Compulsory Licensing
Evidence from the *Trading with the Enemy Act*[*]

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Compulsory licensing, which is permissible under the Trade Related Intellectual Property Rights (TRIPS) agreement, allows domestic firms to produce inventions that are patented by foreign nationals, without the consent of patent owners. As an emergency measure, compulsory licensing offers clear benefits: it helps to deliver life-saving drugs to millions of patients. In the long run, however, the threat of compulsory licensing may reduce access to foreign technologies as it discourages foreign inventors to transfer inventions into the country. But, at the same time, compulsory licensing may generate domestic invention if experience with producing foreign inventions creates opportunities for learning and follow-up inventions. This paper uses an exogenous change in compulsory licensing as a result of World War I to measure the policy's effects on domestic invention. Specifically, we compare changes in patents by domestic inventors across technologies that were differentially affected by compulsory licensing under the Trading with the Enemy Act (TWEA). Our data suggest that compulsory licensing has a large positive effect on domestic invention. Moreover, the effect increases with the intensity of treatment. The effect takes almost 10 years to fully materialize, which suggests that the effects of compulsory licensing may be missed in analyses of contemporary data.

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Compulsory licensing has been advanced as a policy tool to deliver life-saving drugs to millions of patients in developing countries and in the United States (Kremer 2002, Galvão 2002, Gostin 2006). Under this policy, which is permissible under the Trade Related Intellectual Property Rights (TRIPS) agreement,[1] governments grant domestic firms the right to produce inventions that are patented by foreign nationals, without the consent of patent owners. As an emergency measure, compulsory licensing offers clear short-term benefits: It provides quick access to medicines and other essential inventions that have been invented abroad.[2]

The long run effects of compulsory licensing, however, are unclear. Although the risk that compulsory licensing poses to foreign inventors may discourage technology transfers[3], the boost that it provides to domestic invention may more than compensate for the decreased access to foreign inventions. For example, compulsory licensing creates opportunities for learning by doing (e.g. Arrow 1962) by allowing domestic firms to produce foreign inventions. Moreover, problems that arise in production may encourage further learning and investments in scientific training. Thus, compulsory licensing creates opportunities to build a country's capacity for invention in the long run.

This paper uses an exogenous event of compulsory licensing as a result of World War I to measure the effects of compulsory licensing on domestic invention. Specifically, we examine changes in the number of domestic inventors across technologies that were

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[1] TRIPS Art.31 allows compulsory licenses after negotiations for voluntary licenses have failed. In cases of emergency, governments may grant compulsory licenses without first trying to negotiate.

[2] Previous work has focused on compulsory licensing as a mechanism to address anti-competitive patenting behavior in domestic markets. In such settings, the policy is thought to be primarily welfare-enhancing. Thus compulsory licenses can increase overall welfare by encouraging the optimal trade-off between incentives for R&D and the dead weight loss of long-lived patents (Tandon 1982, Gilbert and Shapiro 1990). Moreover, case studies suggest that court-ordered compulsory licenses lower neither the research efforts (as measured in R&D dollars) nor the number of inventions (as measured in patents) of patent holders (Chien 2003).

[3] Although there have been no empirical studies of the effects of compulsory licensing on technology transfers, policies that weaken the property rights of domestic inventors appear to discourage technology transfers (e.g., Branstetter, Fisman, and Foley 2006, Yang and Maskus 2001, Mansfield 1995).

differentially affected by the *Trading with the Enemy Act* (TWEA). Passed by Congress in November 1917, section 10 of this Act permitted U.S. firms to violate enemy-owned patents if they contributed to the war effort. As the war dragged on, the Act became more and more punitive (Steen 2001, p. 99). One week before the Armistice at Compiègne on November 11, 1918, Congress passed an amendment to the TWEA, confiscating all enemy-owned patents, and by February 1919, German patents of textile dyes were systematically licensed to U.S. firms.

Our project uses the TWEA as a natural experiment to identify the effects of compulsory licensing on domestic invention. To measure the policy's effects, it is necessary to control for other factors that may also encourage domestic invention. Most importantly, improvements in education and scientific training, as well as changes in the demand for dyestuffs as a result of World War I or in the supply of foreign dyes may also have increased domestic rates of invention.

To address this issue, our empirical strategy relies on a differences-in-differences estimation, which compares changes in the number of U.S. inventors across subclasses that were affected by the TWEA with those that were not. We then extend this analysis to account for differences in the intensity of treatment. Specifically, we repeat our tests using alternative measures of treatment which control for variation in the number of licenses that were granted in a given subclass and in the remaining lifetime of all patents that were licensed in that subclass.

OLS regressions indicate that compulsory licensing lead to a large increase in the number of patents by domestic inventors.[4] After 1919, when the average subclass had about 0.7 patents per year, classes that were affected by compulsory licensing generated an

[4] Our data cover 191,292 patents in dyestuffs patents between 1875 and 1945.

average of 0.3 additional domestic patents per year. Controlling for the intensity of treatment shows that each additional license increased the number of domestic patents by about one eighth per year; adding ten years of patent life to the licensed patents in a subclass increased domestic patents by one patent every ten years.

Our historical analysis has the additional benefit that it examines a much longer time series than is available to contemporary studies. We use these data to examine the long-run effect of compulsory licensing on domestic invention. This analysis reveals that the benefits of compulsory licensing take much longer to materialize than we would have expected *ex ante*. Specifically, the full effects of compulsory licensing on domestic invention set in only after about 10 years. This result is robust to controlling for the intensity of treatment: subclasses that received a larger number of licenses or a larger total number of remaining years of patent life on their licenses experienced a larger and statistically significant increase in patenting.

Although surprising, the lag between licensing and further invention are intuitive: Compulsory licensing allows domestic firms to produce foreign technologies, but the ability to invent new technologies cannot be generated over night. First, technical information in patent documents is rarely complete enough to replicate an invention; early 20th-century German inventors appear to have intentionally omitted or scrambled information that was necessary to reproduce their dyes. Domestic inventors also often simply did not have the necessary skills that it took to reproduce the foreign inventions. These problems become especially severe with compulsory licensing, when firms whose inventions are licensed may be particularly loath to share the tacit knowledge that complements their patent documents. Our results suggest that it can take countries a decade or more to build its inventive capacity under such circumstances.

Although our results suggest a significant long-run effect of compulsory licensing, they may be compromised if not all aspects of the TWEA were exogenous. The timing of the TWEA was caused by World War I, which is exogenous to our outcome variable. Which technologies were confiscated is also exogenous, because the United States confiscated all enemy-owned property. Which technologies were licensed, however, may not be exogenous. For example, U.S. inventors may have been more likely to license technologies in technological fields where the domestic capacity for invention was low. If these classes experience a weaker increase in invention after the TWEA, OLS will underestimate the effects of compulsory licensing; on the contrary, if invention grows more quickly in these classes, OLS will overestimate the effects of compulsory licensing.

We address this issue by a triple differences estimation. Specifically, we account for unobservable characteristics that may have encouraged patenting by *all* non-German inventors by comparing patents by U.S. and foreign (non-German) inventors across more or less treated subclasses before and after the TWEA. Results from this differences-in-differences-in-differences estimation suggest a slightly smaller positive effect on domestic invention, but they confirm that the TWEA lead to a substantial increase in patenting by domestic inventors, and that this effect took about a decade to fully materialize.

As an additional check, we instrument for compulsory licensing with the share of German inventors among all foreign inventors in a subclass. Intuitively, this is a good instrument for licensing because the quality of German inventions is likely to be higher in classes where the share of German inventions among all foreign inventions is high, and U.S. inventors are therefore more likely to want to license them. On the contrary, the share of German inventors among all foreign inventors should have no direct effect on the development of the U.S. industry in that subclass. The results of instrumental variable estimation suggest that OLS regressions underestimate the effect of compulsory licensing on domestic invention.

Our results are robust to a broad range of alternative tests. First, we control for subclass-specific time trends and find that the results are robust to including such trends. Second, to address the potential of serial correlation in the outcome variable patents within subclasses, we perform a block bootstrap; it confirms that the estimation coefficients are highly significant. Third, we restrict our sample to primary subclasses, which has no significant effect on the coefficients. Fourth, to control for a potential shift in demand as a result of World War I, we examine variation across treated and untreated subclasses within a specific dye (indigo) that was most affected by a shock in demand. Even with a strong demand shock, patenting by domestic inventors increased substantially more in subclasses that were (more) affected by compulsory licensing. Finally, to check whether our results might be due to random variation, we repeat the estimation with a variety of placebo treatments; none of the placebos replicate the observed increase in domestic patents.

The remainder of this paper is structured as follows. Section I describes why the TWEA offers a useful experiment to examine the effects of compulsory licensing, section II presents our empirical strategy. Section III details our data collection and discusses potential sources of bias. Section IV presents our results, Section V presents robustness checks, and Section V concludes.

I. The TWEA as a Natural Experiment of Compulsory Licensing

Although the United States was one of the most developed economies of the early 20th century, its chemical industry was undeveloped at the beginning of the 20th century. In the early 1910s, Germany produced three quarters of the world's supply of coal-tar dyes

(USTC, 1918). Large companies like Badische, Bayer and Hoechst captured most of this market. Between 1900 and 1910, 70 percent of all U.S. patents of all the patents granted in the U.S. of synthetic organics compounds were owned by German firms (USTC 1918, Haynes 1945 p.214, Steen 2001). Imports from Germany provided up to 90 percent of dyes for the U.S. flourishing textiles industry (Haynes, 1945 p.214).

Britain's naval blockade cut U.S. markets off from German imports so effectively, that the last shipment of German dyes arrived in the United States in March 1915 (Haynes 1945, Haber 1971, p.185). The price of dyes skyrocketed in the "dye famine" that followed (Genesove, 2006).[5] For instance, the price of indigo quadrupled between 1914 and 1916 (Haynes 1945, 231).[6] Despite dramatic price increases, the value of dye stuffs imports into the U.S. fell from 7.0 to 3.3 million dollars, between 1915 and 1916.

The U.S. domestic industry was unprepared benefit to fill the gap. On December 18th 1918, the *Wall Street Journal* wrote:

> Users of dyestuffs in quantity are more or less indignant over the fact that the manufacturers of this country are dependent upon other countries, and Germany particularly, for the dye supply. They ask "Why haven't our chemical companies experimented sufficiently to produce synthetic dyes, pharmaceutical products, essential oils and the synthetic perfumes, in the production of which Germany seems to have almost a monopoly?

A. Compulsory Licensing under the TWEA

Created by an act of Congress on October 6, 1917, the TWEA was created with the goal of "dislodging the hostile Hun within our gates" (Alien Property Custodian 1919, p.17) to destroy "Germany's great industrial army on American soil", its "spy centers",

[5] The fanfare caused by the arrival of the submarine *Deutschland* in Baltimore in July 1916 illustrates the urgency of the shortage. It had been sent from Germany to bring hundreds of tons of dyes and pharmaceuticals to the American agents of Badische, Cassella, Hoescht and Bayer.

[6] The United States consumed 8,000,000 pounds of indigo per year before the war; 90 percent of it imported from Germany, the rest from Switzerland, England and India. Once the British blockade prevented imports from Germany, the U.S. sourced its indigo from China (52 percent), Japan, Hong Kong, British India (21 percent) and the U.K (20 percent); total imports, however dropped to 6,600,000 in 1916 (Haynes 1945, p. 231). Imports of alizarin fell even more dramatically by a factor of 3,000 between 1915 and 1916.

and “nests of sedition” (Alien Property Custodian 1919, p.14). To this end, it placed all enemy property “beyond the control of influence of its former owners, where it can not eventually yield aid or comfort to the enemy” (Alien Property Custodian 1919, p. 13).

On March 28, 1918, the TWEA was amended to give the Custodian the power to sell enemy property, including all enemy-owned patents “as though he were the owner thereof” (Alien Property Custodian 1919, p.22)[7] Thus, the Alien Property Custodian began to take over any type of property that was owned by “enemy persons” and corporations doing business in Germany, Austria-Hungary, Bulgaria, and Turkey, as well as the occupied parts of Belgium, France, Russia, and the Balkans (Alien Property Custodian 1919 p.7), administering these properties as a trust.

By February 22, 1919, Mitchell Palmer, the Alien Property Custodian and President of the Bureau of Investigation felt comfortable to say that “practically all known enemy property in the United States has been taken over by me and is administered according to the provisions of the trading with the enemy act” (Alien Property Custodian 1919, p.7). At that time, 35,400 reports of alien property had been received, and 32,296

[7] This amendment reinforced the punitive nature of the act. “When the Congress passed the amendment giving to the Alien Property Custodian the general power of sale, it was the purpose in mind that the German industrial army on American soil should be captured and destroyed” (Alien Property Custodian, 1919, p.15). Beyond resentment, the stated purpose of destroying German property was to keep the country from starting another war: “…the great overshadowing result which has come from this war is the assurance of peace almost everlasting amongst the peoples of the earth. I would help to make that an absolute certainty by refusing to permit Germany to prosecute a war after the war. The military arm of her war machine has been palsied by the tremendous hammering of the allied powers. But her territory was not invaded, and if she can get out of the war with her home territory intact, rebuild a stable government and still have her foreign markets subject to her exploitation, by means no less foul and unfair than those which she has employed on the field of battle, we shall not be safe from future onslaughts different in methods, but with the same purpose that moved her on that fateful day in July when she set out to conquer the world.” (Alien Property Custodian, 1919, p.16)

trusts had been created, with a total value exceeding 500 million in 1919, equivalent to 4.7 billion in 2008 (Alien Property Custodian 1919, p.9).[8]

By 1919, the Chemical Foundation began to license enemy-owned patents to U.S. firms. In 1921 the foundation possessed 4,764 patents, 874 trademarks, and 492 copyrights. From 1919 to 1922 it licensed 103 manufacturers to use its patents; about half of the licensees were manufacturers of synthetic organic chemicals. The foundation collected an income of $700,000, primarily from royalties (Steen 2001, p.100).

Access to German patents, however, was not by itself enough to jump-start U.S. production. For one, U.S. firms may have been lacking in the skills and knowledge necessary to reproduce German inventions. Incomplete descriptions of production processes in patent documents added to these difficulties. For example, Mark Weisberg, owner of the Providence, RI Textile Chemical Company remembers[9]

> …in the early days we purified alpha-naphthol by following the book, dissolving it in caustic soda and filtering. The filtration was arduous….Yields were poor…and the resultant compound was not entirely satisfactory…To remove this isomer, a problem that was not mentioned in the German patents, a concentrated solution of caustic potash was used. The above serve to illustrate the know-how, not in the patent literature, that was required to make success in the dyestuff field" (Haynes 1948, p. 230).

Given that German patents had been licensed without the consent of their inventors, it is unlikely that U.S. firms had access to the know-how of the patent's original owners. In fact, U.S. firms struggled to decipher patent specifications that German firms had, perhaps intentionally, had left unclear. Thus

[8] Using the GDP deflator as a relative conservative measure. Using the relative share of GDP, the 2008 equivalent would be 88 billion dollars (Williamson 2008)
[9] Alpha-napthol is an isomeric form of naphthol, $C_{10}H_7OH$; it typically takes the form of colorless or yellow prisms. In addition to making dyes, alpha-napthol is used to make perfumes and in organic synthesis.

> Acting under a license issued under the Trading-with-the-Enemy Act, Du Pont wrestled with the obscure descriptions in the German patents to work out a practical process (to produce indigo) only after long experimentation. (Haynes 1945, p.245)

Incomplete and obscure patent specifications, along with the rudimentary expertise of U.S. inventors, are likely to have delayed the effects of compulsory licensing.

B. The British TWEA

Other countries adopted similar measure to access German patents after the war. For example, Great Britain had passed an early version of its TWEA in September 1914 forbidding all transactions "that would improve the financial or commercial position of a person trading or residing in an enemy country."[10] Similar to the American TWEA, the intent of the British act was "eliminating enemy control from British trade, either by winding-up the business or by transferring the enemy interest to British subjects."[11]

In parallel with the American TWEA, the British Act was extended in 1919 to allow for compulsory licensing. The amended Act required "the Comptroller to grant a compulsory license under a food or medicine patent to anyone who seemed competent to work the invention" (Davenport 1979, p.81). Its explicit purpose was "to limit the power of United Kingdom patents obtained by foreign, especially German, chemical manufacturers" (Davenport 1979, p.26).

Thus, British inventors were subject to a similar treatment by compulsory licensing as U.S. inventors. Even though we cannot identify the exact subclasses that were treated by compulsory licensing in Britain, it safe to assume that German inventors were strong in the same technologies in Britain and the United States, and that British inventors were

[10] This included "paying debts to him, dealing in securities in which he was invested, handling goods destined for him or coming from him, or contracting with him" (Oppenheim and Roxburgh 2005, p. 155)
[11] *House of Commons Debate 08 August 1916 vol. 85 column 871*.

therefore more likely to license German patents in similar subclasses in Britain and the United States. Thus, patenting by British inventors should increase in the same subclasses in the United States as patenting by U.S. inventors.

II. Empirical Strategy

Our empirical strategy compares changes in invention by U.S. nationals across dye stuffs that were differentially affected by the TWEA. Our unit of observation is the number of patents by U.S. inventors in a USPTO subclass for each year between 1875 and 1945.[12] This yields a basic regression equation of the following form:

$$\textit{Patents by U.S. inventors}_{c;t} = \alpha_0 + \beta TREAT_c \bullet post\text{-}TWEAt + \gamma' Zct + \delta_t + f_c + \varepsilon_{ct}$$

where f indicates subclass fixed effects, δ year fixed effects, Z is a vector of control variables and X is a vector of treatment variables.[13] In its simplest form, we define a subclass as being treated if it contained at least one enemy-owned patent that was licensed to a U.S. firm.

A. Controlling for Differences in the Intensity of Treatment

We extend this treatment variable to create two alternative treatment variables which control for the intensity of treatment. First, we control for the number of patents

[12] The USPTO classifies patents according to technology fields. A (main) class generally distinguishes one technology from another. Subclasses differentiate technologies further into processes, structural, and functional features. Subclasses are uniquely identified by an alphanumeric symbol. See http://www.uspto.gov/web/offices/opc/documents/overview.pdf for a detailed description of the USPTO classification system.

[13] The fixed effects in this equation includes estimates for α_1 and α_2, from the standard differences-in-differences equation $\textit{Patents by U.S. inventors}_{c;t} = \alpha_0 + \alpha_1 TREATc + \alpha_2 post\text{-}TWEAt, \beta TREAT_c \bullet post\text{-}TWEAt + \gamma' Zct + \delta_0 + f_c + \varepsilon_{ct}$, where, in our simplest specification, TREAT equals 1 if the subclass includes at least one licensed patent and 0 otherwise and post-TWEA equals 1 for every year between 1919 and 1945.

that were licensed in each subclass (Figure 1). In most subclasses only one patent was licensed, but in a small number of subclasses many patents were licensed. For instance, a total of 8 patents were licensed in the subclass 106/402, which contains “compositions: coating or plastic – lakes”. If the strength of treatment is increasing in the number of licenses, treatment should be more intense in those classes. Thus, we define our first alternative treatment variable as the number of patents that were licensed within a subclass.

The intensity of treatment may have also varied across old and new patents. For example, consider two patents that were both licensed in 1919; the *Old* patent was granted in 1903 and the *New* patent was granted in 1915. A compulsory license for *New* provides a stronger treatment for two reasons. First, *New* was more novel than *Old* at the time it was licensed, which, assuming that technology improves over time makes *Old* more obsolete. Second, the *Old* had only 1 year of patent life left, while *New* was valid for another 13 years.[14] To account for such variation, our second alternative treatment variable measures the total years of remaining patent life across all patents that were licensed within a given subclass (Figure 2)

$$\sum_{i=1}^{I}(\text{years of life of patent } i \text{ in class } c \text{ in 1918})$$

B. Measuring Year-Specific Treatment Effects

One significant benefit of our analysis is that we can measure the long-run effects of compulsory licensing. To take advantage of this benefit, we allow the treatment coefficient β to vary across years. This yields the regression equation

[14] In the early 20th century, U.S. patents expired 17 years after their grant date.

$$\text{Number of patents by U.S. inventors}_{c,t} = \alpha_0 + \beta_t' \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

where β_t measures the difference in domestic patents for more intensely treated subclasses after 1919 compared with less intensely treated subclasses prior to the TWEA.

C. Triple differences

One potential concern with our estimation strategy is that subclasses that were affected by compulsory licensing experienced an increase in innovation due to unobservable characteristics that are correlated with licensing decisions.[15] In other words, although the timing of compulsory licensing is exogenous, the choice of technology fields in which U.S. firms chose to license enemy-owned patents may not be exogenous. Specifically, U.S. firms may have been more likely to license German patents in those subclasses where U.S. invention was weak (Figure 3).

This creates omitted variable bias, which implies that our results may over- or underestimate the true effects of compulsory licensing. On the one hand, a lack of domestic competitors may have encouraged domestic inventors to patent more; OLS would wrongly attribute this effect to compulsory licensing. On the other hand, domestic firms may have lacked the necessary skills to invent in subclasses where U.S. invention was weak; then OLS underestimates the real effects of compulsory licensing. Thus, OLS may either over- or under-estimate the true effects of compulsory licensing, depending on the

[15] For example, U.S. firms may have been more likely to license enemy-owned patents in subclasses where U.S. invention lagged behind the technological frontier. In such subclasses, domestic invention may have increased as a result of compulsory licensing, as domestic firms learned by producing foreign inventions. But domestic inventors may have also learned through other channels that were independent of compulsory licensing, even though they affected the same subclasses. If this is true, our estimation attributes to compulsory licensing what is in fact a result of independent learning of U.S. inventors.

direction of the bias. To address omitted variable bias, we apply a triple difference estimation

Our triple differences estimator compares changes in patents by U.S. inventors with changes in patents by non-German foreign inventors across more and less intensely treated subclasses before and after the TWEA:

$$\text{Number of patents}_{n,c,t} = \alpha_0 + \alpha_1 USA_n + \alpha_{4t} \cdot TREAT_c \cdot postTWEA_t + \alpha_5 \cdot USA_n \cdot TREAT_c + \alpha_{6t} USA_n \cdot postTWEA_t + \beta_t \cdot USA_n \cdot TREAT_c \cdot YEARpostTWEA_t + \delta_t + f_c + \varepsilon_{n,c,t}$$

where USA counts the number of U.S. patents, *TREAT* is a vector of dummy variables that equal 1 for treated subclasses and 0 for untreated classes, *postTWEA* is a vector of dummies that equal 1 for years after 1919 and 0 for years up to 1919. The coefficient β_t is similar to a triple difference estimator, which measures the additional effect of compulsory licensing that affected patents by U.S. inventors compared with patents by other non-German inventors. In contrast to standard triple difference estimators, however, our estimation allows β_t to vary over time.[16]

D. Instrumenting for Compulsory Licensing

We also instrument the licensing decisions of U.S. firms with the pre-TWEA share of German inventors among all foreign inventors. Foreign inventors include inventors from Britain, Switzerland, and France, who received significant numbers of patents (see

[16] In evaluating this coefficient it is important to keep in mind that British inventors, which contributed the second larges number of foreign patents, may have been affected by compulsory licensing in the same way as U.S. inventors, which implies that the triple differences estimator constitutes a lower bound for the true effect of compulsory licensing. *f* indicates subclass fixed effects, δ year fixed effects, *Z* is a vector of control variables and *X* is a vector of treatment variables, as above.

Figure 7), as well as inventors from Argentina, Australia, Austria, Belgium, Brazil, China, India, Italy, the Netherlands, Russia, Scotland, and Spain ("other countries" in Figure 7), who received only a small number of patents. German inventors are also included among foreign inventors.

Intuitively, the share of German inventors among foreign inventors is a good instrument for the licensing decisions of U.S. firms. In subclasses where the share of German inventors is high relative to other foreign inventors, the quality of German inventions is likely to be higher, which makes German patents in these subclasses more attractive for licensing by U.S. firms. On the contrary, the share of German inventors among all inventors is by itself unlikely to affect the development of the U.S. industry after 1919.[17]

Our data confirm that U.S. firms were then more likely to license patents in those subclasses where the share of German inventors among all foreign inventors was high (Figure 14). Given the absolute number of foreign inventors in a subclass, the share of German and Austrian inventors should be exogenous to the development of U.S. R&D, but the share of German and Austrian inventors increases the probability that patents would be licensed from that subclass.

Thus both the intuitive mechanism and the correlations suggest that the share of German inventors among all foreign inventors as a reasonable instrument for licensing. We therefore instrument our main treatment variable (whether a subclass included at least one licensed patent) and our first alternative treatment variable (the number of licensed patents in that subclass) with the share of German and Austrian patents among all foreign patents

[17] Data on foreign inventors suggest that the shock of compulsory licenses during the war did not discourage German inventors from patenting in the United States. The number of German patents begins to recover immediately after 1919; by the late 1920s more than half of all foreign patents are by German inventors.

that were available for licensing in 1919, which includes all patents that were granted to foreign inventors between 1902 and 1918.

$$\frac{\sum_{\tau=1902}^{1918}\sum_{j=1}^{J_\tau} I\{\text{patent } j \text{ in class } c \text{ in year } \tau \text{ has German or Austrian inventor}\}}{\sum_{\tau=1902}^{1918}\sum_{j=1}^{J_\tau} I\{\text{patent } j \text{ in class } c \text{ in year } \tau \text{ has foreign inventor}\}}$$

We instrument our second alternative treatment variable (the total years of remaining lifetime for all licensed patents in a subclass in 1918) with the share of years of remaining lifetime for all licensed patents in a subclass owned by German inventors in 1918 of the total years of remaining lifetime for all licensed patents in a subclass owned by all foreign inventors in 1918.

$$\frac{\sum_{k=1}^{K}(\text{years of life of German or Austrian patent } k \text{ in class } c \text{ in 1918})}{\sum_{l=1}^{L}(\text{year of life of foreign patent } l \text{ in class } c \text{ in 1918})}$$

III. The Data

Our data include close to 699 enemy-owned patents for dyes that were licensed to U.S. firms, as well as 191,292 patents in 21 classes in dyes that contained at least one patent that was licensed under the TWEA.

A. Data on the Treatment: Licensed Enemy-owned Patents

Under the TWEA, the United States confiscated over 4,500 enemy-owned patents for chemical inventions. Of these patents 699 were licensed by the Chemical Foundation between 1919 and 1936 to one or more of 326 U.S. firms (Haynes, 1945). Licensed patents belong to 21 USPTO classes and 336 subclasses (Table 3). We use the distribution of licensed patents across subclasses (Figure 1), along with the distribution of the total remaining years of patent life across subclasses (Figure 2) to construct treatment variables.

B. Data on the Outcome: U.S. Patents 1875-1945

Our outcome variable is the number of patents by domestic inventors per subclass and year. We have collected these data for all 21 USPTO main classes of dyes that included at least one patent that was licensed under the TWEA. Between 1875 and 1945, these 21 main classes included 191,292 patents, which we collect from the USPTO's official website (www.uspto.gov). These patents covered 9,204 subclasses of dyestuff inventions, of which 336 where affected by the TWEA (Figure 4).

Patents by domestic inventors are measured as the difference between all patents and foreign patents in a subclass. Foreign patents are U.S. patents by inventors that reside in Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain and Switzerland. This list includes the nationalities of all inventors that we found by hand-checking 625 patents of alizarin, indigo, azo dyes, and aniline, which Delamare and Guineau (1999) consider the most important dyes in the early 20th century. Inventors' country of origins are identified through keyword searches for country names in the *Lexis Nexis Chronological Patent Files, 1790-1970* (available at www.lexisnexis.com). For example, we assign a patent to be of a German inventor if it contains the word Germany anywhere in title or in the description of the invention.

C. Measurement Error

Our data may also be subject to measurement error in the way we assign patents to inventor nationalities. Specifically, our matching process may overestimate the number of domestic inventors because we miss inventors from any country that is not included in our search. Another type of measurement error results from using Optical Character Recognition (OCR) to identify patents by foreign inventors. OCR is worse at recognizing misspelled names or untidy script than the human eye, which will also lead us to overestimate the number of U.S. inventors.[18]

There is however, no reason to believe that either of these types of measurement errors varies systematically across treated and untreated classes. To get a better idea of the quality of our data, we hand-collected an alternative data set to assess the quality of our data. This alternative data set covers all patents for subclasses that include the most important dyes of the early 20th century (Delamare and Guineau 1999): alizarin, indigo, azo dyes and aniline, yielding 625 dye patents between 1900 and 1943. We assign each of these patents to inventor nationality by carefully reading the full text of each patent. A comparison of the two datasets reveals no major differences in the assignment of patents to inventor nationalities (Table 3) and subclasses (Figure 6). Thus, there is no indication that measurement error varies systematically across treated and untreated classes. Improvements in the quality of OCR will be captured by annual fixed effects.

[18] To identify as many foreign inventors as possible, we define inventors to be foreign if the name of a foreign country occurs anywhere in the document. This overestimates the number of foreign inventors, if the document refers to the foreign country in a context other than identifying the inventor's country of residence. For example, we wrongly assign USPTO patent 1,674,085 to Great Britain, because its inventors (who came from Massachusetts) also applied for a patent in Britain and mentioned this in their patent document. Several cross-checks of our data, however, indicate that this type of error is relatively rare.

D. Attenuation Bias

The USPTO system of subclasses offers an independent mechanism of classifying patents, but it may bias our results. Most importantly, the range (or breadth) of patents that are included in a subclass may vary across classes, which will lead us to underestimate patenting in subclasses that are narrowly defined. Moreover, inventors' propensity to patent may vary across subclasses and technology fields (Lerner 1995, Moser 2007), which could also bias our results. We address these issues by using class-fixed effects in all regressions.

Another consequence of relying on the USPTO classification system is that we may underestimate the true effects of compulsory licensing. Specifically, our current estimation approach assumes that the effects of compulsory licensing are limited to inventors in the same class. Due to the relatively narrow definition of USPTO classes, however, it is likely that licensing in one subclass also benefits inventors in other classes.[19] In other words, our estimation strategy ignores the externalities of licensing across subclasses. Thus, our treatment could also affect our control group, which will lead us to underestimate the true effects of compulsory licensing.[20]

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[19] To state this more formally, our estimation violates the stable unit treatment value assumption (SUTVA) because there is some interference between treated and untreated units (Rubin 1990, p. 282). If SUTVA were satisfied, our empirical estimation would measure the difference between a world where some subclasses are treated by compulsory licensing and another where compulsory licensing does not exist. But SUTVA is not necessary for measuring a causal effect as long as we can define precisely what we mean by a causal effect. We define causal effects as the difference in the actual number of domestic inventors in a treated subclass and the counterfactual number of domestic inventors in that subclass if it had not been treated by compulsory licensing. Then our estimated effect is the difference between the observed number of domestic inventors for every treated subclass and the number of domestic inventors that would have been observed in each subclass without compulsory licensing. We define the average effect for the treated (ATT) to be the average of these estimated subclass-level effects. It is important to keep in mind that this ATT does not measure the average difference in potential outcomes that would have been observed if all selected subclasses had been subject to compulsory licensing and all others had not (as it would under SUTVA). Most importantly, our empirical strategy requires additional assumptions about how subclasses are assigned to treatment, which we describe in more detail in the text.

[20] We could capture some of these spillover effects by combining subclasses that cover similar technologies, which would, however, be subjective. Instead, we plan to measure spillovers across subclasses by matching

IV. Results

A. Least squares with subclass and year fixed effects

Estimation results of our most basic equation

$$\text{Number of patents by U.S. inventors}_{c,t} = \alpha_0 + \beta \cdot TREAT_c \cdot postTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

show that the correlation between compulsory licensing and an increase in patenting by domestic inventors is high and statistically significant (Table 4).[21] Treated subclasses (where at least one patent was licensed under the TWEA) generate an additional 0.3 patents more for every year between 1918 and 1945 (column I). In comparison, the average subclass produces approximately 0.7 patents between 1918 and 1945. All effects are significant at the 1 percent level.

Controlling for the intensity of treatment strengthens these results. An additional licensed patent raises the annual number of patents by domestic inventors by an average of 0.142 patents per year (column II). OLS also suggest that the marginal effect of additional patents is decreasing.[22] As above, all effects are significant at the 1 percent level.

An additional year of patent life raises the number of annual patents in the treated subclass by 0.0115 patents per year (column IV). This implies that licensing a new patent

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our data set of licensed patents with the NBER Patent Citation Data File (Hall, Jaffe, and Trajtenberg 2001), which includes all citations to U.S. patents that were granted between 1975 and 2002. If the subclasses of citing patents differ from the subclasses of licensed patents, our analysis underestimates the effect of compulsory licensing.

[21] As above f indicates subclass fixed effects, δ year fixed effects; Z is a vector of control variables and X is a vector of treatment.

[22] A negative coefficient on the squared number of licensed patents suggests that the effect of additional patents may become negative when more than 14 patents are licensed in a subclass (compared with an average of 0.7 annual patents per subclass). This effect, however, is dependent on the functional form of our estimation equation. In our data, only 2 o more than 9,000 subclasses had more than 14 licensed patents. This implies that the effect of an additional year of remaining patent life becomes negative when more than 187 years of patent life are added to the remaining lifetime of all licensed patents in a subclass. This number corresponds to roughly 11 new patents in 1918, consistent with the results when treatment is defined as the number of licensed patents.

in 1918, which had 17 years of life left, increases patenting by nearly 0.2 patents per year, while an older patent, which had just one year of life left, only increase patenting by 0.115 patents per year. Similar to the case above (when treatment is defined as the number of licensed patents), the marginal effects of additional patents is decreasing. Again all effects are significant at the 1 percent level.[23]

B. Year-specific Treatment Effects

We take advantage of the long run nature of our historical data to identify the timing of the effect of compulsory licensing. Specifically, we estimate year-specific treatment effects, where β_t measures the effect of compulsory licensing on patents by domestic inventors in year t

$$\text{Number of patents by U.S. inventors}_{c,t} = \alpha_0 + \beta_t' \cdot TREAT_c \cdot YEARpostTWEA_t + \gamma \cdot Z_{c,t} + \delta_t + f_c + \varepsilon_{c,t}$$

In our simplest specification treated subclasses are defined as classes where at least one patent was licensed under the TWEA.

These data suggest that the effect of compulsory licensing on domestic inventors takes about 10 years to fully materialize (Figure 8). For treated subclasses, the effect of licensing on the number of patents by domestic inventors becomes stable and statistically significant around 1932 (at 5 percent, Figure 8). Patents are measured at their grant date, and it takes at least two years for a patent to progress from application to granting.[24] Thus,

[23] These results are robust to the introduction of linear and quadratic subclass-specific time trends.
[24] The lag between application and grant date varies over time. In a random sample of 20 chemical patents in our data set, patents were granted up to five years after the application, compared to an average of two years for 19th century innovations (e.g., Moser 2007, Lampe and Moser 2008).

patenting by domestic inventors begins to increase significantly about 10 years after licensing. The results, however, also suggest that a small effect was already present in the late 1920s; the year-specific treatment coefficient β_t is first significant in 1927.

The data also show that the effect on compulsory licensing is persistent throughout the 1930s. After 1932, treated subclasses produce between 0.4 and 0.6 additional patents per year. At the end of our sampling period, in 1945, subclasses that were affected by compulsory licensing continue to generate approximately 0.4 additional patents per year compared with unaffected subclasses. This significant and persistent increase in domestic patents is robust to controls for differences in the intensity of treatment.

Adjusting for the intensity of treatment through the number of licenses per subclass confirms that compulsory licensing had a statistically significant patents effect on patenting by U.S. inventors since the early 1930s, although the year-specific treatment effect are positive and statistically significant in 1927 already. When treatment is defined as the number of licenses per subclass and year, point estimates suggest that an additional license generates between 0.2 and 0.3 additional patents in the early 1930s, compared with 0.05 in second half of the 1920s. When treatment is defined as the total number of years of remaining patent life, estimates suggest an equally persistent effect in the early '30s and a less precisely estimated effect starting in the late 1920s (Figure 10)..[25]

[25] We also repeat our regressions including both types of treatment: the simplest specification of treatment where *TREAT = 1* if a subclass receives at least one license as well as one of the two intensity-adjusted forms of treatment. Specifically, we include controls for the number of licenses per subclass (in addition to our simplest measure of treatment that a subclass was affected by compulsory licensing), which yields the estimation equation

$$\textit{Patents by U.S. inventors}_{c;t} = \alpha_0 + \beta(\textit{Dummy=1 if subclass received at least once license}) \bullet \textit{post-TWEA}_t + \xi_t (\textit{Number of licenses})_c \bullet \textit{post-TWEA}_t + \gamma' Zct + \delta_t + f_c + \varepsilon_{ct}$$

The equivalent regression with our second intensity-adjusted treatment variable as a control (remaining lifetime of all licensed patents) yields the equation

$$\textit{Patents by U.S. inventors}_{c;t} = \alpha_0 + \beta(\textit{Dummy=1 if a subclass includes at least license})_c \bullet \textit{post-TWEA}_t + \xi_t (\textit{Remaining lifetime for all licensed patents})_c \bullet \textit{post-}$$

C. Triple differences

Triple differences account for omitted variables that affect all non-German inventors by comparing changes in treated and untreated classes before and after the TWEA across U.S. and other non-German inventors. Triple difference estimate confirm that compulsory licensing had a significant positive effect on domestic invention (Figure 11). Subclasses that received at least one license during the TWEA began to produce more patents by domestic inventors around 1926, and had consistently larger number of domestic invention in the 1930s. Compared with patents by other non-German inventors, U.S. inventors produced 0.4 more patents in the 1930s (significant at 5 percent, Figure 11) in subclasses that were affected by the TWEA. This effect is especially significant compared with the average 0.7 patents per subclass and year. Equivalent regressions for intensity-adjusted measures of treatment (number of licenses and remaining patent years for all licensed patents) confirm this effect.

E. Instrumental variable estimation

As discussed above, omitted variables may bias the OLS results of OLS. To address this issue, we instrument compulsory licensing with the share of German inventors among all foreign inventors. Instrumental variable results suggest that OLS estimates are downward biased.

First stage regressions of our treatment variables on alternative specifications of the instruments (the share of patents by German inventors and the share of patent years owned

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$TWEA_t + \gamma' Zct + \delta_t + f_c + \varepsilon_{ct}$

Estimating time-varying treatment coefficients confirms that patenting was responsive to the intensity of treatment and that the effect of compulsory licensing was particularly large in the early 1930s.

by German inventors) indicate that our instruments are strongly and significantly correlated with the treatment (Table 5). For example, first stage results imply that U.S. firms are 20 percent more likely to license a German patent within a subclass where all of the foreign inventors are German than they would be from a subclass where only half of the foreign inventors are German (2*10 percent, from column I). Similarly, U.S. inventors license on average 0.4 more patents in a subclass where all foreign inventors are German than they would in a subclass where only half of the German inventors are German (2*0.2 from column II).

Second stage estimates for the instrumental variable regressions imply a substantially higher treatment effect than OLS. In subclasses were at least one patent was licensed, domestic inventors produced an average of 14 additional patents per year between 1918 and 1945 (Table 6, column I). Controlling for the intensity of treatment suggests that each additional licensed patent increased the number of patents by domestic inventors by 6 patents per year (Table 6, column III),. Each additional year of patent life added half a patent by domestic inventors per year (Table 6, column V).

These results are based on a subset of our sample. Because our instrument is the share of German inventors among all foreign inventors, subclasses without foreign inventors in the years from 1902 and 1918 were dropped from the IV regressions. Thus the IV sample includes only 3,664 subclasses compared with 9,204 subclasses in the OLS sample. To account for this, we repeat our OLS regressions on this restricted sample (Table 6). OLS estimates for the restricted sample are slightly smaller, but they remain positive and statistically significant at the 1 percent level.[26]

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[26] Instrumental variable where the instrument is set to 0 for these missing observations yields qualitatively and quantitatively similar results. These regressions can be run on the entire sample.

IV. Robustness checks

This section presents a series of robustness checks for our results, including controls for subclass-specific time trends, a block bootstrap to account for serial correlation, an analysis of compulsory licensing at the level of primary subclasses, and at the level of an individual dye (indigo), and several tests of placebo treatments.

A. Controlling for Subclass-specific Time Trends

One potential problem with the difference-in-differences estimation is that it may confound the dynamic effects of compulsory licensing with pre-existing differences in time trends across treated and untreated subclasses. In other words, subclasses that were affected by compulsory licensing may have experienced an increase in domestic patenting after the TWEA due to differences in time trends that *preceded* the TWEA. To address this issue, we extend the regressions to include subclass-specific time trends in addition to the year-specific treatment effects and year fixed effects:[27]

$$\textit{Number of patents by U.S. inventors}_{c;t} = \alpha_0 + \beta_t\, \textit{TREAT} \bullet \textit{post-TWEA}_t + \gamma' Zct + \phi_c \bullet t + \delta_t + f_c + \varepsilon_{ct}$$

where β_t measures treatment effects in year t and δ_t captures year fixed effect *controlling for subclass specific time trends*.[28] Untreated subclasses are affected only by the coefficient δ_t, whereas treated subclasses are affected by both β_t and δ_t.

[27] This methodology follows Wolfers (2007), who uses it to separate the dynamic effects of a shift towards no-fault divorce on divorce rates from pre-existing differences in time trends in divorce rates across states. We have repeated all regressions with quadratic time trends, but quadratic time trends are not statistically significant.

[28] Including class fixed effects along with linear time trends and quadratic fixed effects increases the number of right hand side variables by a lot. Thus we restrict this analysis to subclasses in the two main classes 8 and 534 where the largest number of patents were licensed (Table 2). This still yields nearly 2,500 right hand

Given the large number of subclasses, we cannot estimate the expanded regression for the entire data set; it would estimate about 20,000 coefficients, including 9,204 class fixed effects and 9,204 linear time trends in addition to time dummies, treatment variables, and controls. To address this constraint, we restrict our sample to subclasses in two main that included the largest number of licenses (classes 8 and 534, Table 2). These two classes include a total of 776 subclasses (which yield about 1,800 coefficients.)

Results shows that even after controlling for subclass-specific time trends, the number of domestic patents increased significantly more in treated subclasses than in untreated subclasses after the TWEA. Year-specific treatment coefficients are significant at the 5 percent or 1 percent level for 18 years and at the 10 percent level for 5 years between 1919 and 1945.

To repeat this test on the entire data set, we introduce *treatment-specific* time trends. Specifically, we re-estimate the above equation that includes subclass-specific time trends, allowing time trends to vary only between treated and untreated classes, estimating a single time trend for all treated classes.

$$\textit{Number of patents by U.S. inventors}_{c;t} = \alpha_0 + \beta_t \, \textit{TREAT} \bullet \textit{post-TWEA}_t + \gamma' Zct + \phi \, \textit{TREAT} \bullet t + \delta_t + f_c + \varepsilon_{ct}$$

Even controlling for treatment-specific time trends, year-specific treatment coefficients β_t are significant at the 1 percent level (Figure 12).

B. Block bootstraps to account for serial correlation

side variables: 776 subclasses, which yields nearly 2,500 right-hand-side variables: 776 fixed effects, 776 linear time trends, and 776 quadratic time trends, in addition to other variables, such as time dummies, treatment variables and controls.

Given the long time series of our data we also want to account for serial correlation in the outcome variable (the number of patents by domestic inventors per subclass and year), which could lead us to understate the standard error of the treatment coefficient β. In estimations with a large number of groups a block bootstrap, which maintains the autocorrelation structure within groups by keeping observations in the same group together, has been shown to perform best (Bertrand, Duflo, Mullainathan 2004).[29] Applied to our specific case, the block bootstrap maintains the structure of correlations at the level of subclasses, as it samples subclasses instead of observations (the number of patents per subclass and year). Specifically, we randomly draw subclasses with replacement, estimate OLS on each boot-strapped sample, and record coefficients and standard errors to compute the absolute t-statistic $t_r = abs\,(\hat{\beta}_r - \hat{\beta})/SE(\hat{\beta}_r)$. We draw a large number (79) bootstrapped samples, and reject the hypothesis that $\beta = 0$ at a 99 percent confidence interval if the 99 percent of the t_r are smaller than the t-statistic of our original regression.[30] The results of this block bootstrap estimation confirm that all treatment coefficients are significant at the 1 percent level (Table 6).

C. Restricting the Sample to Primary Subclasses

We also check our regressions by restricting the sample to primary subclasses. As described in the data section, patents may be assigned to one or more secondary

[29] With OLS low standard errors due to serial correlation in the dependent variables can lead to significant differences-in-differences estimates of a treatment effect, even if the treatment is artificial and assigned as a placebo. Even when standard errors are clustered at the level of groups, serial correlation may produce significant coefficients with placebo treatments. This problem seems to be less severe when the number of groups is large (as is true in our case). In simulations, the block bootstrap is least likely to produce significant coefficients for placebo treatments (Bertrand, Duflo, and Mullainathan (2004)), which is why we perform the block bootstrap sampling as a robustness check.

[30] 79 repetitions were set at random by the crashing of a computer. The sampling distribution of t_r is random and changing in N (the number of subclasses). As the number of groups increases, the difference between the distribution of t_r and the distribution of the t-statistic for the original regression tend to zero.

subclasses, in addition to their primary subclass. Because a compulsory license affects both primary and secondary subclasses, we include secondary subclasses in all analyses. As a robustness check, however, we restrict our sample to primary subclasses. If including secondary subclasses puts a lot of weight on patents that belong to many subclasses, the estimated coefficients from this restricted sample (which includes 7,513 subclasses instead of 9.204) should differ substantially from the estimated coefficients of the full sample.[31]

Estimation results from the restricted confirm that compulsory licensing encourages domestic invention (Table 5). In primary subclasses that received at least one license under the TWEA, patenting increased by about 0.05 patents per year after the TWEA (Table 5, column I), compared with an average of 0.2 patents per primary subclass per year over that period. Controlling for the intensity of treatment suggests that an additional license generated an additional 0.03 patents per treated primary subclass and year (Table 5, column II). An additional year of patent life generated 0.003 additional patents per primary subclass and year. These results are significant at the 1 percent level.

D. Controlling for a Demand Shock in a Subsample of Indigo Patents

Another potential concern with our identification strategy is that the increase in domestic invention may be caused by a demand shock for the U.S. dyestuffs industry that was caused by World War I, even without compulsory licensing. Specifically, World War I cut off imports of dyes from Germany, but it also increased demand for certain dyes. For instance, the war increased demand for indigo, which was required to create the blue shade of Navy uniforms (e.g., Navy Department, 1917). Given the narrow definition of

[31] Eliminating secondary subclasses -- which cross-reference related technology areas -- may also reduce correlation across subclasses; this is important because both clustering at the level of subclasses and the block bootstrap at the level of subclasses assume that the number of patents is independent across subclasses.

subclasses, it is not unreasonable to assume that the demand shock affected both treated and untreated subclasses *within* indigo; we examine such variation as a robustness check.

Price data show that the shock that World War I created for chemical prices preceded the TWEA, and that prices had returned to pre-war levels by 1919. Compared with the general price index an index for the wholesale price of chemicals increased by almost 50 percent in 1915, but it declined almost as rapidly as it had increased (Figure 16).

The demand shock was particularly strong for indigo. Before the war the United States consumed 8,000,000 pounds a year of indigo, 90 percent imported from Germany. Between June 1914 and June 1915, this quantity did not change, but the price of indigo rose by 50 percent. From June 1915 onwards no indigo was imported from Germany, but the price of indigo quadrupled between 1914 and 1916. Data from the U.S. Tariff Commission show that the price shock for indigo was more persistent, but it, too, lost much of its force by 1919. The price of indigo increased from less than 20 cents per pound (in real prices) before World War I to almost 70 cents in 1917. By 1919, the price of indigo had dropped back to approximately 40 cents (Haynes 1945, p. 231).

To analyze the effect of indigo, we identified all U.S. patents of indigo between 1875 and 1945. In practice, this meant searching *Lexis Nexis Chronological Patent Files, 1790-1970* for the keyword "indigo"; our search returned 1,253 patents. Merging this list with our data set on U.S. patents yields 843 patents of indigo between 1875 and 1940; these indigo patents cover a total of 849 subclasses.

OLS regressions of the indigo sample confirm that treated subclasses were significantly more likely to experience an increase in domestic patents (Table 9). Analyses of year-specific treatment effect show that year-specific treatment effects become stable and statistically significant around 1931, even though there are positive and statistically significant effect in the late 1920s. Partly because of the small number of observations in this subsample, the treatment effect ceases to be statistically significant in the late 1930s.

E. Placebo Treatments

Another potential shortcoming of empirical strategy is that our results may be driven by random correlation between other explanatory variables and actually be independent of the treatment. To address this issue, we create a placebo treatment which randomly assigns subclasses to be "treated" (e.g., Di Giorgi 2007). The share of subclasses that are randomly assigned to the placebo treatment is equal to the share of subclasses that are treated under the TWEA (3.65 percent). We re-estimate our most basic regression equation 50 times with a randomly selected placebo treatment. In these tests, the hypothesis that the placebo treatment is significant is rejected for 45 of 50 placebos at the 5 percent level.[32]

An alternative placebo treatment predates the "treatment" by a random number of years. In this case, we artificially predate the treatment by 10 years, to 1905. If the increase in patenting by domestic inventors in treated classes is due to pre-existing trends this test will show a significant effect of the TWEA before it actually occurs. More formally, we estimate

$$\textit{Patents by U.S. inventors}_{c;t} = \alpha_0 + \beta_t\, YEAR_t \bullet TREAT_c \bullet post\text{-}1905_t + \gamma' Zct + \delta_t + f_c + \varepsilon_{ct}$$

This specification allows for year-specific treatment effects beginning in 1905 (β_t for t = 1905,…, 1945) instead of 1919 in the other specifications. Thus, between 1905 and 1918,

[32] See Table 7 for a random sample of these 50 tests. These results are without clustering the standard errors at the level of subclasses; clustered standard errors would yield even higher rejection rates.

coefficients β_t between 1905 and 1918 create a placebo treatment. For years between 1919 and 1945, treatment continues to be measured by coefficients β_t.

Regression results indicate that the pre-TWEA placebo treatment had no effect prior to the TWEA. Estimates of δ_t for untreated subclasses and $\delta_t + \beta_t$ for treated classes suggest that there is no difference in domestic patenting for treated and untreated classes prior to the TWEA (Figure 18).

An additional robustness check, repeats the pre-TWEA placebo treatment for patents by French inventors. Similar to the United States, France did not have a strong presence in organic chemistry. Thus, French inventors may have benefitted from the absence of German inventors during the war. In our data, 3,000 patents, approximately 1.7 percent, were granted to French inventors[33]. Estimating year-specific treatment effects shows no clear effect of this pre-TWEA placebo treatment on patenting by French inventors (Figure 19)..

V. Conclusions

This paper has used the Trading with the Enemy Act as a natural experiment to examine whether compulsory licensing encourages domestic invention. Our analysis indicates that compulsory licensing has a strong and persistent positive effect on domestic invention. In USPTO subclasses, where at least one enemy-owned patent was licensed to a under the TWEA, U.S. inventors produced an average of 0.3 additional patents per year after the TWEA. These results are robust to controlling for the intensity of treatment.

[33] As we explained above, the nationality of inventors in measured with some error and it is therefore possible that some U.S. inventors or from other countries belong to this group.

Instrumental variable estimates suggest that OLS estimates are a lower bound for the real effect of compulsory licensing.

Our historical data also allows us to measure the timing of the effect of compulsory licensing. This analysis suggests that the effect of compulsory licensing only materializes after 10 years and proves highly persistent over time. Although these results are surprising, they are intuitive: countries that lack the ability to innovate in specific sectors take several years to build their domestic capacity to invent, even if they have free access to foreign inventions. Despite their importance, contemporary analysis may underestimate these long-run effects, which can only be captured in long-run estimations.

References

Arrow, Kenneth. "The Economic Implications of Learning by Doing." *Review of Economic Studies* 29.3 (1962): 155-173.

Branstetter, Lee, Ray Fisman, and Fritz Foley. "Do Stronger Intellectual Property Rights Increase International Technology Transfer? Empirical Evidence from U.S. Firm-Level Panel Data." *Quarterly Journal of Economics* 121.1 (2006): 321-349.

Chien, Colleen. "Cheap Drugs at What Price to Innovation: Does the Compulsory Licensing of Pharmaceuticals Hurt Innovation?" *Berkeley Technology Law Journal* (2003).

Davenport, A. Neil. *The United Kingdom Patent System*, Homewell, UK: Kenneth Mason, 1979.

Di Giorgi, Giacomo, Michele Pellizzari and Silvia Radaelli, "Be as Careful of the Books You Read as of the Company You Keep. Evidence on Peer Effects in Educational Choices", IZA discussion paper No. 2833, 2007

Delamare François and Bernard Guineau, "Colors – The Story of Dyes and Pigments", Harry N. Adams Inc., 1999

Galvão, J. "Access to Antiretroviral Drugs in Brazil." *The Lancet* 360.9348 (2002): 1862-1865.

Genesove, David ,”The Dye Famine and its Aftermath: Knowledge Diffusion and Entry” (October 2006). CEPR Discussion Paper No. 5890.

Gilbert, Richard, and Carl Shapiro. “Optimal Patent Length and Breadth.” *RAND Journal of Economics* 21.1 (1990): 106-112.

Gostin, Lawrence O. “Medical Countermeasures for Pandemic Influenza: Ethics and the Law.” *Journal of the American Medical Association* 295.5 (2006): 554-556.

Haber Ludwig Fritz, "The Chemical Industry, 1900-1930: International Growth and Technological Change", Clarendon Press, 1979

Hall, Bronwyn H., Adam B. Jaffe, and Manuel Tratjenberg (2001). "The NBER Patent Citation Data File: Lessons, Insights and Methodological Tools." NBER Working Paper 8498.

Haynes Williams, “American Chemical Industry – The World War I Period 1912-1922”, Vol.III, D. Van Nostrand Company, 1945

Helpman, Elhanan. “Innovation, Imitation, and Intellectual Property Rights.” *Econometrica* 61.6 (1993): 1247-1280.

House of Commons, *The Official Report*, (5th Series) Vol 1 (Jan 1909) to Vol 1000 (March 1981).

Oppenheim, Lassa and Ronal Roxburgh, *International Law: A Treatise*, The Lawbook Exchange, Ltd., 2005.

Steven Ruggles, Matthew Sobek, Trent Alexander, Catherine A. Fitch, Ronald Goeken, Patricia Kelly Hall, Miriam King, and Chad Ronnander. Integrated Public Use Microdata Series: Version 4.0 [Machine-readable database]. Minneapolis, MN: Minnesota Population Center [producer and distributor], 2008.

Kremer, Michael. “Pharmaceuticals and the Developing World.” *Journal of Economic Perspectives* 16.4 (2002): 67-90.

Lampe, Ryan, and Petra Moser. “Do Patent Pools Encourage Innovation? Evidence from the 19th-century Sewing Machine Industry”, Stanford University working paper, 2008.

Lerner, Joshua. “100 Years of Patent Protection.” *American Economic Review Papers and Proceedings*, 92 (May 2002) 221-225.

Lerner, Joshua, “Patenting in the Shadow of Competitors” *Journal of Law and Economics,* 38.2 (October1995): 463-95.

Mansfield, Edwin. “Intellectual Property Protection, Direct Investment, and Technology Transfer: Germany, Japan, and the United States.” *International Journal of Technology Management* 19.1 (2000): 3-21.

Moser, Petra. “Why Don’t Inventors Patent?”, *NBER Working Paper No. W13294,* August 2007.

Navy Department, *Uniform Regulations, United States Navy, Together with Regulations Together with Regulations Common to Both Navy and Marine Corps*, Washington, DC: Government Printing Office, 1917.

Rubin, Donald B. Formal Modes of Statistical Inference For Causal Effects. Journal of Statistical Planning and Inference. 25 (1990), 279-292.

Ruggles, Steven, Matthew Sobek, Trent Alexander, Catherine A. Fitch, Ronald Goeken, Patricia Kelly Hall, Miriam King, and Chad Ronnander. *Integrated Public Use Microdata Series: Version 4.0.* Minneapolis, MN: Minnesota Population Center, 2008.

Steen, Kathryn. “Patents, Patriotism, and "Skilled in the Art" USA v. The Chemical Foundation, Inc., 1923-1926”, *Isis*, 92.1 (2001): 91-122.

United States, and Thomas H. Norton. 1916. *Artificial dyestuffs used in the United States*. Washington: Government Printing Office.

Tandon, Pankaj. “Optimal Patents with Compulsory Licensing.” *Journal of Political Economy* 90.3 (1982): 470-486.

United States Tariff Commission,, “Census of Dyes and Coal-tar Chemicals”, several years, Tariff Information Series No.11, Government Printing Office, Washington, 1918-1923

Yang, Guifang, and Keith E. Maskus. “Intellectual Property Rights, Licensing, and Innovation in an Endogenous Product-Cycle Model.” *Journal of International Economics* 53.1 (2001): 169-187.

Williamson, Samuel H. "Five Ways to Compute the Relative Value of a U.S. Dollar Amount, 1790 to Present," *MeasuringWorth*, 2008

Wolfers Justin, 2006, “Did Unilateral Divorce Raise Divorce Rates? A Reconciliation and New Result”, *American Economic Review*, 96(5), December, pp.1802-1820

TABLE 1 – TWEA TRUSTS BY NATIONALITY OF ENEMY

Nationality	Number of trusts	Estimated value
German enemies	17,339	326,855,090.39
Austrian enemies	7,580	39,555,557.34
Interned enemies	140	3,457,898.17
American enemies	648	91,866,053.40
Other enemies	1,567	40,371,354.63
Net income from Treasury investments	-	839,770.82
Total	**27,274**	**502,945,724.75**

Notes: In nominal 1919 dollars; from *Custodian of Alien Property Report, 1919*.

TABLE 2 – MAIN USPTO CLASSES FOR DYES

Class	Title	Licenses
534	Organic Compounds—Containing a noble gas	133
8	Bleaching and dyeing; fluid treatment and chemical modification of textiles and fibers	47
552	Organic Compounds—Azides	27
548	Organic Compounds—Containing 5-membered hetero rings	23
544	Organic Compounds—Containing 6-membered hetero rings with at least one nitrogen	16
106	Compositions: coating or plastic	14
546	Organic Compounds—Containing 6-membered hetero rings with 5 carbons and 1 nitrogen	14
549	Organic Compounds—Containing sulfur hetero rings	11
528	Synthetic resins or natural rubbers	10
564	Organic Compounds—Containing amino nitrogen	7
562	Organic Compounds—Persulphonic acids and salts	6
536	Organic Compounds—Carbohydrates and derivatives	3
172	Earth working	2
74	Machine element or mechanism	1
101	Printing	1
192	Clutches and power-stop control	1
204	Chemistry: electrical and wave energy	1
416	Fluid reaction surfaces (i.e., impellers)	1
430	Radiation imagery chemistry: process, composition, or product thereof	1
568	Organic Compounds—Containing boron	1
570	Organic Compounds—Containing halogen	1

Notes: Data from Haynes (1945) and *www.uspto.gov*. Licenses refer to the total number of enemy-owned patents that were licensed to U.S. firms by the Chemical Foundation. Class numbers and class names refer to main classes within the USPTO system of classifying patents. Main classes are divided into subclasses, which are the unit of observation for this analysis. Our data include all main classes of dyes from which at least one enemy-owned patent was licensed to a U.S. firm.

TABLE 3 – INVENTOR NATIONALITY ASSIGNED BY HAND VERSUS SEARCH

Inventor Nationality	Hand-collected	Algorithm
United States	241	290
German	226	197
Other foreign	159	138
Total	625	625

Notes: Based on a sample of 649 patents between 1900 and 1943. Data from Haynes (1945), www.uspto.gov, www.lexisnexis.com, and www.patents.google.com. To collect our data on inventor nationality, we create an algorithm that performs keyword searches on LexisNexis. Our algorithm relies on Optical Character Recognition (OCR) to recognize keywords. OCR is worse at recognizing misspelled names or untidy script than the human eye. Thus we hand-collected an alternative data set to get an idea of the size of measurement error. Our hand-checked data include all 625 patents of dyes in what Delamare and Guineau (1999) consider the most important dyes in the early 20th century: alizarin, indigo, azo dyes, and aniline. In the hand-collected sample, all inventors come from one of the following countries: Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

TABLE 4 - OLS, DEPENDENT VARIABLE IS PATENTS BY U.S. INVENTORS PER USPTO SUBCLASS AND YEAR (1875-1945)

	I	II	III	IV	V	VI	VII
Subclass has at least one license	0.304***						
	(0.0435)						
Number of licenses		0.142***	0.0882***	0.136***			
		(0.0273)	(0.0217)	(0.0288)			
Number of licenses squared		-0.00989***					
		(0.00256)					
Remaining lifetime of licensed patents					0.0115***	0.00788***	0.0118***
					(0.00232)	(0.0017)	(0.00212)
Remaining lifetime of licensed patents squared					-0.0000617**		
					(0.0000268)		
Number of patents by foreign inventors	0.144***	0.352***	0.353***		0.352***	0.353***	
	(0.00738)	(0.0185)	(0.0185)		(0.0185)	(0.0185)	
Subclass fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	653,484	653,484	653,484	653,484	653,484	653,484	653,484
Number of subclasses	9,204	9,204	9,204	9,204	9,204	9,204	9,204

Robust standard errors clustered at the subclass level in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Note: Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. These 21 main classes are subdivided into 9,204 subclasses. Data on inventor nationality are based on a key word search of the *Lexis Nexis*. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

TABLE 5 – OLS, DEPENDENT VARIABLE IS PATENTS BY U.S. INVENTORS PER USPTO SUBCLASS AND YEAR (1875-1945) – SAMPLE RESTRICTED TO PRIMARY SUBCLASSES

	I	**II**	**III**
Subclass has at least one license	0.049***		
	(0.016)		
Number of licenses		0.030***	0.003***
		(0.009)	(0.0006)
Remaining lifetime of licensed patents			
Number of patents by foreign inventors	0.196***	0.197***	0.197***
	(0.014)	(0.014)	(0.014)
Subclass fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	533,423	533,423	533,423
Number of subclasses	7,513	7,513	7,513

Robust standard errors clustered at the subclass level in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Note: Each patent is assigned to one primary subclass, and may be assigned to one or more secondary subclasses. While other regressions include all subclasses that appear on a patent document, this regression includes only primary subclasses. This restricts the data to 7,513 subclasses in the 21 main classes. Primary subclasses in this sample produce an average of 0.2 patents per year. Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexi*s. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

TABLE 6 – CONFIDENCE INTERVAL OF THE BLOCK BOOTSTRAP COEFFICIENTS

Treatment coefficient	**99% confidence interval**		**BDM test**
Subclass includes at least one license	0.1116936	0.2992342	99%
Number of licenses	0.0582361	0.1428935	99%
Remaining lifetime of licensed patents	0.005129	0.0113065	99%

Note: Data from www.uspto.gov and the Lexis Nexis Chronological Patent Files (1790-1970). Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. These 21 main classes are subdivided into 9,204 subclasses. Data on inventor nationality are based on a key word search of the Lexis Nexis. Confidence interval obtained by running OLS regressions on 80 block bootstrap samples of the original dataset as in Bertrand *et al.* (2004), that draw entire subclasses to maintain the structure of correlation constant.

TABLE 6 – INSTRUMENTAL VARIABLES FIRST STAGE:
DEPENDENTS VARIABLES ARE ALTERNATIVE MEASURES OF TREATMENT

	Subclass includes at least one license	**Number of licenses**	**Remaining lifetime of licensed patents**
Patents (by Germans inventors/ all foreign inventors)	0.097***	0.210***	
	(0.001)	(0.003)	
Remaining lifetime of patents (owned by Germans/ by all foreign inventors)			2.6345***
			(0. 038)
Constant	0.000	0.000	0.000
	(0.002)	0.005	(0.067)
Subclass fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	260,144	260,144	260,144
Number of subclasses	3,664	3,664	3,664

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Notes: Data from www.uspto.gov and the Lexis Nexis Chronological Patent Files (1790-1970). Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. These 21 main classes are subdivided into 9,204 subclasses. Data on inventor nationality are based on a key word search of the Lexis Nexis. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

TABLE 7 – INSTRUMENTAL VARIABLE SECOND STAGE
DEPENDENT VARIABLE IS PATENTS BY U.S. INVENTORS PER USPTO SUBCLASS AND YEAR (1875-1945)

	Patents by U.S. inventors	**(OLS)**	**Patents by U.S. inventors**	**(OLS)**	**Patents by U.S. inventors**	**(OLS)**
Subclass includes at least one license	14.69***	0.112***				
	(0.238)	(0.019)				
Number of licenses			6.791***	0.069***		
			(0.116)	(0.008)		
Remaining lifetime of licensed patents					0.531***	0.006***
					(0.009)	(0.0006)
Constant	0.267***	0.267***	0.267***	0.267***	0.267***	0.267***
	(0.0399)	(0.22)	(0.0423)	(0.22)	(0.0427)	(0.22)
Subclass fixed effects	Yes		Yes		Yes	
Year fixed effects	Yes		Yes		Yes	
Observations	260,144		260,144		260,144	
Number of subclasses	3,664		3,664		3,664	

Robust standard errors clustered at the subclass level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note: Data from www.uspto.gov and the Lexis Nexis Chronological Patent Files (1790-1970). Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. These 21 main classes are subdivided into 9,204 subclasses. Data on inventor nationality are based on a key word search of the Lexis Nexis. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment these lists to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

TABLE 8 - OLS RESULTS WITH PLACEBO TREATMENT

	I	II
Placebo treatment (random assignment to treatment)	-0.001	0.004
	(0.0104)	(0.0105)
Number of patents by foreign inventors	0.356***	
	(0.003)	
Constant	0.141***	0.143***
	(0.010)	(0.010)
Subclass fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	653,484	653,484
Number of subclasses	9,204	9,204

Robust standard errors clustered at the subclass level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note: The placebo treatment group has been created by randomly assigning treatment to 3.65% of subclasses, which is proportion of subclasses in our sample that included at least one license under the TWEA. Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. These 21 main classes are subdivided into 9,204 subclasses. Data on inventor nationality are based on a key word search of the Lexis Nexis. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment these list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

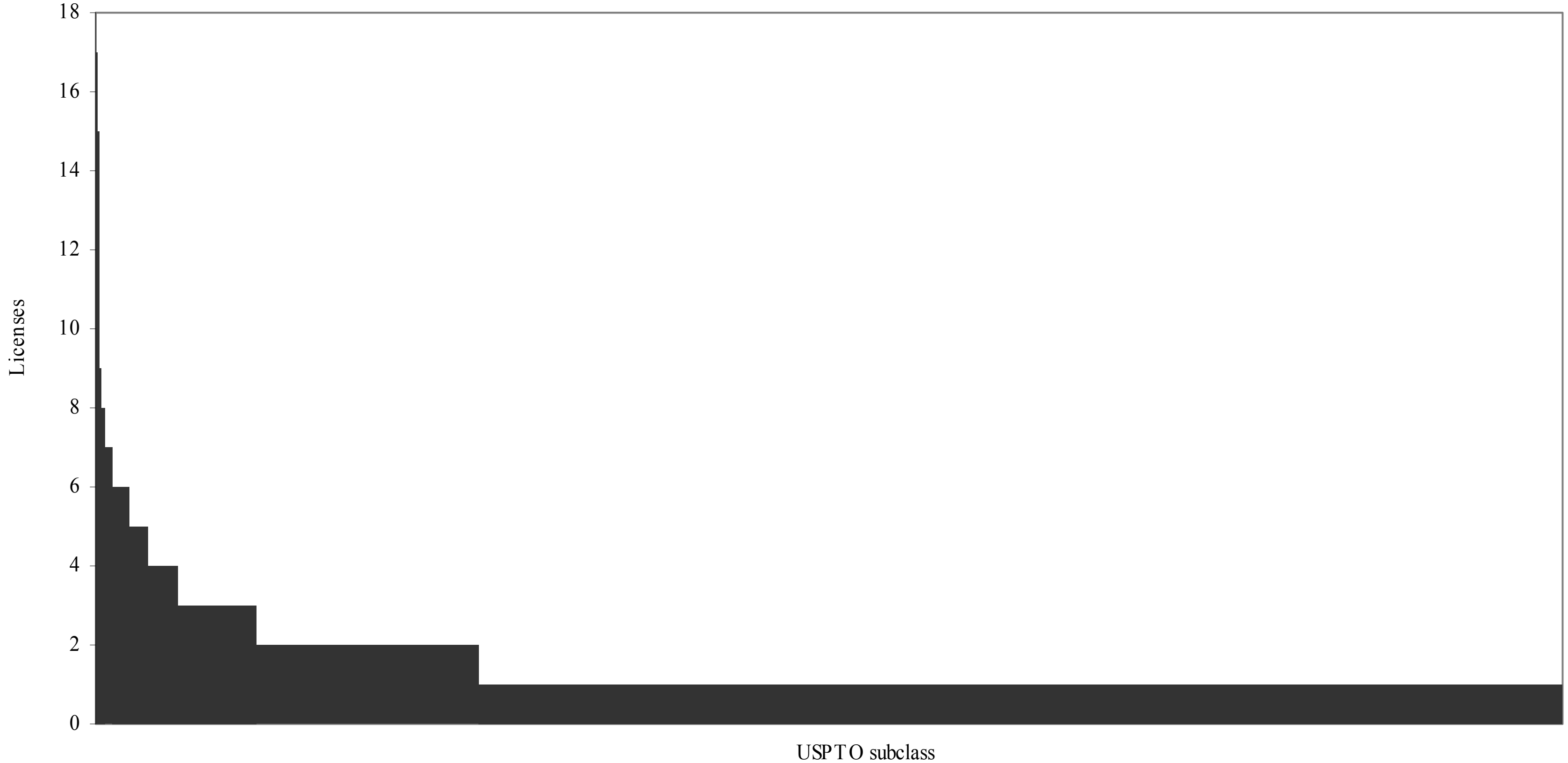
TABLE 9 - OLS DEPENDENT VARIABLE IS PATENTS BY U.S. INVENTORS PER USPTO SUBCLASS AND YEAR (1875-1945) – INDIGO PATENTS

	I	II	III
Subclass has at least one license	0.0421***		
	(0.0155)		
Number of licenses		0.0255**	
		(0.0106)	
Remaining lifetime of licensed patents			0.00224**
			(0.001)
Number of patents by foreign inventors	0.0289**	0.0290**	0.0292**
	(0.0118)	(0.0115)	(0.0114)
Subclass fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	60,279	60,279	60,279
Number of subclasses	849	849	849

Robust standard errors clustered at the subclass level in parentheses
*** p<0.01, ** p<0.05, * p<0.1

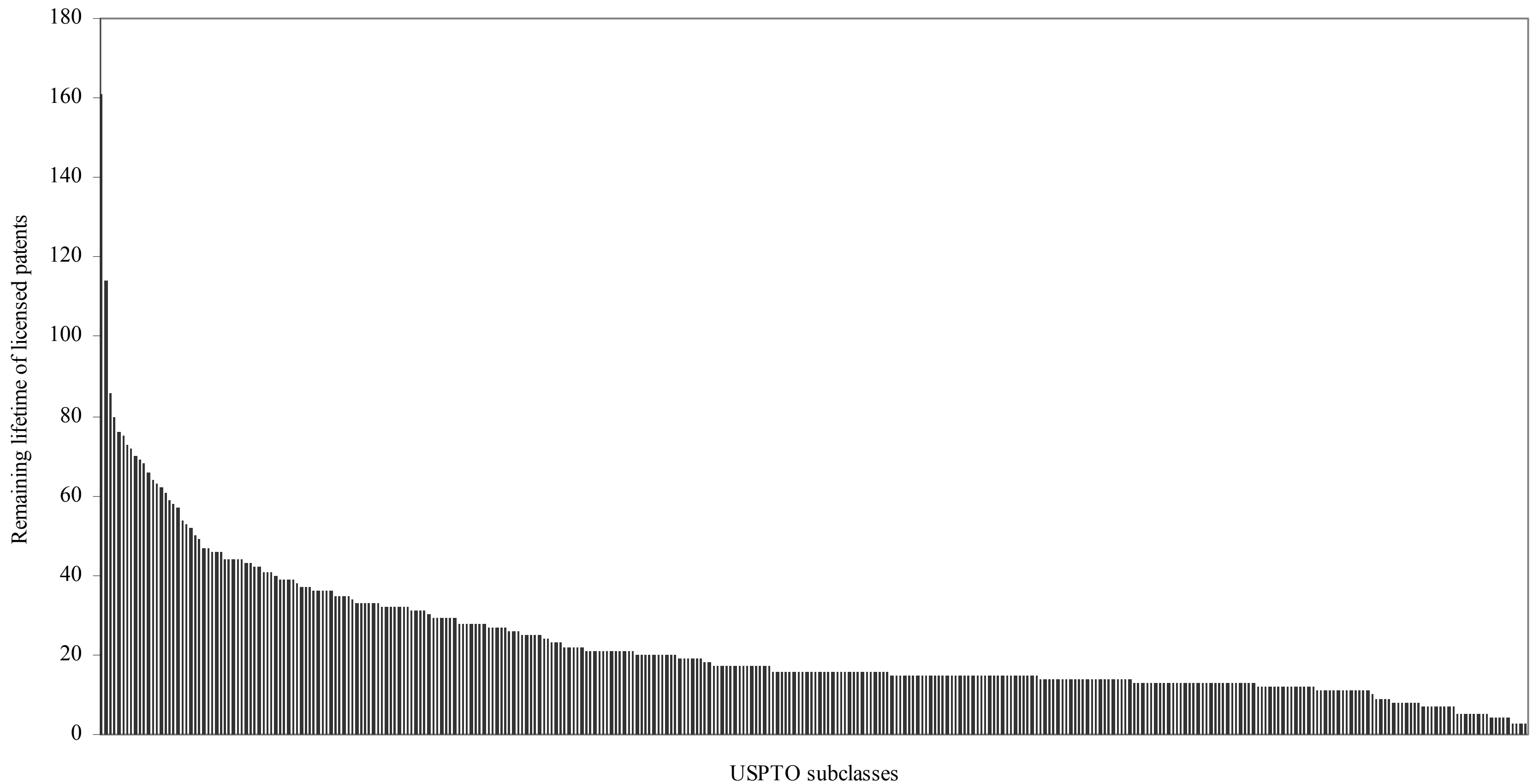
Note: Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. In those classes, we identify all 843 patents that contain the word "indigo" in the description of the invention and record the subclasses to which each patent belongs. Data on inventor nationality are based on a key word search of the *Lexis Nexis*. The average number of indigo patents in each subclass-cell is 0.035.

FIGURE 1 - NUMBER OF LICENSED PATENTS PER SUBCLASS



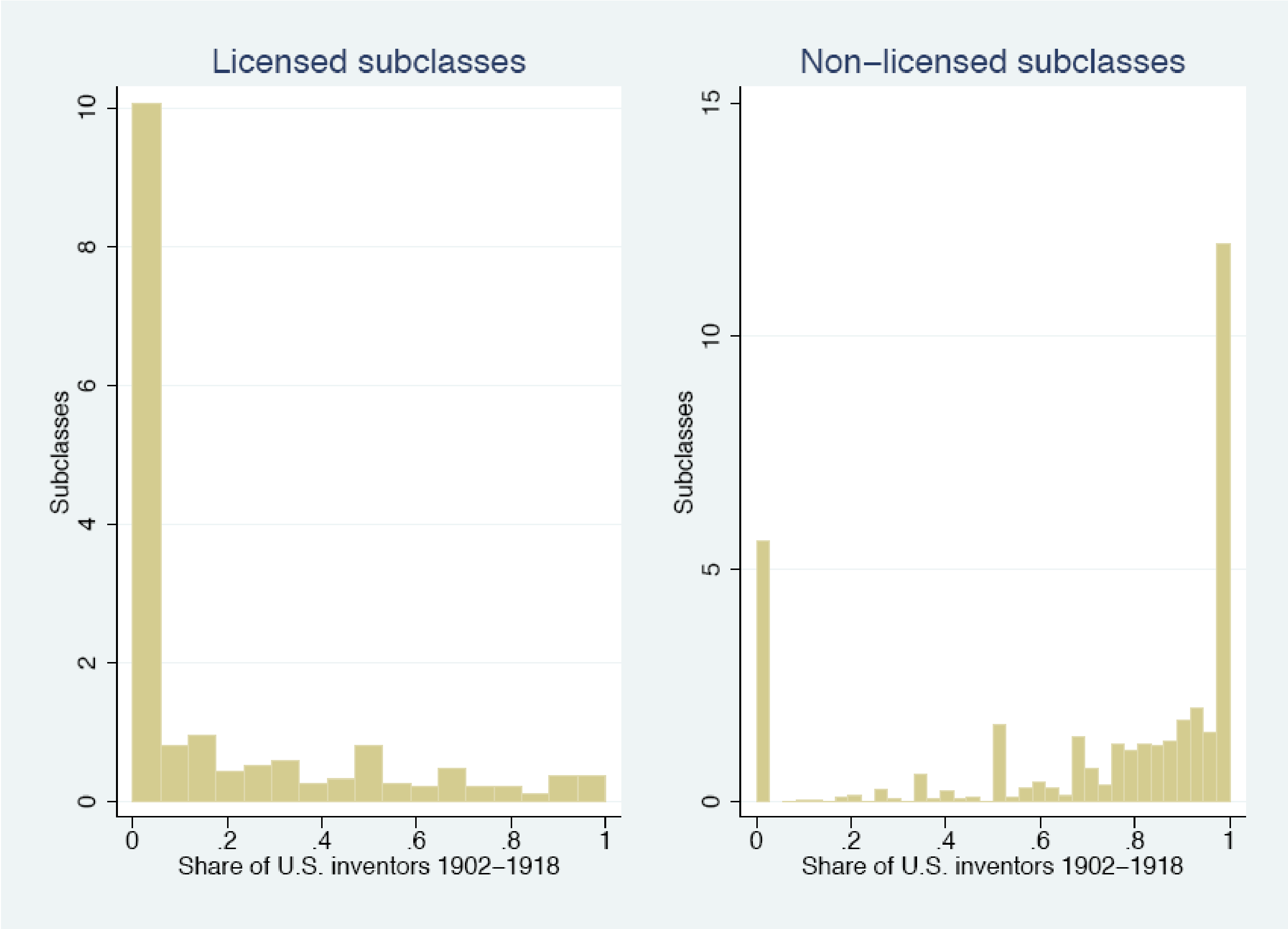
Notes: Data from Haynes (1945) and www.uspto.gov. Licenses refer to the total number of enemy-owned patents that were licensed to U.S. firms by the Chemical Foundation. Classes and subclasses refer to main classes and subclasses within the USPTO system of classifying patents. Main classes are divided into subclasses, which are the unit of observation for this analysis.

FIGURE 2 - REMAINING LIFETIME OF LICENSED PATENTS PER SUBCLASS



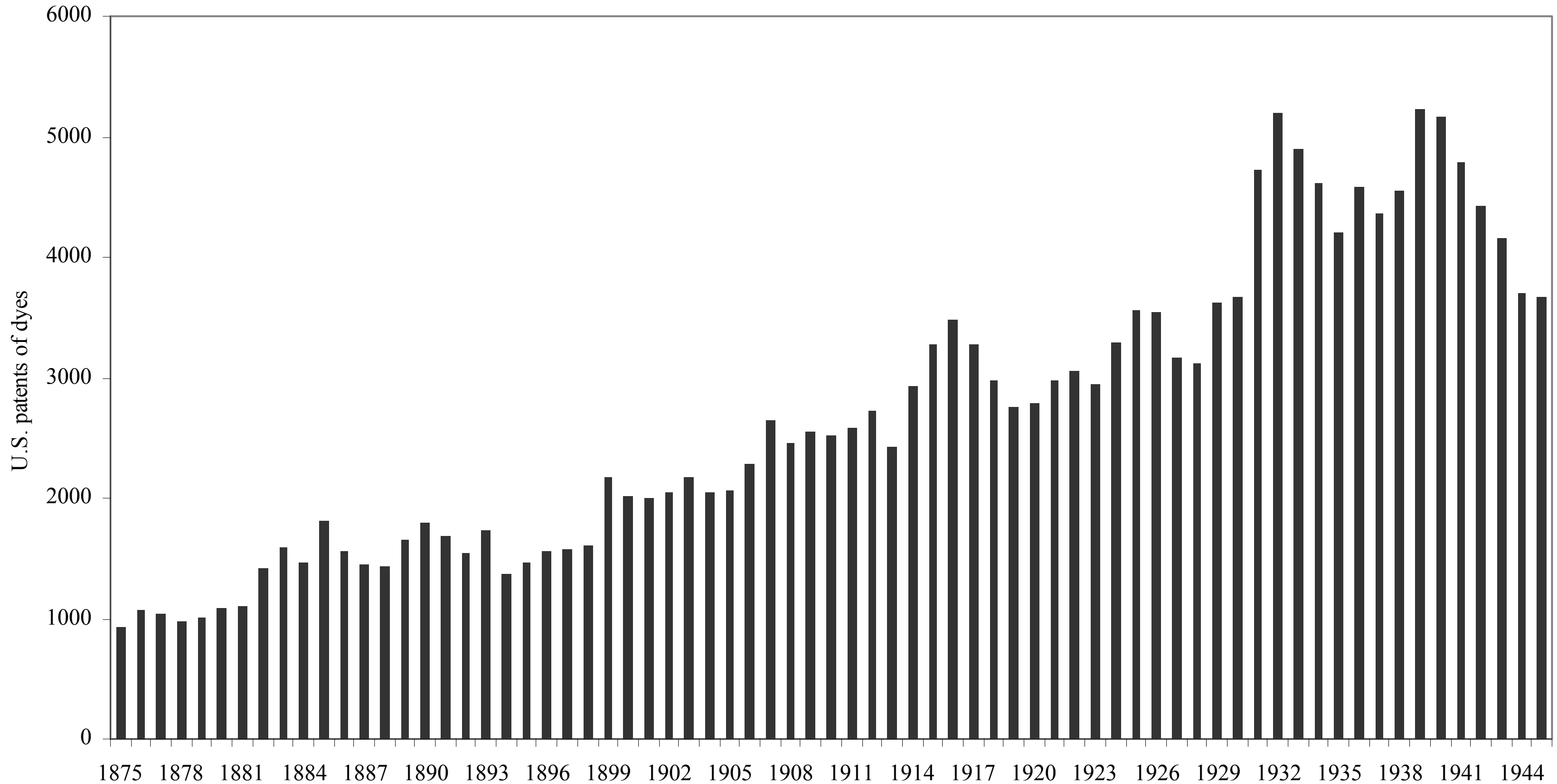
Source: Data from Haynes (1945) and *www.uspto.gov*. Licenses refer to the total number of enemy-owned patents that were licensed to U.S. firms by the Chemical Foundation Classes and subclasses refer to main classes and subclasses within the USPTO system of classifying patents. Main classes are divided into subclasses, which are the unit of observation for this analysis. The remaining lifetime of licensed patents is calculated adding 17 years to the year of granting and subtracting 1918, which is the year of initial licensing.

FIGURE 3 – NUMBER OF SUBCLASSES WITH AND WITHOUT LICENSE BY PRE-TWEA SHARE OF DOMESTIC INVENTORS



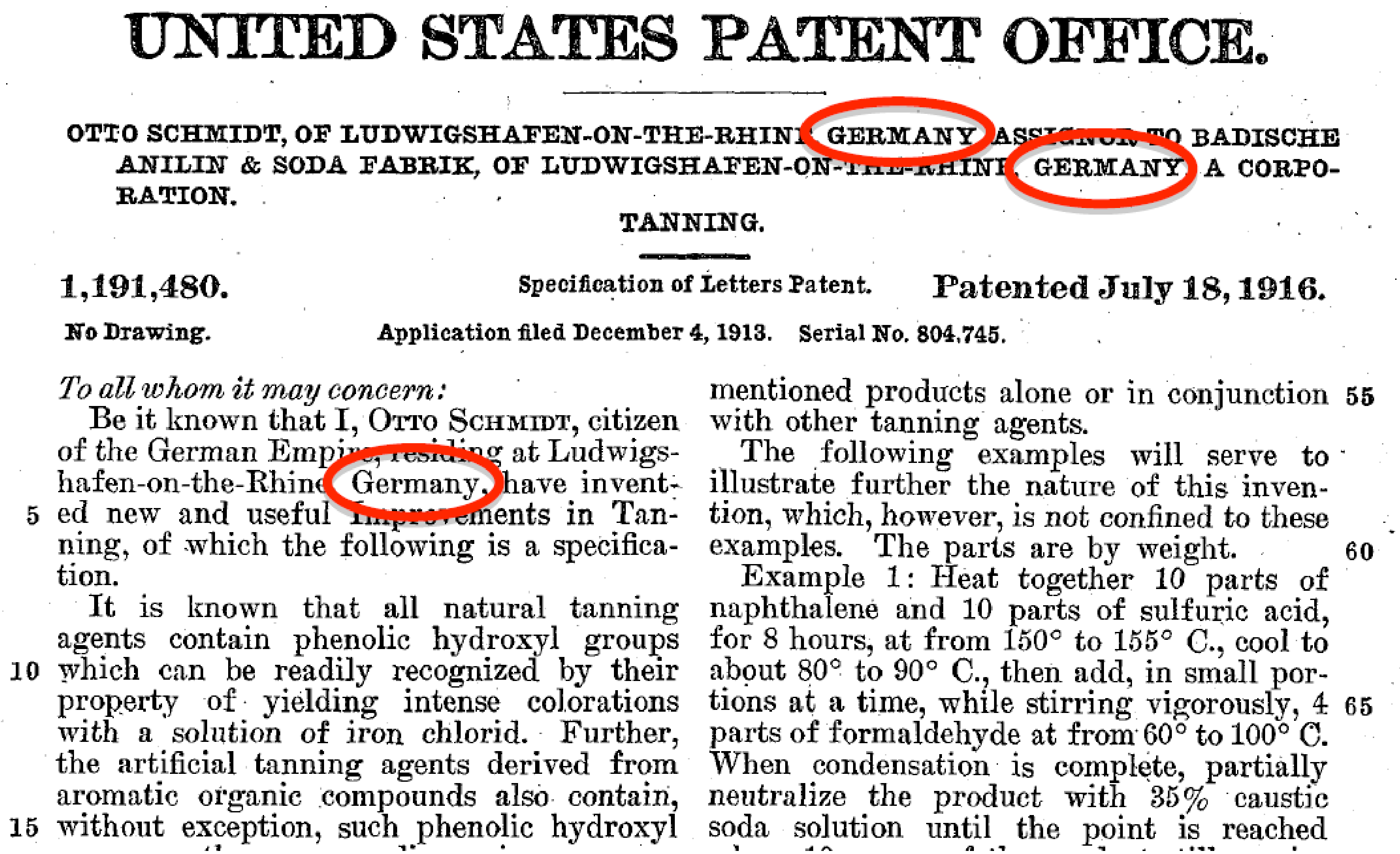
Notes: Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexi*s. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

FIGURE 4 - U.S. PATENTS OF DYESTUFF PER YEAR (1875-1945)



Notes: Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexi*s. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

FIGURE 5 – SAMPLE U.S. PATENT OF DYESTUFF



UNITED STATES PATENT OFFICE.

OTTO SCHMIDT, OF LUDWIGSHAFEN-ON-THE-RHINE, GERMANY, ASSIGNOR TO BADISCHE ANILIN & SODA FABRIK, OF LUDWIGSHAFEN-ON-THE-RHINE, GERMANY, A CORPORATION.

TANNING.

1,191,480. Specification of Letters Patent. **Patented July 18, 1916.**

No Drawing. Application filed December 4, 1913. Serial No. 804,745.

To all whom it may concern:

Be it known that I, OTTO SCHMIDT, citizen of the German Empire, residing at Ludwigshafen-on-the-Rhine, Germany, have invented new and useful Improvements in Tanning, of which the following is a specification.

It is known that all natural tanning agents contain phenolic hydroxyl groups which can be readily recognized by their property of yielding intense colorations with a solution of iron chlorid. Further, the artificial tanning agents derived from aromatic organic compounds also contain, without exception, such phenolic hydroxyl

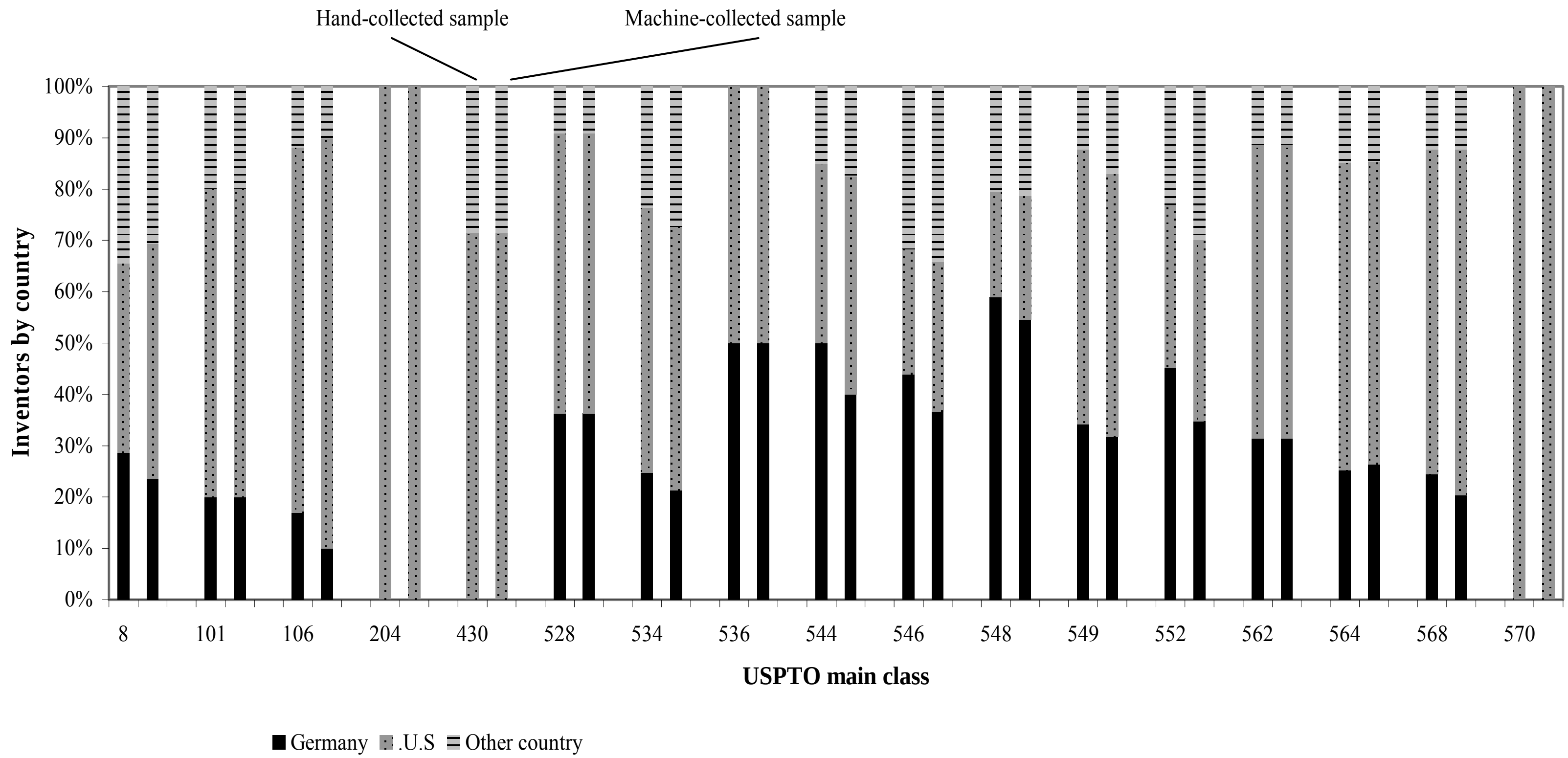
mentioned products alone or in conjunction with other tanning agents.

The following examples will serve to illustrate further the nature of this invention, which, however, is not confined to these examples. The parts are by weight.

Example 1: Heat together 10 parts of naphthalene and 10 parts of sulfuric acid, for 8 hours, at from 150° to 155° C., cool to about 80° to 90° C., then add, in small portions at a time, while stirring vigorously, 4 parts of formaldehyde at from 60° to 100° C. When condensation is complete, partially neutralize the product with 35% caustic soda solution until the point is reached

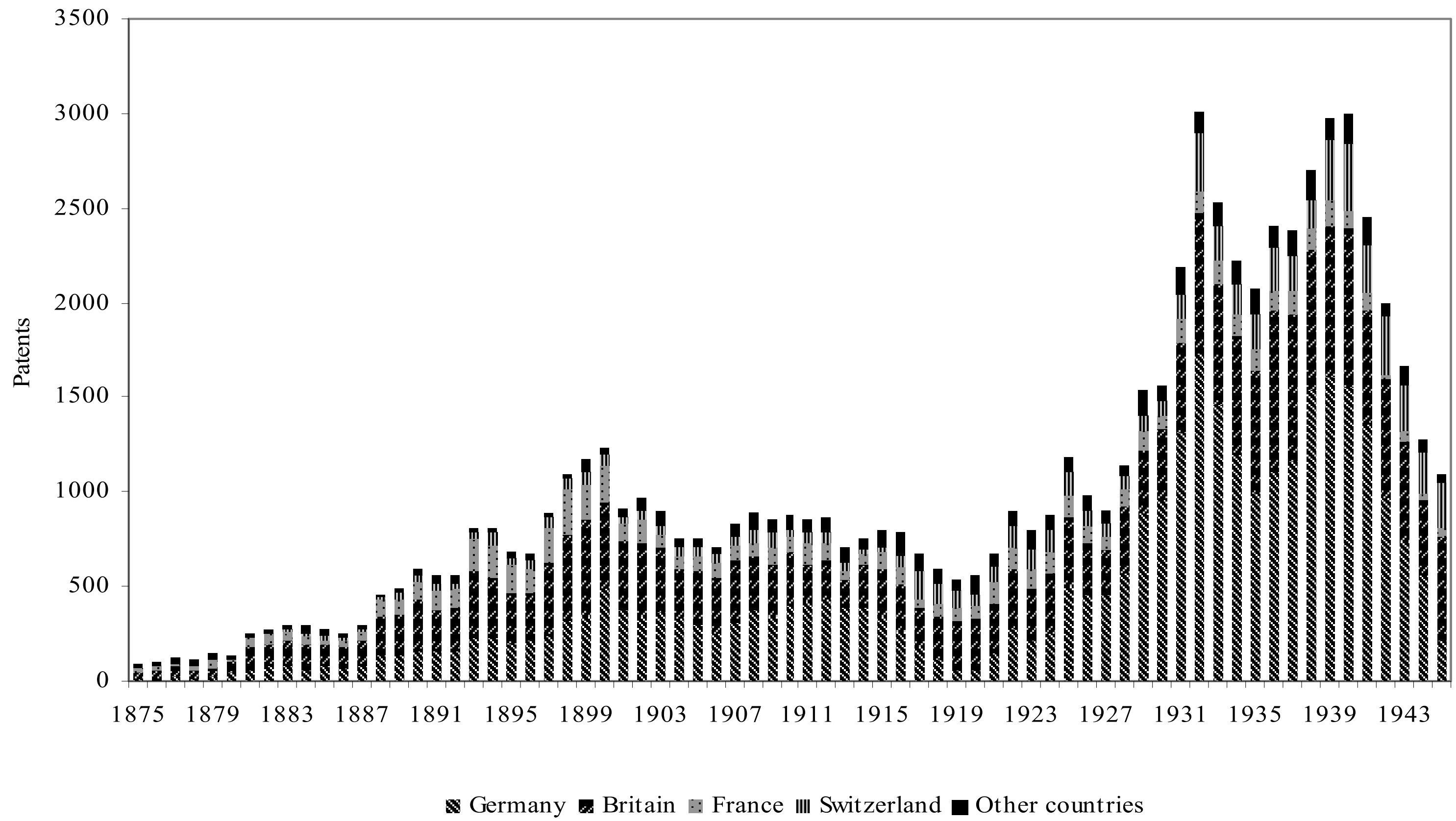
Notes: This patents illustrates the process by which optical character recognition assigns patents to inventor nationality. Our algorithm searches both the title and the full text of the patent in *Lexis Nexis*.

FIGURE 6 – HAND-CHECKED AND ALGORITM ASSIGNED NATIONALITES BY USPTO CLASS (1900-1943)



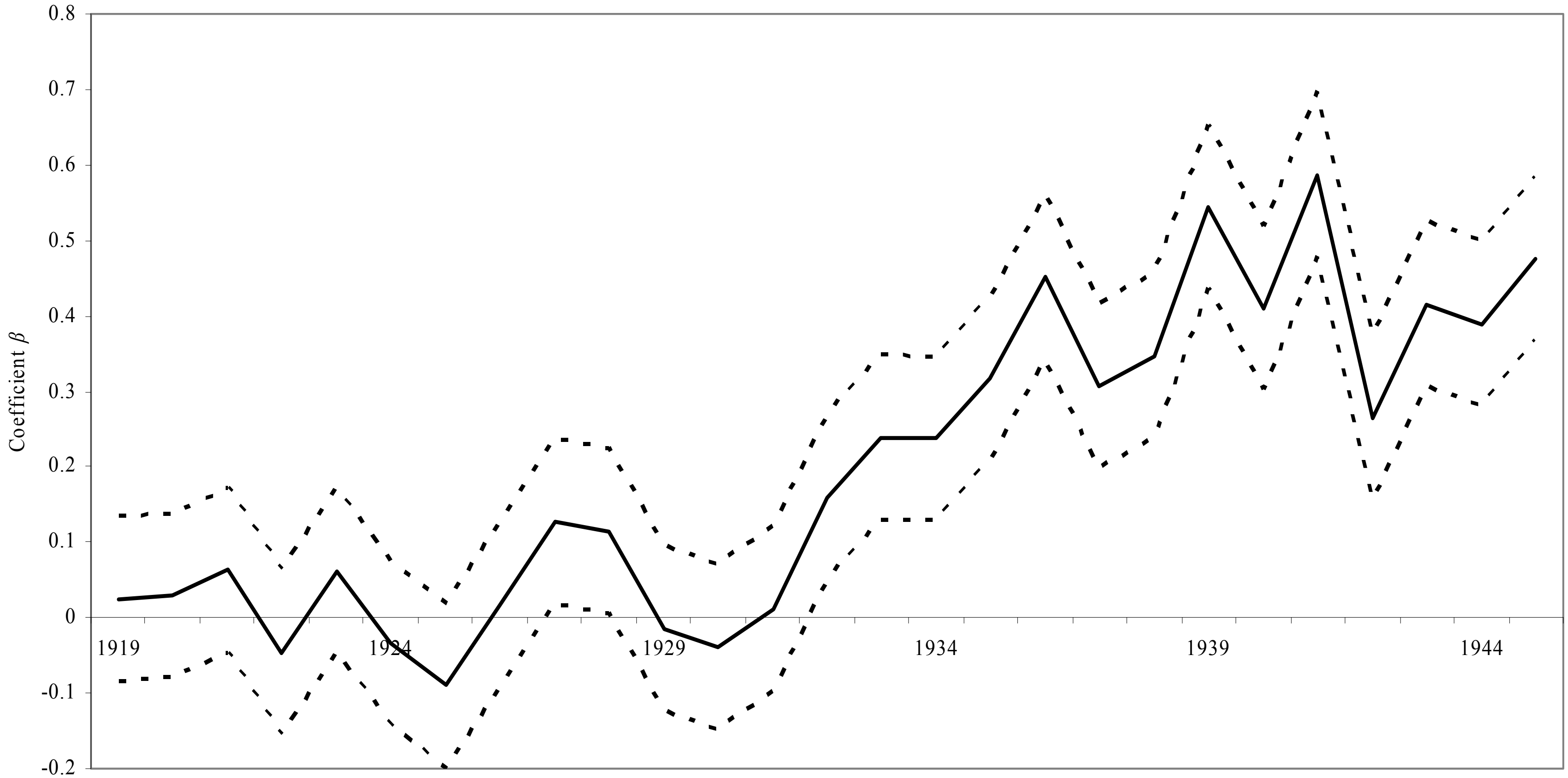
Notes: Based on a sample of 649 patents between 1900 and 1943. Data from Haynes (1945), www.uspto.gov, www.lexisnexis.com, and www.patents.google.com. To collect our data on inventor nationality, we create an algorithm that performs keyword searches on LexisNexis. Our algorithm relies on Optical Character Recognition (OCR) to recognize keywords. OCR is worse at recognizing misspelled names or untidy script than the human eye. Thus we hand-collected an alternative data set to get an idea of the size of measurement error. Our hand-checked data include all 625 patents of dyes in what Delamare and Guineau (1999) consider the most important dyes in the early 20th century: alizarin, indigo, azo dyes, and aniline. In the hand-collected sample, all inventors come from one of the following countries: Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

FIGURE 7 - U.S. PATENTS OF DYES BY FOREIGN INVENTORS (1875-1945)



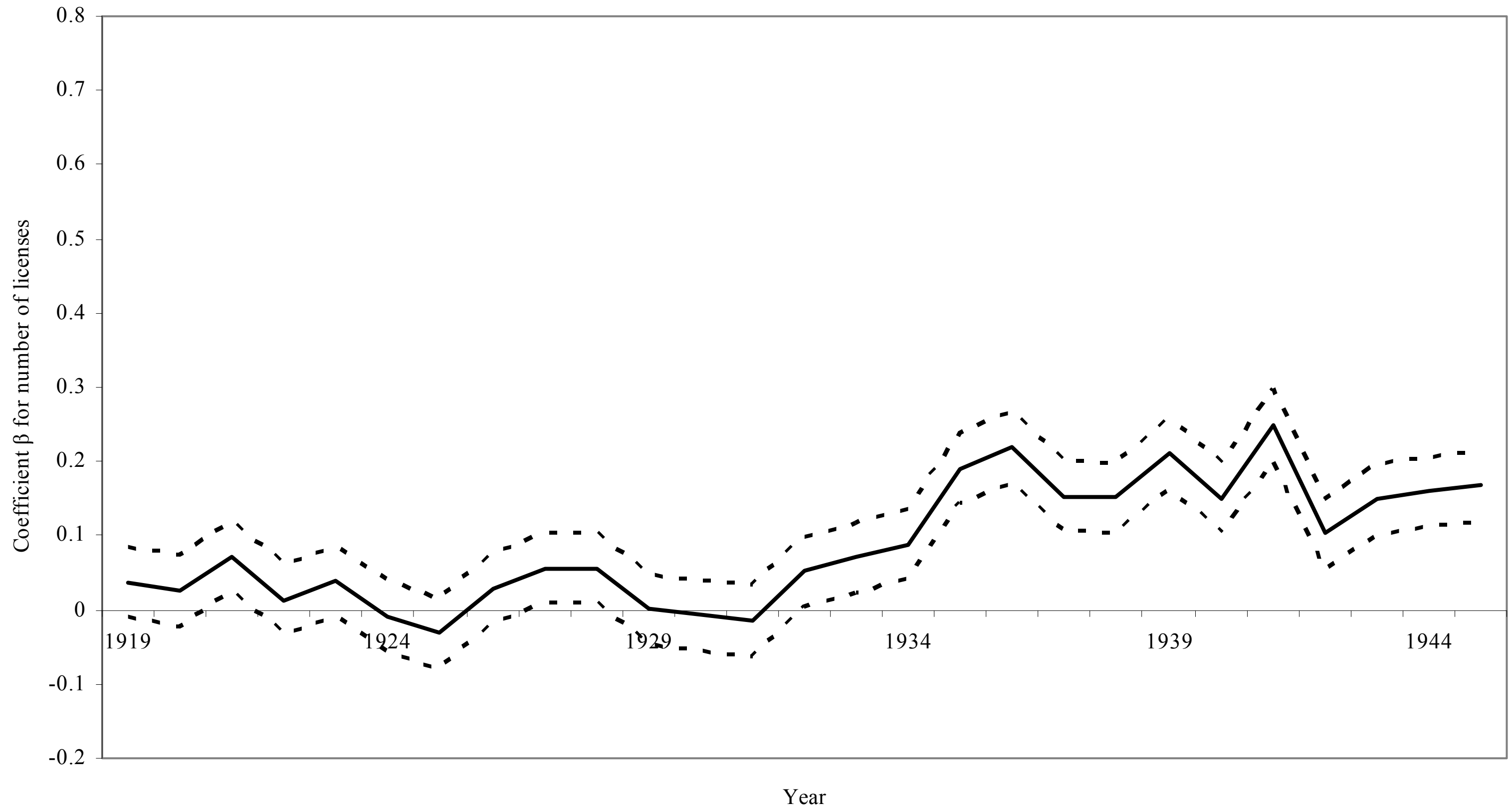
Notes: Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexi*s. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

FIGURE 8 – YEAR-SPECIFIC TREATMENT EFFECT, (1919-1945)
DIFFERENCE-IN-DIFFERENCES ESTIMATION



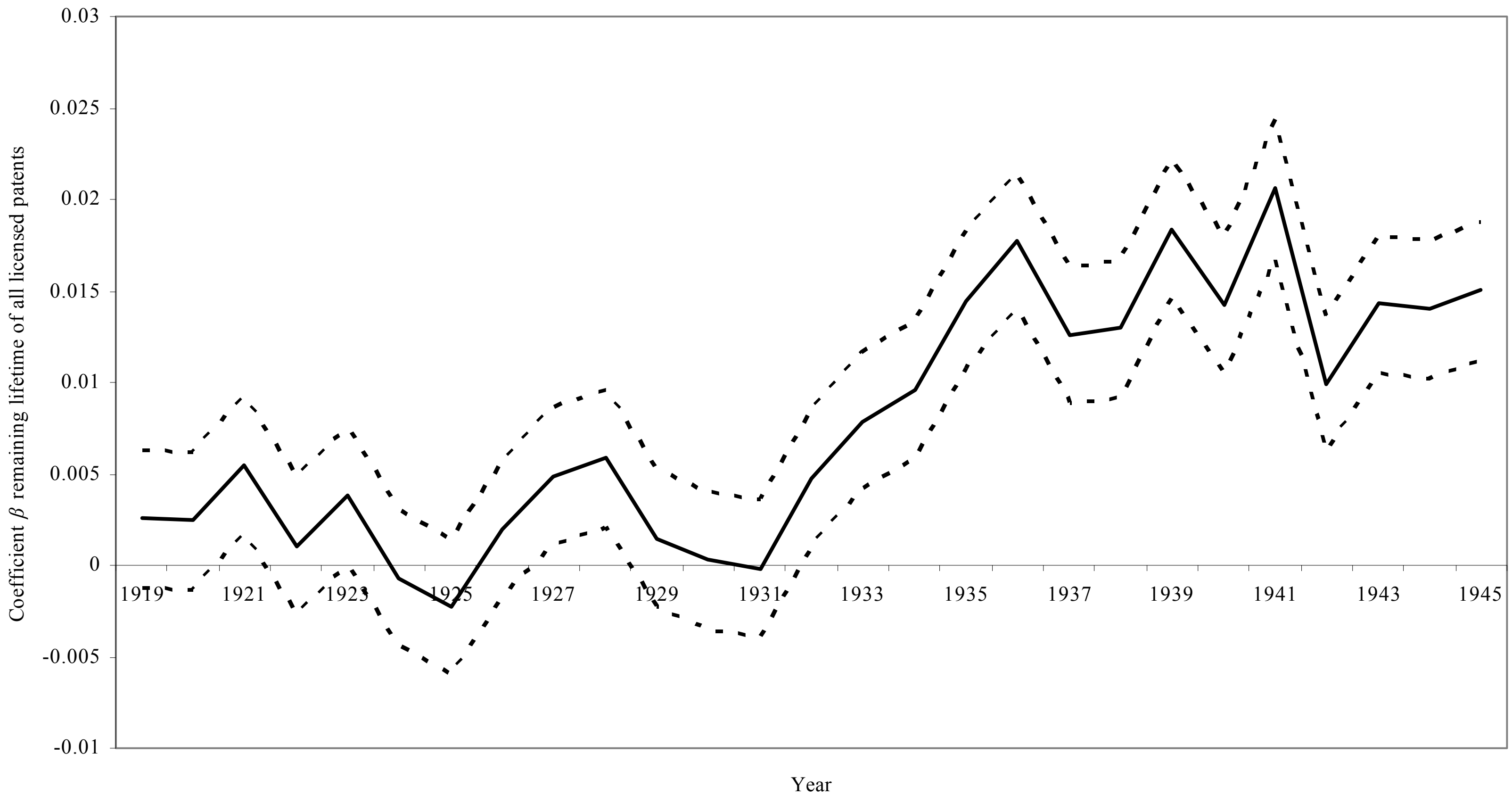
Notes: For a 95-percent confidence interval. Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexi*s. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

FIGURE 9 – YEAR-SPECIFIC TREATMENT EFFECT OF AN ADDITIONAL LICENSE UNDER THE TWEA (1919-1945), DIFFERENCE-IN-DIFFERENCES ESTIMATION



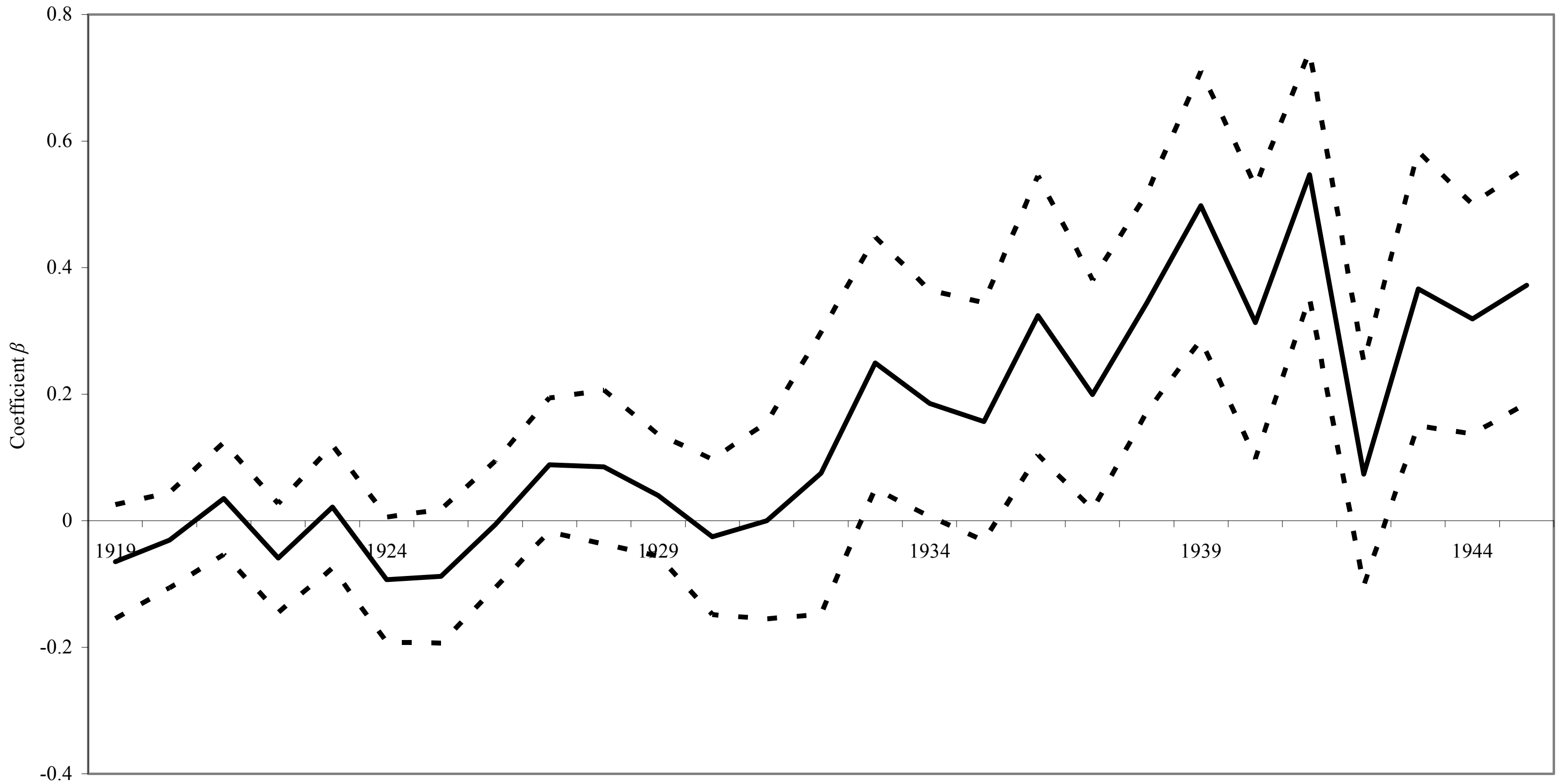
Notes: For a 95-percent confidence interval. Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexi*s. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland. The figure plots the coefficients of the year-specific treatment effect of one additional licensed patent.

FIGURE 10 – YEAR-SPECIFIC TREATMENT EFFECT OF AN ADDITIONAL YEAR OF PATENT LIFE (1919-1945), DIFFERENCE-IN-DIFFERENCES ESTIMATION



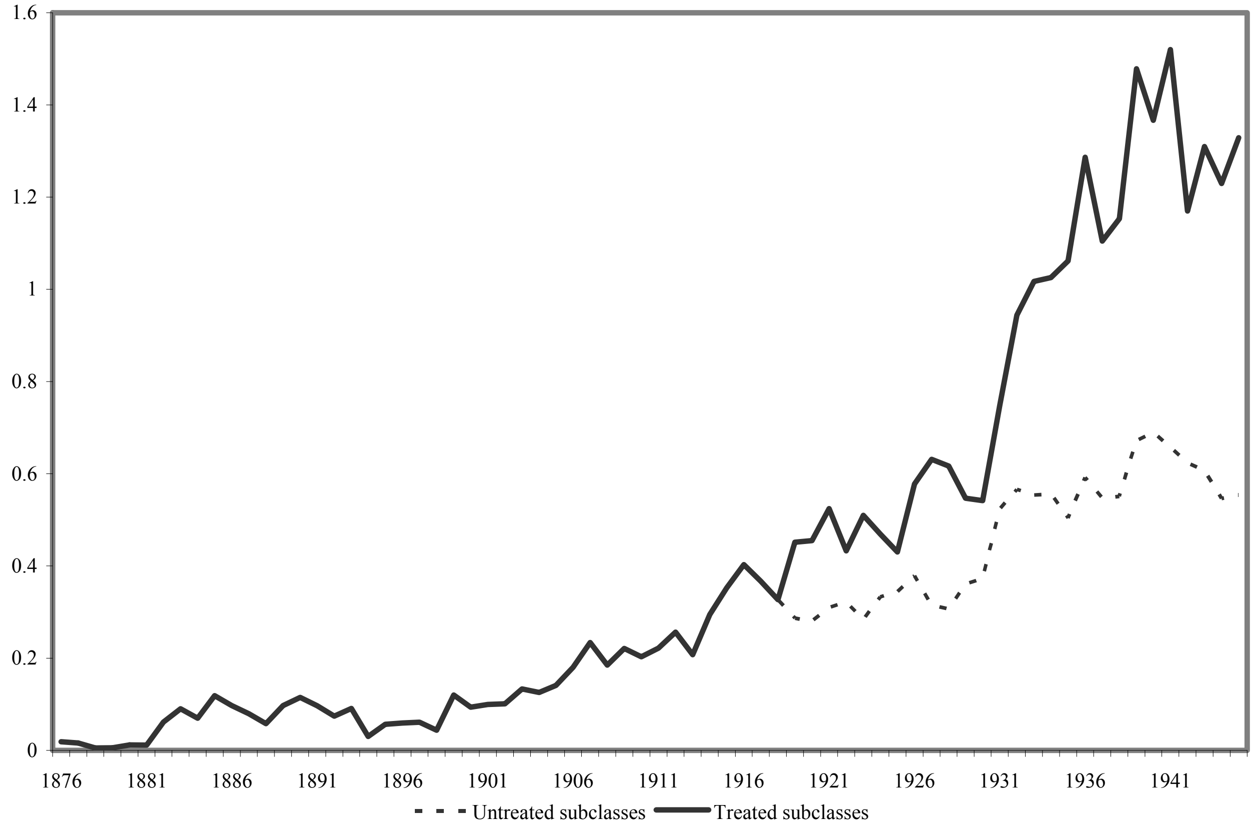
Notes: For a 95-percent confidence interval. Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexis*. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland. The figure plots the coefficients of the year-specific treatment effect of one additional year of life of a licensed patent in 1918.

FIGURE 11 - TREATMENT EFFECT OF THE TWEA BY YEAR, TRIPLE DIFFERENCES (1919-1945)



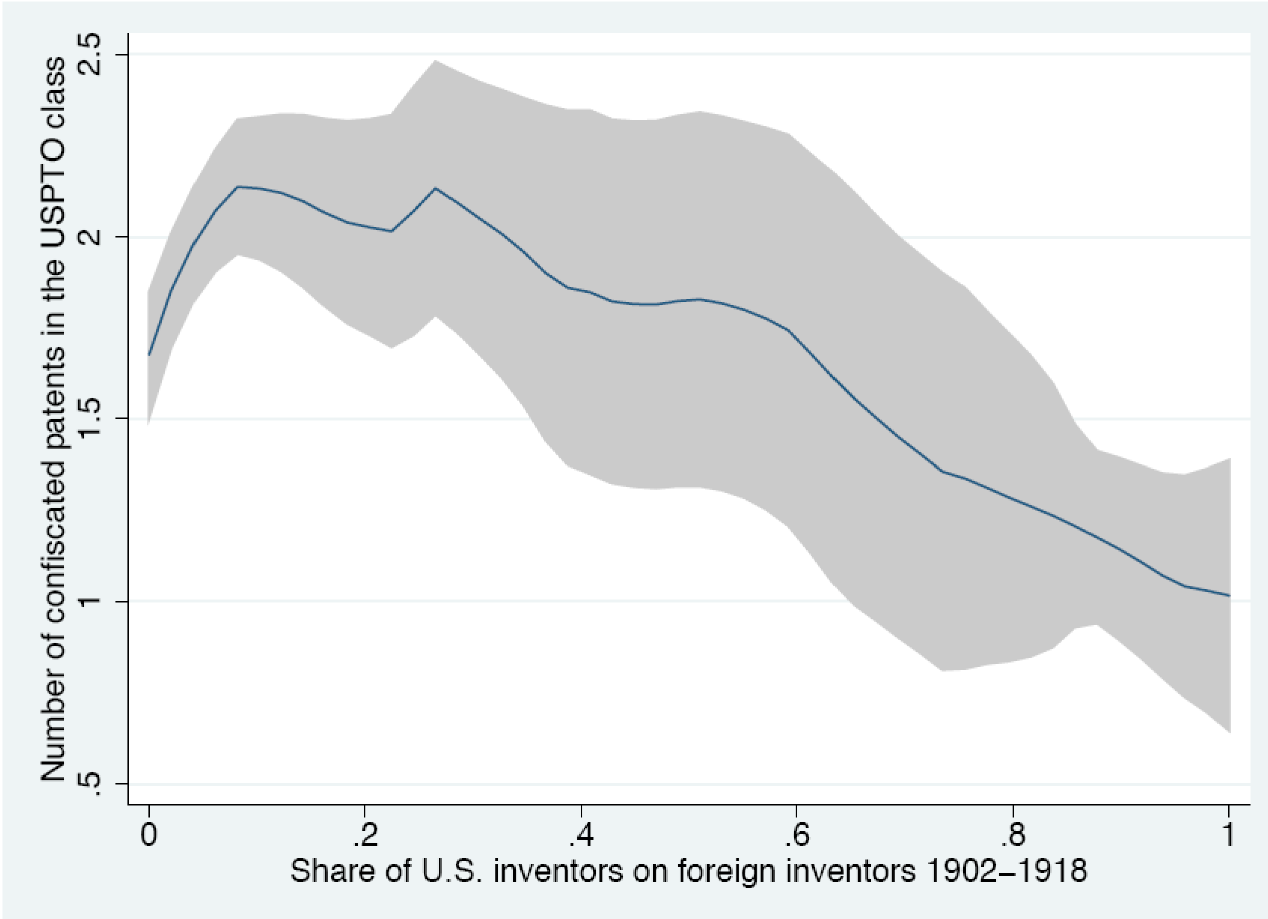
Notes: For a 95-percent confidence interval. Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexi*s. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland. The differences in differences in differences estimator compares treated and untreated classes, before and after the TWEA and patents by U.S. inventors with patents by foreign (non-German) inventors.

FIGURE 12 – YEAR-SPECIFIC TREATMENT EFFECTS (1919-1945)
DIFFERENCE-IN-DIFFERENCES, CONTROLLING FOR LINEAR TIME TRENDS



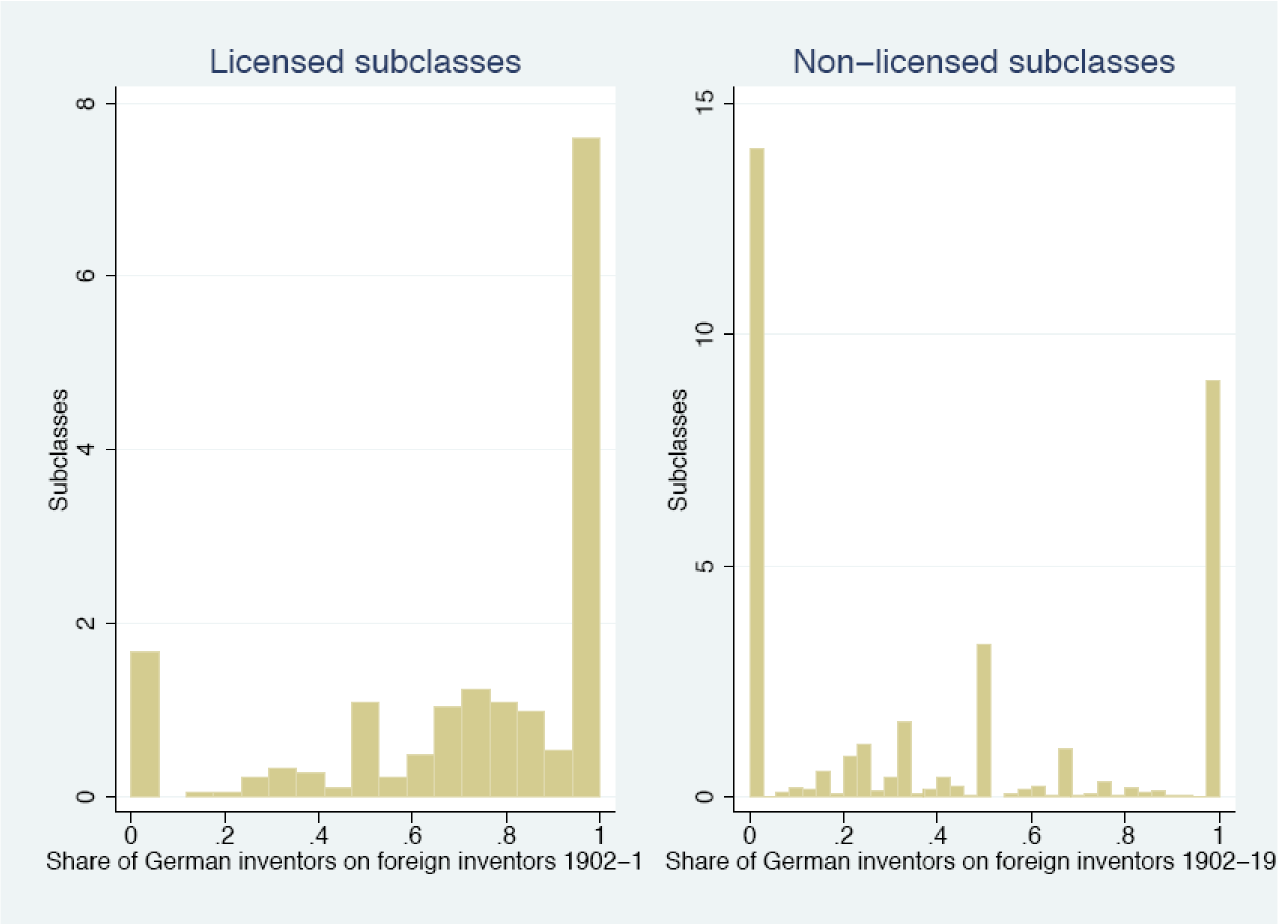
Notes: Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexis*. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland. The figure plots the coefficients of the year-specific treatment effect of having at least one patent licensed under the TWEA. The regression includes a control for linear time trends for treated subclasses.

FIGURE 13 - LICENSED PATENTS BY SHARE OF U.S. INVENTORS



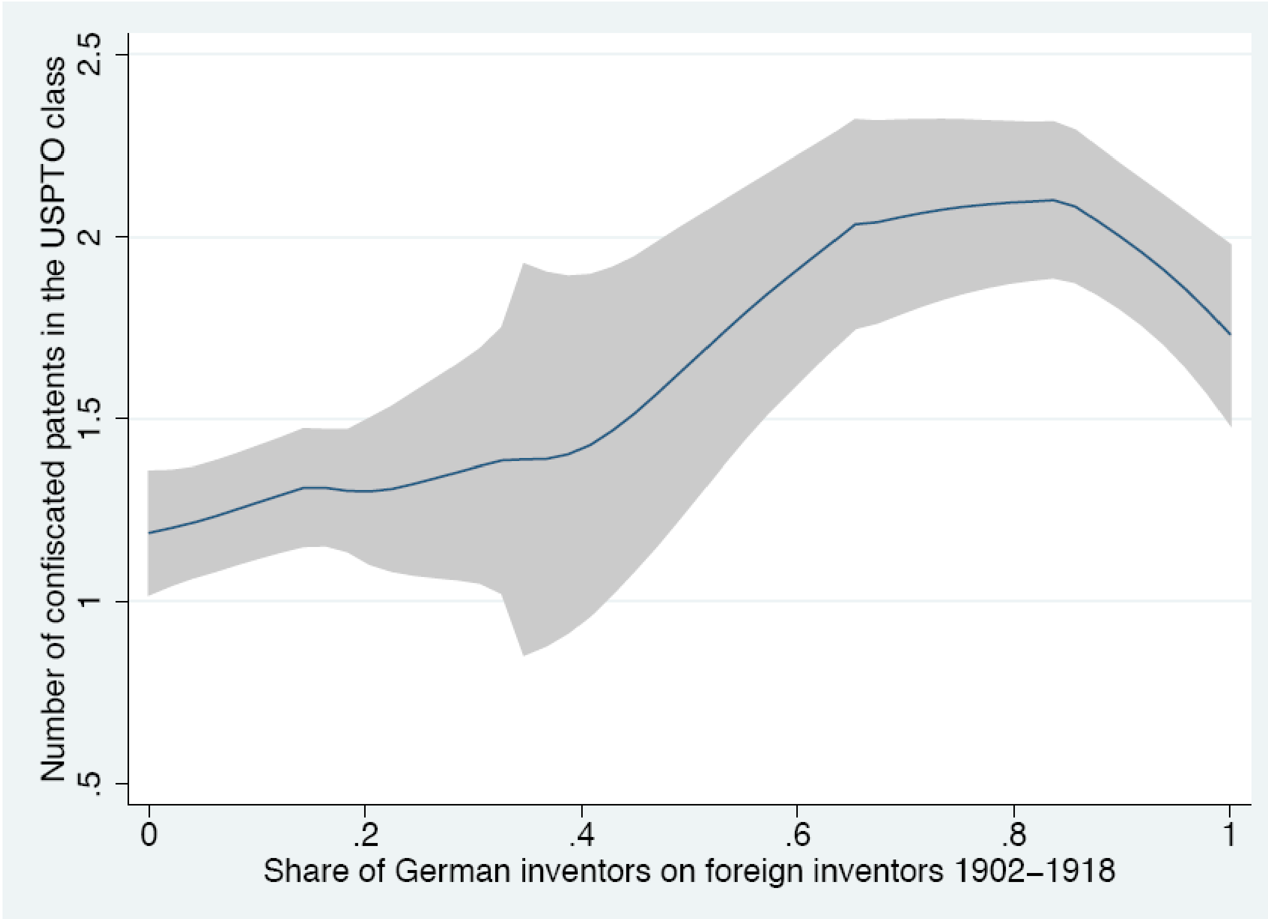
Notes: Locally linear fan regression with 95% confidence interval. Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexi*s. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

FIGURE 14 – NUMBER OF SUBCLASSES WITH AND WITHOUT LICENSE
BY PRE-TWEA SHARE OF GERMAN INVENTORS AMONG FOREIGN INVENTORS



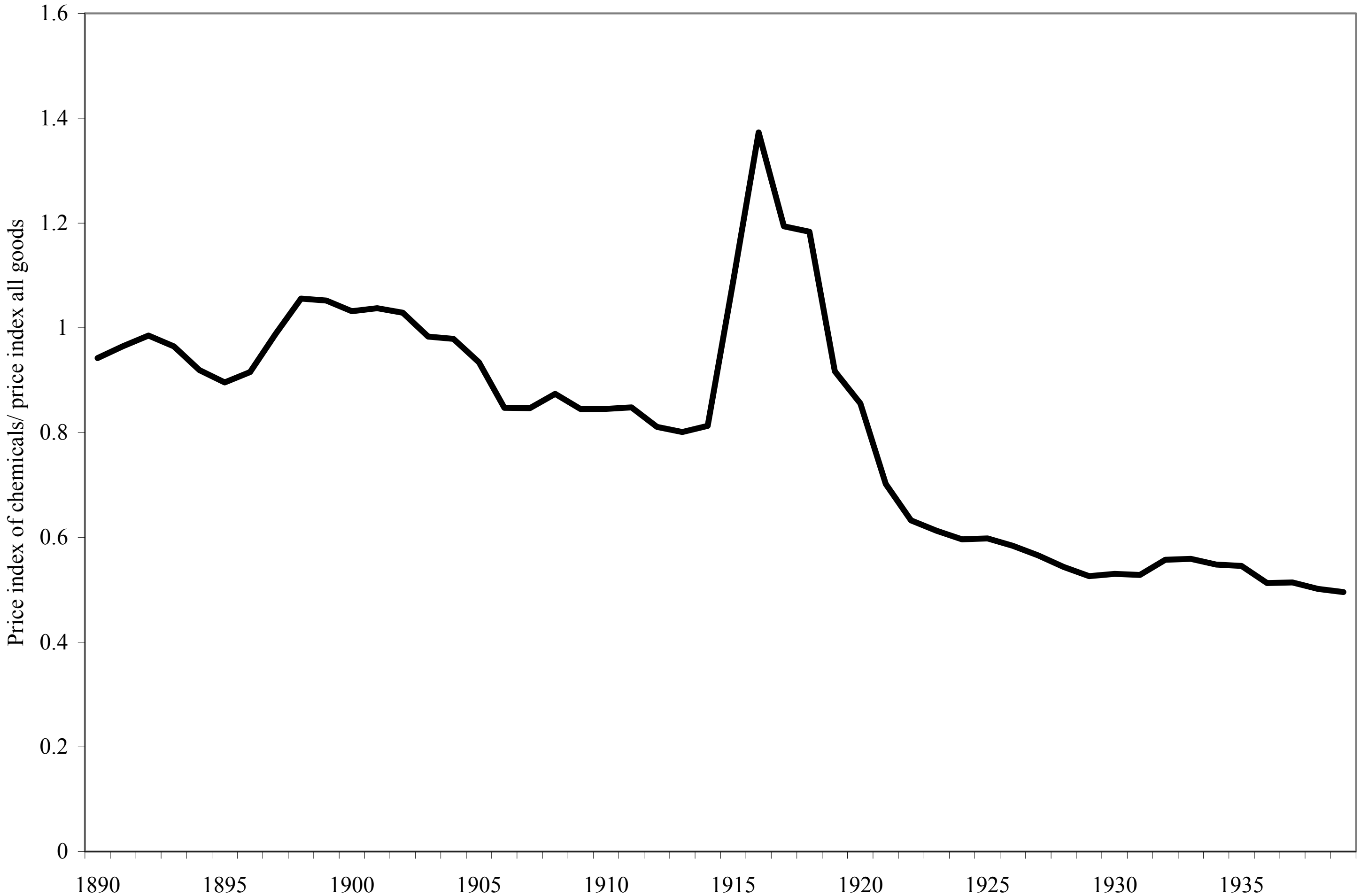
Notes: Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexis*. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

FIGURE 15- NUMBER OF LICENSED PATENTS BY PRE-TWEA SHARE OF GERMAN INVENTORS



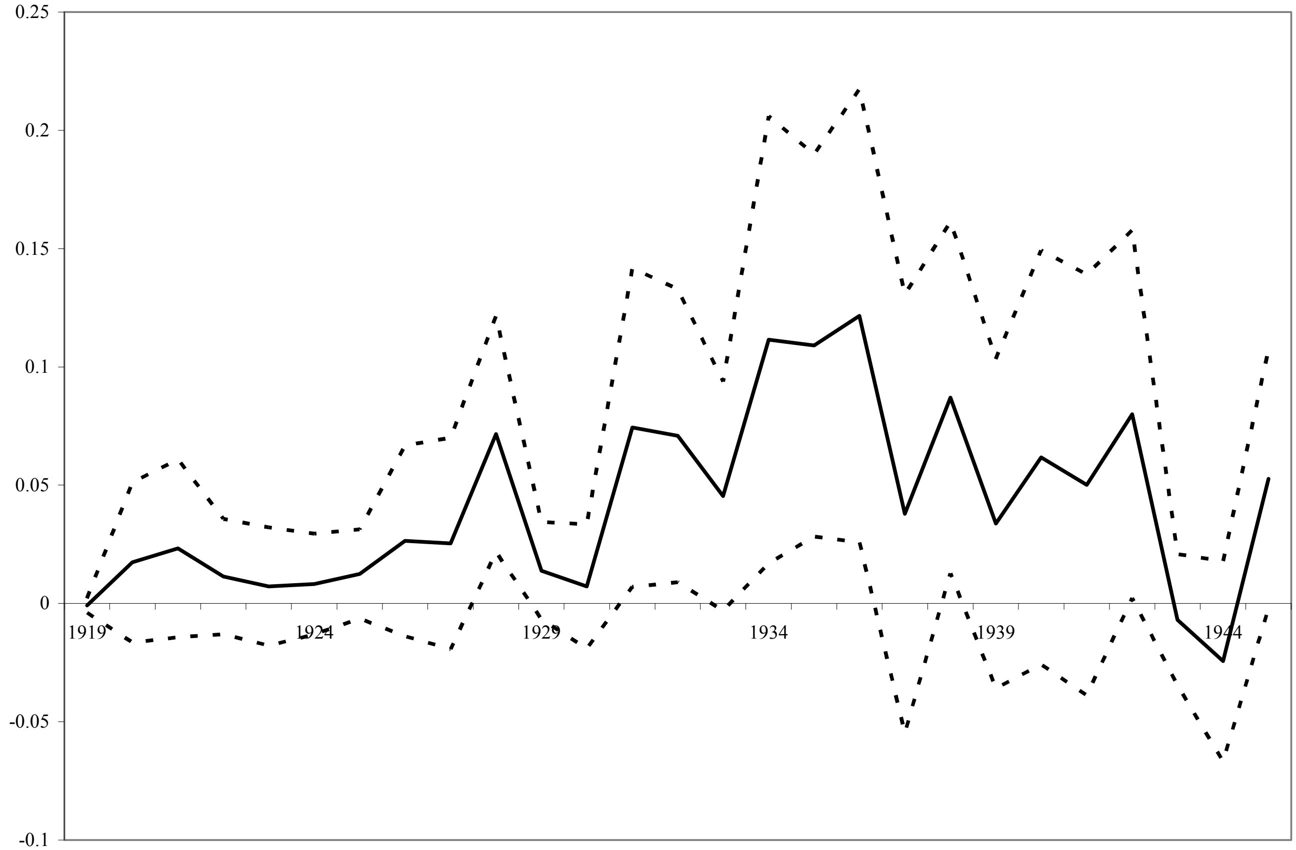
Notes: Locally linear fan regression with 95% confidence interval. Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexi*s. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland.

FIGURE 16- RATIO OF PRICE INDEX OF CHEMICALS AND DRUGS OVER THE GENERAL LEVEL OF PRICES (1890-1940)



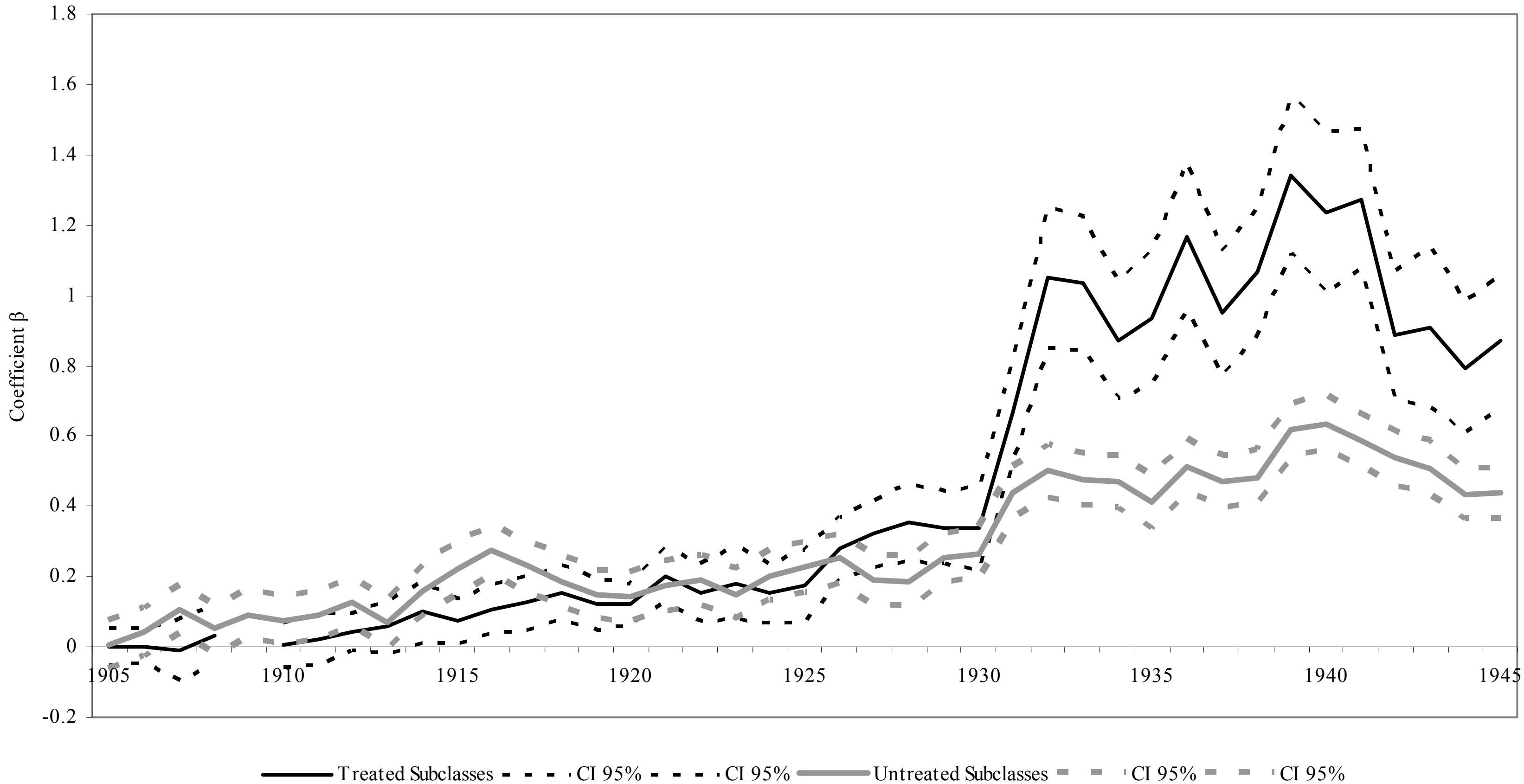
Notes: Price data from the NBER Macrohistory series 2007: "U.S. Index of the General Price Level 01/1860-11/1939" and "U.S. Index of Wholesale Price Of Chemicals and Drugs, Bureau Of Labor Statistics 01/1890-12/1951".

FIGURE 17 - YEAR-SPECIFIC TREATMENT EFFECT S DIFFERENCES IN DIFFERENCES (1919-1945) – PATENTS OF INDIGO DYES



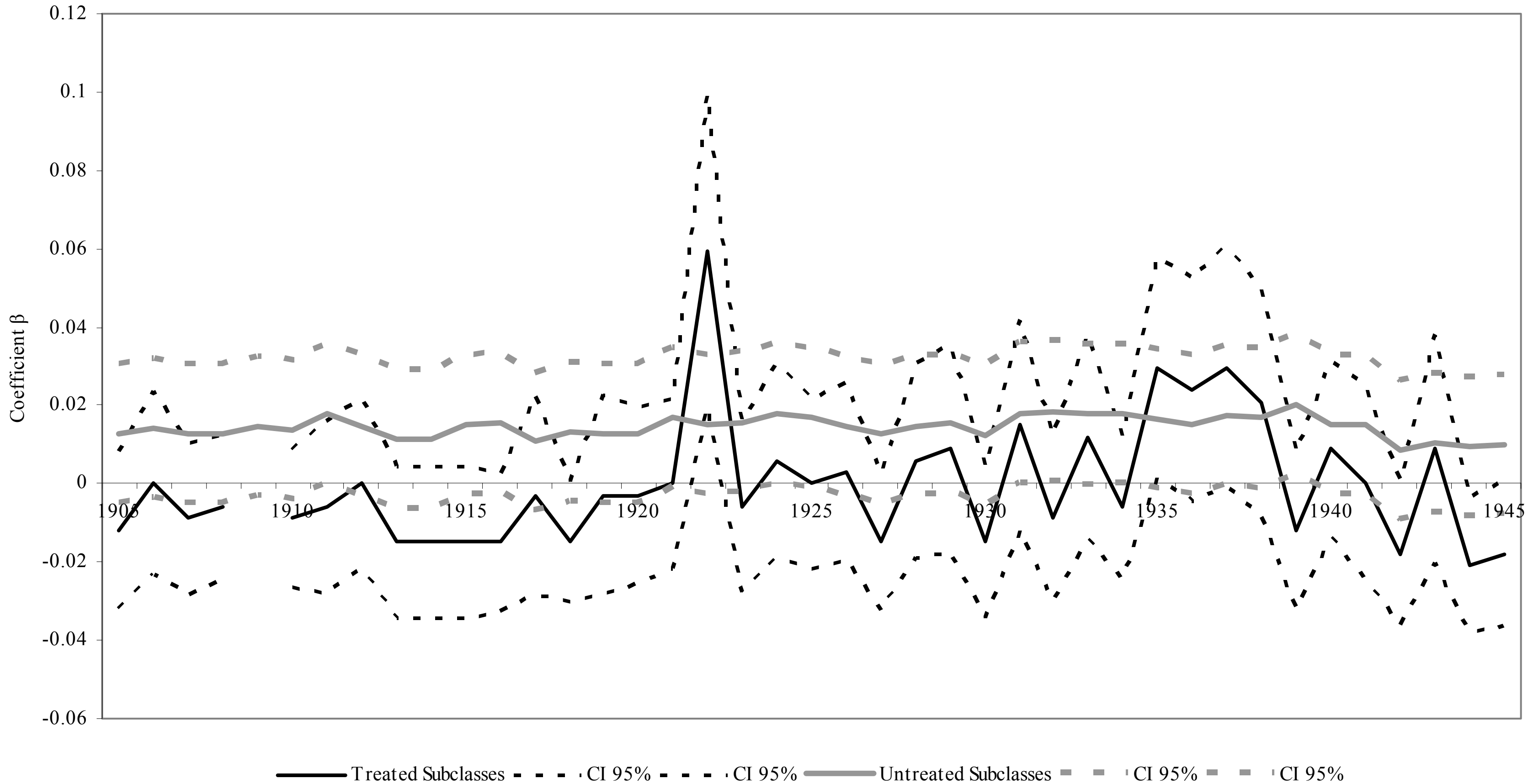
Note: For a 95-percent confidence interval. Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. In those classes, we identify all 843 patents that contain the word "indigo" in their text and identify the subclasses they belong to. Data on inventor nationality are based on a key word search of the *Lexis Nexi*s. The average number of indigo patents in each subclass-cell is 0.035.

FIGURE 18 - PLACEBO TREATMENT (1905-1945)



Notes: For a 95-percent confidence interval. Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexis*. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland. The figure plots the coefficients of the year-specific effect of treatment starting in 1905.

FIGURE 19 - PLACEBO TREATMENT ON FRENCH INVENTORS (1905-1945)



Notes: For a 95-percent confidence interval. Data from www.uspto.gov and the *Lexis Nexis Chronological Patent Files (1790-1970)*. Our data consist of all 192,121 patents between 1875 and 1945 in 21 USPTO main classes that contained at least one licensed enemy patent. Data on inventor nationality are based on a key word search of the *Lexis Nexis*. We search for all inventors from any country that occurs as a country of origin in any patent of our hand-collected sample of 625 patents and augment this list to include all countries that are listed as exporters of dyes in Haynes. Thus, we distinguish patents by inventors from Argentina, Australia, Austria, Belgium, Brazil, China, England, France, Germany, India, Italy, the Netherlands, Russia, Scotland, Spain, and Switzerland. The figure plots the coefficients of the year-specific effect of treatment starting in 1905 on the number of patents from a French inventor.