the age and gender composition of the workforce, location (state and urban status) and industry. Annual hours of operation, however, were virtually the same because water-powered establishments had longer daily hours than steam-powered establishments (details of these regressions are available from the authors on request). All of factors equal, workers preferred a shorter to a longer work day but whether manufacturing owners could comply with this preference depending on the effect of a shorter work day on productivity; see Atack et al. (2003a).

[8] We would have liked to extend the analysis to the end of the nineteenth century but no establishment level manufacturing data survive after 1880. For post-1880 developments in steam power, see Hunter (1985).

[9] Census enumerators were given no guidance, as far as we can tell, as to whether ‘‘value’’ of capital meant book value or market value. The question itself was nothing more than ‘‘*Capital invested in real and personal estate in the business*’’, the aggregate amount of the capital, real and personal, is to be inserted' (U.S. Census Office, 1860, 25). Census officials at the time routinely questioned the quality of the information on capital. Francis A. Walker, onetime Superintendent of the Census, for example, opined ‘it is a pity . . . that statistical information . . . of high authority and accuracy should be discredited by association with statements so flagrantly false' (U.S. Census Office, 1872, 381–382). While these concerns about data quality are important, they should not be over-emphasized; if the data on capital were mostly noise, we would not find systematic positive relationships between labor productivity and capital labor ratios (see Section 3). See also Gallman (1986, p. 174; 1987, pp. 220–222), has argued, however, that book value was uncommon in the nineteenth century and that the capital figures refer typically to market value.

Table 1
Steam power in American manufacturing, 1850–1880

	1850	1860	1870	1880
Panel A: Percent using steam or water power, establishments equally weighted				
Percent using steam	6.8%	14.6%	20.1%	20.5%
Percent using water	26.4	24.1	14.8	12.3
Percent using steam or water	33.2	38.7	34.9	34.0
Sample size	4855	4940	3779	7062
Panel B: Percent using steam or water power, establishments weighted by employment				
Percent steam	17.7%	24.1%	40.8%	50.9%
Percent water	26.6	25.9	17.1	4.7
Percent using steam or water	44.3	50.0	57.9	59.4[a]

Notes to Panels A and B, figures are computed from samples of establishments from the 1850–1880 manuscript censuses of manufactures; see Atack and Bateman (1999) and available from http://www.vanderbilt.edu/econ/faculty/Atack/atackj.htm. To be included in the samples, establishments had to report positive values of: value added (value of outputs – value of raw materials); raw materials; employment (= sum of male and female workers in 1850 and 1860 or sum of adult male, adult female, and children in 1870 and 1880); and capital. Establishments in SIC industries 351, 492, and 999 were excluded, as were a small number of observations judged to be outliers. 1880 sample is re-weighted to take account of under-reporting of "special agent" industries; see text. Establishments with missing information on power source (1850–1870) or steam and water horsepower (1880) are presumed to rely on hand power exclusively. 1850–1870, percent steam and water are computed from statistics on the incidence of power use. 1880, computed from statistics of horsepower generated; see text for complete details.

[a] Establishments using both steam and water; see text.

mation on the principal source of power used by each firm but these data were only tabulated by the census beginning in 1870 (Atack et al., 1980).[10]

Although the samples analyzed here are nationally representative of the surviving manuscript schedules, they are not necessarily nationally representative of all manufacturing establishments. Some establishments were missed by careless enumerators. Some schedules have not survived. However, with one exception—1880—we can presume that such failures were random and, hence, do not bias the results. In 1880, however, certain industries (including textiles and iron and steel) were assigned to special enumerators chosen for their specialized knowledge about the industry. Their enumerations were not deposited with the other census data and the records have never been found (Delle Donne, 1973). Comparing the sample proportions with those of the population, it is clear that establishments in the "special agent" industries are under-represented in the sample, even though a few establishments in these industries do appear in the sample—probably collected by overly zealous enumerators or from areas where these activities were not common. We have used these scattered observations to re-weight the 1880 sample to make the totals more representative of the aggregate.[11]

Table 1 shows estimates of the incidence of use of steam- or water-powered machinery in manufacturing. Panel A displays the shares of plants using steam or water power as a percent of all establishments weighting

[10] Each census collected somewhat different information. In 1850 and 1860, respondents answered the question "Kind of motive power?" In 1860 they also reported steam horsepower. In 1870, steam and water horsepower was reported and also (in some cases) whether hand or animal power was used. In 1880, horsepower was reported separately for steam and water-powered machinery but no specific information was given about other possible sources of power. See U.S. Census Office, 1853; U.S. Census Office, 1860, 27; U.S. Census Office, 1870, 22–23; Wright, 1900. Our treatment of missing values regarding power use deserves specific comment. Missing values in the original manuscripts are indicated by blank spaces in the relevant columns. We have treated these as the absence (that is, the non-use) of powered machinery. Inspection of the original manuscripts strongly suggests that missing values are not due to a failure by the enumerators to collect the underlying information. They were generally assiduous in recording steam, water or animal but often did not explicitly write "hand".

[11] The basic idea in the re-weighting is increase the weight on those establishments from the special agent industries that do appear in the 1880 sample so that the aggregate industry totals on, for example, output or capital by industry are as close as possible to those reported in the published volumes of the 1880 census. This is difficult to do, however, simultaneously on all relevant establishment characteristics; in particular, even when re-weighted the 1880 sample may under-represent larger establishments. Consequently, when we compute employed-weighted averages of establishment-level variables which are known to depend positively on employment (or other indicators of size), such as the use of steam power (see Tables 1 and 2), our estimates may be biased downwards. Although we do not believe that downward bias to be large, the estimates should still be viewed with some caution (see also our discussion of this issue in Section 4). Further details of the re-weighting are available from the authors on request. The 1880 sample used in this paper improves on those used in Atack (1980).

each equally in calculating the statistics. About one-third of all establishments used steam- or water-powered machinery in 1850. Among those that were powered inanimately, water was much more popular than steam, accounting for 80 percent (26.4/33.2) of establishments using powered machinery.

Over time, steam power displaced water power as fuel, particularly coal, became cheaper, as the efficiency and capacity of steam engines rose, and as available water power sites grew increasingly limited (Atack, 1979). By the eve of the Civil War, about 15 percent of establishments reported using steam, while the fraction using water power fell slightly over the 1850s. However, establishments using water power were still more numerous than those using steam. Use of water power slid during the Civil War decade but, as with steam power, further change appears to have been muted in the 1870s. As of 1880, steam power was used in about 21 percent of establishments, while water power use had declined to 12 percent of establishments, compared with 26 percent in 1850. However, while the pronounced shift towards steam is apparent in these data, total use of inanimate power (steam or water) was barely higher in 1880—34 percent of establishments—than in 1850—33 percent.[12]

Panel B casts the diffusion of powered machinery generally, and steam power in particular, in quite a different light by weighting each establishment by its share of total employment. The figures thus show the proportion of manufacturing workers employed in establishments using powered machinery by power source. Two aspects of Panel B are worth noting. First, in each year, the share of *workers* employed in establishments using steam is considerably higher than the share of *establishments* using steam as early as 1850.[13] However, no similar contrast across Panels A and B emerges in the use of water power and, by 1880, the share of all manufacturing workers using water power was significantly smaller than the share among manufacturing establishments.[14]

Second, weighting by employment produces a steady increase in the overall use of powered machinery, due entirely to the growth of employment in plants using steam.[15] The increase in the share of workers using powered machinery and the growing share who were employed in establishments with steam is fully consistent with the secular trends in user costs of steam and water. In 1850, approximately 18 percent of manufacturing workers were employed in establishments using steam power compared with 27 percent of workers in establishments using water power. By 1880, just over half of all manufacturing workers were employed in establishments using steam power, whereas the employment share in establishments using water power alone had declined to around 5 percent. The increase in steam power usage, weighted by employment, was substantial enough that, by 1880, over 59 percent of all manufacturing workers labored in establishments with powered machinery, an increase of about 16 percentage points over the level prevailing in 1850.

The clear implication from Panel B in Table 1 is that use of steam power was positively correlated with establishment size, as measured by employment. Panel A in Table 2 explores this correlation further by showing (1) the distribution of employment by factory status and (2) the percent of employment by power use, holding factory status constant.[16]

[12] In 1880, it is possible to distinguish establishments using both steam and water (1.2 percent) which is why the total (34 percent) is slightly higher than the sum of the percent using steam (20.5 percent) and the percent using water (12.3 percent) in 1880. The stasis in overall share of power use seems inconsistent with the declining user costs in both technologies over the period reported by Atack (1979, Table 2).

[13] That is, well before the relative costs of average-sized steam and water power plants switched. Atack (1979, Table 2) shows that steam was cheaper than water in 1850 for large (100 hp) prime movers but the 1850 census itself provides no detail on steam engine horsepower. For the 1880 sample analyzed in this paper, the average engine size in steam-powered factories (16 or more workers, see the text) was 47.8 hp, compared with 24.7 hp in steam powered establishments with fewer than 16 workers. The mean differences in engine size by factory status (23.1 hp) were virtually the same if estimated in a regression controlling for the gender and age composition of the workforce (percent women and children), location (state and urban status) and three-digit SIC (standard industrial classification) industry codes; details available from the authors on request.

[14] The results for water power are heavily influenced by flour milling and sawmills. In these, the use of powered machinery was universal in all census years. In 1850, the smallest flour or saw mills, even those employing just one person, according to the census enumeration , used water power. Over time, these smaller establishments were replaced by larger ones relying on steam. If establishments in these two industries are excluded or if industry is controlled for in a regression a positive relationship emerges between water use and size although less steep than the relationship between size and use of steam.

[15] The substantive patterns are unaffected if we weight instead by value added or capital invested.

[16] The basic patterns in Panel A are substantively unaffected if we vary the employment definition of a "factory" between reasonable lower and upper bounds (for example, 10 versus 25 workers). In Panel B and elsewhere in the paper we also provide robustness checks using linear terms in employment.

Table 2
Power use and establishment size

	1850	1860	1870	1880
Panel A: Percent employed: factories, and power use conditional on factory status				
Percent of employment in factories	61.5%	67.9%	73.5%	77.4%
Percent of factory employees in steam-powered establishments	22.8	27.1	46.6	63.2
Percent of factory employees in water-powered establishments	29.9	28.9	19.2	7.0
Percent of non-factory employees in steam-powered establishments	9.5	17.9	24.8	25.5
Percent of non-factory employees in water-powered establishments	21.4	19.5	11.1	12.3
	Factory = 1	Factory = 1	Log (# of workers)	Log (# of workers)
Panel B: Establishment size regressions: coefficients of time trend and power dummies				
Steam = 1		0.332 (0.017)		1.281 (0.083)
Water = 1		0.180 (0.020)		0.706 (0.107)
Time trend (year—1850)	0.0043 (0.0006)	0.0021 (0.0006)	0.016 (0.003)	0.007 (0.003)
Adjusted R^2	0.350	0.354	0.481	0.551

Source for Panels A and B, see Table 1. To be included in Panels A and B an establishment had to meet the criteria described in the notes to Table 1. Establishments weighted by reported employment. In Panel B, robust standard errors are shown in parentheses. Notes to Panels A and B, control variables include percent female, dummies for urban status, state, three-digit SIC industry codes, interactions between region and year, and year and two-digit SIC industry code.

Three features of Panel A in Table 2 are noteworthy. First, employment shifted towards steam-powered establishments and away from water- (and hand-)powered establishments between 1850 and 1880 and the net shift (steam–water) was greater in factories than in non-factories. Second, the proportion of workers using steam was, at each point in time, much higher in factories than in smaller establishments; and the ratio of the two proportions actually rose slightly between 1850 and 1880, even as the share of factory employees using steam approached nearly two-thirds in 1880. Third, the share of workers employed in factories rose by 16 percentage points between 1850 and 1880. Combining the second and third features, it follows that the overall increase in the share of employees in establishments using steam power (Table 1) was driven primarily by increases in its use among factory establishments and the shift in employment towards factories.[17]

One implication from the previous discussion is that, by enhancing the division of labor, and because the relative costs of steam varied with establishment size, falling user costs of steam power encouraged the growth of large-scale enterprises. Panel B in Table 2 reports coefficients of dummy variables for steam and water power use from regressions of factory status based on a pooled version of the manufacturing samples (described in Section 4 below).[18] In addition we report regressions using the log of employment as a robustness check. In columns 1 and 3, the independent variables are a time trend, the percentage of employees who were women, urban status, and dummies for the state in which the establishment was located and for three-digit SIC (standard industrial classification) industry codes. These dummy variables are intended to control for factors that may have been correlated with the use of steam or water power and the size of the establishment, but for reasons that are unrelated to those proposed in Section 2. Columns 2 and 4 add dummy variables for steam and water power.

[17] If the share of employment in factories and the share of workers in factories using steam had remained constant at their respective 1850 levels, the figures in Panel A in Table 2 imply that just 24 percent of workers in 1880 would have used steam, compared with an actual figure of 51 percent—more than twice as many (Table 1).
[18] The substantive findings are not affected if logit or probit is used.

While many factors other than cheap steam power influenced the growth of employment in factories after 1850 and these are imperfectly controlled for in the regression specification, there are ample historical reasons to believe that larger positive coefficient on steam power than on water power (columns 2 and 4) captures, as least in part, a causal impact. That is to say, owners of manufacturing plants responded to the improvements in steam technology and to differences in the relative costs of steam and water by ''growing'' their establishments in terms of the number of workers. Indeed, controlling for power use accounts for slightly more than half of the growth in employment in larger enterprises regardless of whether ''large'' is measured by the factory dummy or by the actual number of workers.[19]

4. Labor productivity and steam power

The productivity effects observed by the U.S. Department of Labor (1899) do not control for factors other than machine use—mostly of it powered by steam—that influenced productivity. Moreover, the effects may have been different earlier in the century. Further, the evidence underlying Atack's (1979) cost estimates is fragmentary. Consequently it would be useful if we could provide additional evidence on the effects of power source on productivity in nineteenth century manufacturing; and whether such differences varied with establishment size.

The samples from the manufacturing censuses have been pooled and culled to those reporting positive employment, capital, value-added, and raw materials (Atack and Bateman, 1999). In addition, we excluded those firms from the very top and the very bottom of the distribution of rates of return on capital, trimming the distribution to the 1–99 percentile range, on the grounds that those outside this range likely had data that were suspect.[20]

We measure labor productivity, the dependent variable in the regressions, by the log of (nominal) value added per worker. Our control variables are the percentage of workers who were female, and dummy variables for establishment size as measured by employment, urban status, state, three-digit (SIC) industry codes, census year, and interactions between industry (at the two-digit level) and year, and between census region and year.[21] In some specifications we also include the log of the capital-labor ratio (see below).[22] The establishment size dummies are integer-valued for sizes 1 through 50, then 51–60 employees, and so forth through 100; followed by 101–200, 201–300, and so forth through 500; and lastly, 501–1000. As in Table 2, establishments are weighted by reported employment prior to estimation.

Our goal is to isolate differences in labor productivity associated with inanimate power use (steam and water) and to determine whether these differences varied with establishment size. Thus, our key independent variables

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[19] For example, controlling for power use in column 2 reduces the coefficient on the time trend to 0.0021 from 0.0043, implying that the net shift toward steam explains 51 percent [= ((0.0043 − 0.0021)/0.0043) × 100 percent] of the growth in employment in factories. This figure is likely to be biased upwards because, as noted in the text, we have only partially controlled for factors other than changes in the relative costs of inanimate power in the regression specification.

[20] Rates of return were estimated using the accounting procedure discussed in Bateman and Weiss (1981) and Atack et al. (2003b). We exclude observations with very high or low rates of return on the grounds that capital (in particular) in such establishments is likely to have been (severely) mis-measured. We also excluded observations in three industries, SIC 999 (miscellaneous), SIC 492 (gas works), and SIC 351 (steam engines). SIC 999 is excluded because it is an extremely heterogeneous group; SIC 492 is excluded because it is not a true manufacturing industry; and SIC 351 is excluded because we do not wish to confound our analysis with estimates of the effects of steam usage on the production of steam engines. We have also excluded observations in 1850–1870 reporting a mix of power sources and, for consistency, those in 1880 reporting both steam and water use. We exclude establishments reporting more than 1000 employees as the results can be sensitive to the inclusion of such establishments when the data are weighted by employment. Lastly, we also excluded one observation with an extremely low capital labor ratio; see the notes to Table 3.

[21] Experiments with more disaggregated interactions did not materially affect the substantive findings with respect to power use, so we opted for the simpler specification. We have constructed an aggregate output price deflator for manufactured goods (see below and Atack et al., 2005). However, because the regression includes year dummies and the dependent variable is measured in logs, deflating by our aggregate index would have no effect on the coefficients of the power variables, which are the main coefficients of interest. In principle, it would be desirable to deflate by industry or region-specific output price indices (see Sokoloff, 1986); however, some preliminary work suggests that our substantive findings would not be affected. In addition, given the nature of the available price evidence, industry-specific indices could not be more detailed than the two-digit SIC level so that our inclusion of industry-year interactions may already capture these price effects as well.

[22] Again, in principle, it would be desirable to deflate by industry or region-specific output price indices (see Sokoloff, 1986) but preliminary work suggests that our substantive findings would not be affected and the price effects may already be captured by our inclusion of industry-year interactions.

Table 3
Effect of steam and water power use on labor productivity: pooled manufacturing sample, 1850–1880

Log of capital labor ratio included?	No	No	Yes	Yes
Steam = 1	0.238 (0.038)	0.256 (0.046)	0.041 (0.034)	0.017 (0.040)
Steam = 1 × Factory = 1	0.185 (0.053)		0.140 (0.047)	
Steam = 1 × (# of workers/10)		0.011 (0.004)		0.011 (0.004)
Water = 1	0.127 (0.042)	0.149 (0.055)	−0.074 (0.037)	−0.051 (0.047)
Water = 1 × Factory = 1	0.115 (0.076)		0.054 (0.064)	
Water = 1 × (# of workers/10)		0.005 (0.004)		−0.00003 (0.003)
Adjusted R^2	0.525	0.528	0.644	0.648

Sample is pooled across all census years (1850–1880). Unit of observation is the establishment ($N = 20{,}243$); observations weighted by reported employment. Factory = 1 if reported employment >=16. To be included in the regressions, the following criteria have to be met: positive values of capital, labor (sum of male and female employees, 1850–1860, and male, child, and female employees, 1870–1880), value added (value of outputs – value of raw materials), and value of inputs. Excluded are establishments reporting (1) a ''mix'' of power sources (2) more than 1000 employees (3) especially high values of an estimated rate of return to capital invested (4) SIC codes 351 (steam engines), 492 (gas works), and 999 (miscellaneous) (5) one establishment with an extremely low capital labor ratio that was deemed to be an error in measurement. Dependent variable is the log of nominal value added per employee. Control variables include the percentage of employees who were women, dummies for firm size measured by the number of employees, dummies for urban status and state, dummies for three-digit SIC industry codes, year dummies, and interactions between two-digit SIC industry and year, and census region and year. Coefficients of all control variables, including capital intensity, are available from the authors on request. For pre-1880 observations, mixed power source is indicated directly (power type is coded as ''5''). For 1880, mixed = 1 if both steam and water are used. Robust standard errors are shown in parentheses. Employment weight is adjusted to correct for under-sampling of special agent industries in 1880. No adjustment is made for the alleged under-reporting of the entrepreneurial labor input (see text for complete details).

are the dummy variables for water power and steam power (no inanimate power is the omitted category) and interactions between steam- and water-power and establishment size. We explore two such interactions: (1) a dummy variable for factory status, and (2) a linear term in the number of workers. The coefficients on the interaction terms should be positive if productivity differences in favor of inanimate power were increasing in establishment size. These differences in labor productivity by source of power could arise because of differences in capital intensity or because of differences in total factor productivity—that is, holding capital intensity fixed. Thus we report results from regressions with and without a control for the amount of capital per worker.

Our estimation strategy is essentially the standard cross-sectional ''value-added'' production function in per-worker form (but with a very flexible specification) rather than a true panel of establishments in which we could include establishment fixed effects.[23] We view this flexibility as critical because the census was far from comprehensive in their reporting of relevant information. The implicit assumption in our analysis is that, conditional on our specification, there is no remaining correlation between the error terms in the regression equation and the type of power.[24] Originally, we made estimates with and without Sokoloff's (1984, 1986) well-known adjustment for the alleged under-reporting of the entrepreneurial labor input by adding one person to the reported count of

[23] Current best practice in the literature on production function estimation rely on panel data techniques—see Ackberg et al. (2006).

[24] We adopt a ''selection on observables'' identification strategy because, unfortunately, there are no plausible instrumental variables for use of steam power in the 1850–1880 samples. For example, one might argue, on the basis of Atack (1979) that establishments located in urban areas were more likely to use steam power because there were fewer available water power sites; however, it is difficult to claim, on a priori grounds, that urban status had no independent effect on labor productivity (see, for example, Kim, 2005). An alternative is to treat power type as endogenous and estimate a version of the Heckman selectivity-bias correction model; however, as a practical matter, the validity of any such model relies heavily on exclusion restrictions (variables that affect the likelihood of using, say, steam power but have no independent effect on productivity) and, as just noted, it is difficult to justify such restrictions on an a priori basis. However, we believe that bias due to unobservable factors correlated with use of steam or water powered machinery is likely to be very small. This is suggested by the fact that once we do control for establishment size, industry, and location in the very flexible manner described in the text the coefficients of the power variables are essentially invariant to minor variations in the regression specification (for example, inclusion or exclusion of interaction terms).

workers. This, as might be expected, makes a difference in the estimated coefficients but mainly with respect to the use of hand (or animal power). It has little impact on the contrasts between steam and water. Consequently, we simply report the coefficients on the power dummy variables and their respective interaction terms without any adjustment for the possible omission of entrepreneurial labor (see Table 3).

Columns 1 and 2 show the impact of steam and water power use on labor productivity without controlling for capital intensity. Clearly, inanimately powered establishments, whether driven by steam or water, had significantly higher labor productivity than non-powered establishments. More importantly, however, the effect varied with the power source. Steam-powered establishments were more productive than water-powered establishments and the productivity gap between steam and water was increasing in the number of workers regardless of whether the interaction effect is captured by the factory dummy (column 1) or by a linear term in employment (column 2). The differences in this regard are economically significant: among smaller establishments, steam enjoyed a 12 percent productivity advantage over water, whereas among factories, the gain was approximately 20 percent.[25]

As we have noted already, establishments using powered machinery were more capital intensive and this, by itself, would have generated higher labor productivity. Consequently, in columns 3 and 4 we have controlled for capital intensity. Controlling for capital intensity greatly reduces the productivity advantage of powered establishments over non-powered ones. Indeed, according to our results, non-factory establishments using water power were, in general, less productive than non-factories relying on hand or animal power once we controlled for capital intensity. However, the steam-factory interaction coefficient remains positive and statistically significant whether the interaction is captured by the factory dummy (column 3) or a linear term in employment (column 4). Further, differences in productivity between steam and water-powered establishments are approximately the same after we control for capital intensity as before: the efficiency gain from shifting to steam from water for factories without controlling for capital intensity (column 1) is 0.07 in log terms (=0.185–0.115), or about 7 percent; whereas after controlling for capital intensity (column 3), the efficiency gain is 0.086 in log terms (=0.140–0.054), or about 9 percent.

With the information from the census, it is not possible to identify precisely the sources of the positive effect on total factor productivity based solely upon the interaction of steam and size. One possibility as we have seen is the enhanced division of labor found in such plants. However, the regression already controls for the effects of establishment size *per se* in a very flexible way, so any such enhancements would have to have been more subtle than those already captured by the regression specification.[26]

In Section 2, we suggested that larger establishments could opt for a different mix of steam engine sizes and number of boilers than smaller establishments. It is possible to test whether this might be responsible for the efficiency gains in 1880 when the census reported engine size and the number of boilers. To this end, we estimated a version of our basic regression specification restricting the sample to just those establishments in 1880 that were using steam, with and without controls for engine size and number of boilers. When the controls were added, about half of the positive effect of factory status on labor productivity can be explained.[27] Further

[25] Calculated from differences between the coefficients on the relevant dummy variables—$e^{(0.238-0.127)} = 1.117$ (=11.7% gain) for steam over water whereas for steam-powered factories versus water-powered factories, the productivity gain is $e^{((0.238+0.185)-(0.127+0.115))} = 1.198$ (= 19.8% gain). The census did not report the length of time the establishment had been in business which, if there were learning by doing effects, would be positively correlated with labor productivity. It is certainly possible that smaller establishments, particularly those relying on hand or animal power, had shorter life spans than larger, powered establishments. The best that we can do to deal with this issue is to restrict the analysis to establishments that operated on a full-year basis, which can be determined in 1870 and 1880; this restriction will at least eliminate all establishments that had operated for less than one year which (if the above argument is correct) were more likely to be non-powered. If this is done, output per worker is still highest in steam powered factories but the gap between steam and water is smaller; details available from the authors on request.

[26] One important possibility in this regard that we cannot control for is the fraction of production tasks that were steam assisted. If this fraction were increasing in establishment size this could explain the positive interaction effect.

[27] In addition to a dummy for factory status, this regression includes controls for three-digit industry code, state, urban status, the proportion of workers who were female, the number of full-time equivalent months of operation, the number of steam engines, and the log of the capital–labor ratio. We restrict the sample to establishments that operated for at least 10 full-time equivalent months; the substantive results are not affected if we include all steam-powered establishments regardless of number of months of operation. If engine size (measured by the log of hp/engine) and the presence of multiple boilers are not included in the regression, the coefficient on factory status is 0.116 ($t = 1.79$), indicating about a 12 percent gain in efficiency. If engine size and the dummy for multiple boilers are included, the coefficient is 0.052 ($t = 0.68$). Further details are available from the authors on request.

Table 4
Actual vs. simulated real labor productivity

Number of employees	Output price deflator	<16	<16	>=16	>=16
		Actual	Simulated	Actual	Simulated
1850	100.0	100.0	100.0	100.0	100.0
1860	103.6	115.6	115.0	132.2	131.2
1870	165.2	107.3	105.8	134.6	129.2
1880	109.2	113.8	112.3	137.0	127.9
"Treatment Effect" of steam			0.041		0.181
"Treatment Effect" of water			−0.074		0.02
% explained, 1850–1860			3.8%		3.1%
% explained, 1850–1870			20.5		15.6
% explained, 1870–1880			0		>100.0%
% explained, 1850–1880			10.9		24.6

Index of nominal labor productivity is calculated from weighted sample mean of output per worker; weight is reported employment, adjusted for 1880 under-sampling of special agent industries. Real labor productivity: index of nominal labor productivity/output price deflator (see Atack et al., 2005). Simulated: real labor productivity index holding distribution of employment across steam and water use constant at 1850 values using "treatment effects" of steam and water; treatment effects are relative to non-power and are computed from Table 3, Panel A, column 3. Example calculation: simulated value of real labor productivity, >=16 employees in 1880. Step #1, compute reduction factor in 1880 actual index number using 1850 employment distributions (from Table 2) = $\exp[((0.141 + 0.4) \times (0.228 - 0.632)) + ((0.074 + 0.054) \times (0.299 - 0.07))] = 0.934$. Step #2, multiply reduction factor by 1880 actual index = $0.934 \times 137.0 = 127.9$. Step #3, percent explained = (Actual, 1880 − Simulated, 1880)/(Actual, 1880 − Actual 1850) × 100% = 9.1/37 × 100% = 24.6%.

experimentation suggests that the primary factor was the number of boilers. This not only allowed the steam engine to be kept in operation while one or more boilers was "off-line" for service (such as de-scaling or repair) but multiple boilers also provided additional steam generation capability to overdrive machinery when necessary.

We have used the regression results to compute how much of the change in labor productivity in manufacturing from 1850 to 1880 may be attributed to the diffusion of steam power. By "attribute" we mean that, if the distribution of employment with respect to the use of steam in 1880 been unchanged from its distribution in 1850, how much lower, on average, would labor productivity have been in 1880 relative to the level actually observed?

The first step is to compute an index of labor productivity from the sample evidence, weighting the labor productivity of each establishment by employment to produce the overall average. These calculations are performed separately for factories and non-factories. Nominal values were converted to real values by deflating by an index of manufacturing output prices (see Atack et al., 2005 and Table 4). The results are shown in Table 4. In real terms, output per worker rose by about 14 percent in establishments other than factories and by 37 percent in factories between 1850 and 1880.

Next, we compute what the productivity levels would have been if the distribution of employment between steam, water, and non-powered establishments were held constant at 1850 values, conditional on establishment size. This generates the "simulated" indices shown in Table 4. In making this calculation, we use the power coefficients from column 3 of Table 3 which hold capital intensity constant. A specific example illustrating how the simulated figures were computed is shown in the notes to Table 4.[28] If the distribution of power use had remained unchanged from 1850, productivity would have still increased but at a slightly slower pace. Treating 1880 as the long-run then, in establishments other than factories, output per worker in 1880 would have been 12.3 percent higher than in 1850, rather than the 13.8 percent gain observed. In factories, the gain would have been 27.9 percent instead of 37 percent. Thus the spread of steam power accounts for 11 percent of the increase in labor productivity between 1850 and 1880 in non-factories (=(1.5/13.8) × 100%) but 25 percent (=(9.1/37) × 100%) of the gain in factories.

[28] The treatment effects measure the gains in use of steam or water relative to non-powered production. The effects for steam can be computed from the regression coefficients in Table 3. The substantive conclusions are not affected if we compute the treatments effects from regressions where the Sokoloff adjustment for entrepreneurial labor has been applied.

The impression from Table 4 is that steam had only a very modest on labor productivity growth in manufacturing during the entire period 1850–1880, even in larger establishments. The sample evidence shows that most of the growth in labor productivity over our period occurred in the 1850s and, while the shift to steam had a positive effect then, the effect was very small. Instead, other factors must have been responsible for the rising labor productivity during this decade, including a rising concentration of production in urban areas, greater capital intensity, growing division of labor from larger scale establishments, and shifts in production towards industries with higher total factor productivity. The effect of steam was much bigger after 1860, especially for large establishments, but when the effects are averaged over three decades, the overall impact is modest.

Second, it is well known that aggregate output per worker in manufacturing fell during the Civil War (Engerman, 1966) while a full recovery had still not taken place by 1880. This imparts a downward bias to our estimates for the period 1860–1880. Taking our results at face value, labor productivity in factories would have declined from 1860 to 1880 (from an index value of 131.2–127.9) but for the diffusion of steam. Instead, actual productivity in factories rose from an index value of 132.2–137. Among establishments other than factories, the diffusion of steam helped prevent a much steeper decline in labor productivity in the 1860s than would otherwise have occurred. Our reading of these findings, then, is that cheap steam helped cushion the Civil War's blow to labor productivity in the 1860s and assisted in recovery in the 1870s, particularly in large establishments.

Third, because the simulated indices capture the impact of the diffusion of steam solely through changes in total factor productivity as we have measured it and assume that all of the forces influencing labor productivity growth would have remained the same—including, in particular, the aggregate amount of capital invested in manufacturing.[29] If, instead, we allow capital intensity to increase along with the diffusion of steam—that is, we use the coefficients from column 1 of Table 3 to compute the simulated indices, the impact of steam over the 1850–1880 period, is substantially higher—for example, 41 percent instead of 25 percent in the case of factories. Even this will understate the effect because the indices in Table 4 are conditional on factory status, whereas we have argued that there are strong historical reasons to believe that cheap steam power encouraged the growth of larger establishments by enhancing the division of labor. This effect is not captured in Table 4 either directly or indirectly because the regressions in Table 3 hold establishment size fixed.

5. Concluding remarks

Over the course of the nineteenth century, steam and water power technologies improved dramatically but steam became the power source of choice for manufacturing establishments. Previous work has neglected an important feature of this diffusion—namely, the positive relationship between the size of the establishment as measured by employment and the use of steam. Establishments became larger when they adopted powered machinery because there were gains to be realized through the enhanced division of labor as well productivity gains from higher capital intensity,. For most establishments, steam was a better choice than water when they sought to mechanize and when they became larger, because the costs of steam (per required horsepower) relative to water were less for larger than for smaller establishments. When we measure the incidence of powered machinery at the establishment level, there is little evidence of a trend towards a greater proportion of such establishments over the period covered in this paper, 1850 to 1880. However, when we measure the proportion of workers employed in establishments that were powered by steam or water, this proportion rises over the period, entirely because of a pronounced movement towards steam. This trend occurs precisely because steam power and establishment size were positively related.

It is difficult to compare our findings with those of other recent studies of the economic impact of steam because these other studies have largely focused on aggregate productivity effects rather than productivity in manufacturing but studies by Crafts (2004) and von Tunzelman (1978) for Great Britain found only modest gains. At the same time, it is important to emphasize that our analysis controls, in a very flexible way, for the

[29] This is the same view of the "social savings" of a technological improvement implicit in Fogel's (1964) claim that, in a counterfactual world with no railroads, water transportation (river, canal, and so on) would have been expanded.

direct effects of establishment size *per se*. Economies of scale arising through an enhanced division of labor as a consequent of the application of powered machinery were difficult to capture through traditional waterpower which was not as reliable as steam and which faced significant rising marginal costs of use as output increased compared with steam.

Because manufacturing accounted for a relatively small fraction of aggregate output in the nineteenth century United States, our results do not imply that the diffusion of steam dramatically altered the course of aggregate productivity growth. Nevertheless, they show that the diffusion of steam raised labor productivity in manufacturing and, if this diffusion had not occurred, the pace of industrialization would have been slower. Indeed, considering all of the specific technologies that diffused in manufacturing between 1850 and 1880, none may have had a bigger impact, in the sense of affecting more manufacturing workers, than the shift to steam power.

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