Capital-Skill Complementarity and the Emergence of Labor Emancipation*

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Abstract

This paper advances a novel hypothesis regarding the historical roots of labor emancipation. It argues that the decline of coercive labor institutions in the industrial phase of development has been an inevitable by-product of the intensification of capital-skill complementarity in the production process. In light of the growing significance of skilled labor for fostering the return to physical capital, elites in society were induced to relinquish their historically profitable coercion of labor in favor of employing free skilled workers, thereby incentivizing the masses to engage in broad-based human capital acquisition, without fear of losing their skill premium to expropriation. In line with the proposed hypothesis, exploiting a plausibly exogenous source of variation in proto-industrialization across regions of nineteenth-century Prussia, the initial abundance of elite-owned physical capital that also came to be associated with skill-intensive industrialization is shown to have contributed to the subsequent intensity of *de facto* serf emancipation.

Keywords: Labor coercion, serfdom, emancipation, industrialization, physical capital accumulation, capital-skill complementarity, demand for human capital, nineteenth-century Prussia

JEL classification codes: J24, J47, N13, N33, O14, O15, O43

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1 Introduction

The rise and fall of coercive labor market institutions over the course of human history has been a subject of intensive exploration across a broad range of academic disciplines. The emergence of labor coercion has generally been attributed to the increased demand for agricultural labor as well as the deepening of class stratification and the scope for domination within societies in the aftermath of the transition from hunting and gathering to agriculture during the Neolithic Revolution. In contrast, the origins of labor emancipation and the universal protection of individual property rights have been largely ascribed to sociopolitical forces in the early modern period, such as the influence of the Age of Enlightenment on the perceived value of personal freedoms or attempts by the elites in society to appease the masses in order to mitigate the adverse consequences of popular revolts.[1] Nevertheless, the advent of coercive institutions following the Neolithic Revolution and their decline over the course of the Industrial Revolution suggest that the economic forces underlying these profound changes in the structure of production were also at the roots of the associated transformations in labor market institutions. In particular, while the agricultural revolution was associated with the rise of unskilled labor-intensive production, the Industrial Revolution marked a systematic transition to a skill-intensive production structure.

This paper advances a novel hypothesis regarding the historical roots of labor emancipation. It suggests that the decline of labor coercion in the industrial stage of development has been an inevitable by-product of the emergence of capital-skill complementarity in the production process. In the earlier agricultural stage of development, production was largely intensive in unskilled labor, and landowning elites had an incentive to promote and maintain coercive institutions that limited labor mobility and boosted land rents.[2] Over the course of industrialization, however, the accumulation of physical capital by the landed elites coupled with the advent of capital-skill complementarity altered their viewpoint regarding the profitability of exploiting coerced labor, thus bringing an end to this oppressive institutional regime. Specifically, in light of the growing significance of skilled labor for fostering the return to physical capital, landowning capitalist elites were induced to relinquish their historically advantageous coercion of labor in favor of employing free skilled workers. These uncoordinated actions of the elites, in turn, incentivized the masses to engage in broad-based human capital acquisition, without fear of losing their skill premium to expropriation.[3] The posited mechanism therefore suggests that willingness to abandon the extant

[1] In particular, the Age of Enlightenment is known to have triggered major institutional transformations (e.g., *de jure* agrarian reforms and the abolition of serfdom) throughout regions of Europe that were occupied by Napoleon's French Revolutionary Army, paving the way for subsequent economic development (Acemoglu et al., 2011; Buggle, 2016).

[2] It is generally agreed, however, that because feudal relations prevented labor from being allocated efficiently, the process of society-wide economic development was held back in regions characterized by coercive institutions and elite absolutism (North and Thomas, 1973; Brenner, 1976; De Long and Shleifer, 1993; Acemoglu et al., 2011).

[3] The emancipation of labor in this hypothesis therefore reflects institutional reform that is mutually beneficial for all the social classes, rather than an outcome of a divisive struggle between the working class and the elites. A similar viewpoint is shared by Lizzeri and Persico (2004) in their study of the extension of suffrage institutions during Britain's "Age of Reform." The role of alternative economic forces in the emergence of labor emancipation is explored by Lagerlöf (2009). In his theory, the elites choose between imposing serfdom and freedom in order to maximize their payoffs, as determined by population density and the level of technology.

regime of labor coercion was more pronounced amongst elites with larger initial stakes in forms of physical capital that came to be associated with skill-intensive industrialization.[4]

The proposed hypothesis is examined empirically by exploiting both cross-sectional and temporal variations in *de facto* serf emancipation in nineteenth-century Prussia. Although serfdom was *de jure* abolished throughout Prussia in 1807, the process of *de facto* emancipation from coercive institutions evolved heterogeneously across regions, extending well into the second half of the nineteenth century. In particular, at the individual level, the termination of feudal labor relations was the outcome of a bilateral negotiation regarding the compensation owed to the manorial landlord for the redemption of lifetime servile duties by the serf, thus introducing sufficient scope for variation in the duration of the *de facto* emancipation process.[5] The empirical analysis therefore links the differential timing of *de facto* emancipation across regions of Prussia with corresponding variation in the initial abundance of a *relevant* form of proto-industrial physical capital; i.e., one that not only prefigured broad-based skill-intensive industrialization but was also exclusively owned by the landed elites.

Exploiting unique data on emancipation cases, originally collected and reported at the county level by the Prussian state agency that supervised these settlements, the analysis finds a positive and significant relationship across counties between the initial stock of relevant physical capital, as proxied by the number of water mills (per 1,000 inhabitants) in 1819, and the share of serfs that were *de facto* emancipated between 1821 and 1848.[6] This relationship proves to be remarkably robust to accounting for a wide range of potentially confounding factors, including observed heterogeneity across regions in geographical, cultural, and institutional characteristics and in various dimensions of historical development.[7]

The analysis implements two alternative strategies to mitigate potential concerns regarding endogeneity in the relationship between the initial abundance of relevant proto-industrial capital and the subsequent intensity of *de facto* serf emancipation. The first strategy, implemented in the

[4] In contrast to the notion that average worker skills were generally unimportant until later stages of industrialization, Franck and Galor (2017) uncover new evidence linking early industrialization with the rise in the demand for human capital in mid-nineteenth-century France, consistent with an earlier emergence of technology-skill complementarity. Moreover, Squicciarini and Voigtländer (2015) show that although the density of "upper tail" human capital, as proxied by the prevalence of knowledge elites, was instrumental for productivity *growth* (innovation) and urbanization during the first phase of the French Industrial Revolution, average worker skills, as proxied by literacy rates, were nevertheless important for the *level* of productivity under the existing technologies, in accordance with the complementarity of average skills with industrial production. Further, in the context of nineteenth-century Prussia, Becker, Hornung and Woessmann (2011) document that basic education was significantly associated with industrialization in its early stages. Similarly, Cinnirella and Streb (2017) find that literacy rates were positively related to productivity during the second phase of Prussian industrialization.

[5] In addition, state supervision provided a commitment device for both serfs and their manorial landlords to honor the redemption agreement (Ogilvie, 2014).

[6] As will be made evident in Section 4.2, for the purposes of empirically examining the proposed hypothesis, water mills are particularly suitable as a proxy measure of proto-industrial physical capital, first, because their ownership was institutionally restricted to the landed elites, and second, because they foreshadowed the adoption of steam engines and related skill-intensive methods of industrial production. Other contemporaneous proxy measures of proto-industrial physical capital, however, fail to satisfy either or both of these important restrictions.

[7] Interestingly, the prohibition of child labor outside of agriculture was adopted in Prussia in 1839 and, akin to our hypothesis of serf emancipation, may have been partly triggered by the emergence of skill-intensive industrialization and the associated decline in the relative productivity of child labor (Doepke and Zilibotti, 2005). In particular, the 1839 legislation prohibited the employment of children under nine in factory work, and it also stipulated that children under sixteen were to be excluded from such employment unless they previously completed at least three years of schooling or the factory provided its own school.

baseline cross-sectional setting, exploits the average slope of the terrain as a plausibly exogenous source of variation in the prevalence of water mills across counties in 1819, conditional on a sizable vector of other geographical factors. This strategy yields 2SLS estimates for the influence of initial capital abundance that are quantitatively similar to the baseline OLS estimates, suggesting that the latter are not marred by any substantial amount of endogeneity bias, given the identifying assumption regarding the conditional excludability of terrain slope.[8] The second strategy exploits time-varying district-level data on the number of settled redemption cases during the latter half of the nineteenth century, implementing a flexible panel setting in which the initial stock of relevant fixed capital is permitted to possess a time-varying relationship with the average annual *flow* of *de facto* emancipated serfs in different five-year periods. This strategy is able to account for unobserved heterogeneity across districts in time-invariant geographical, cultural, and institutional characteristics, in addition to the dynamic effects of time-varying sociopolitical and demographic observables at the district level as well as region-specific time trends in emancipation flows at higher levels of spatial aggregation.

The empirical analysis also explores the extent to which the main findings may reflect alternative theories of the historical decline in coercive labor institutions.[9] For instance, one class of theories emphasizes that coercion can decline either with an increase in labor abundance, due to the resulting depression in market wages, or when an increase in outside options for workers poses the threat of labor scarcity (Postan, 1966; Domar, 1970; Brenner, 1976; Acemoglu and Wolitzky, 2011).[10] Another alternative explanation is that the elites strategically relinquished political (and coercive economic) power over the masses in order to avert social unrest (Acemoglu and Robinson, 2000; Aidt and Franck, 2015). The analysis accounts for these particular alternative mechanisms by introducing controls for labor abundance, urbanization, and the prevalence of social uprisings. More generally, although these and other alternative theories are found to possess some explanatory power for the decline of serfdom in Prussia, the proposed hypothesis continues to explain a significant portion of the variation in the timing of *de facto* serf emancipation.

Furthermore, the empirical analysis provides additional corroborating evidence lending credence to the proposed interpretation of the positive reduced-form relationship between the initial

[8] A similar but conceptually more refined 2SLS strategy is implemented in Appendix B. This alternative strategy constructs and exploits an index of mill suitability – capturing *both* the topographic and the hydrological suitability of a location for constructing and operating a water mill – as a plausibly exogenous source of variation in the initial prevalence of water mills. As will become evident, due to the fact that mill suitability is overwhelmingly determined by topographic factors in the data, this alternative strategy yields results that are comparable to those obtained under the baseline 2SLS strategy.

[9] See Ogilvie and Carus (2014) for an overview of alternative explanations.

[10] More recently, Naidu and Yuchtman (2013) document labor market tightness as a driver of the selective use of coercive institutions in nineteenth-century industrial Britain, whereas Dippel, Greif and Trefler (2015) provide evidence that the decline of coercive institutions in the sugar plantations of the British Caribbean is associated with a rise in the inside potential for labor scarcity due to superior outside options for workers. An empirical exploration of the salience of the labor-scarcity mechanism across societies in a global sample is conducted by Fenske (2013). At a conceptual level, the threat of outside options for workers becomes binding for the abolition of coercive institutions when the concentration of economic resources in the hands of the elites – i.e., resources that could be used to counter such a threat – is either stagnant or declining. In contrast, the proposed hypothesis suggests that the abolition of coercive institutions can occur when the concentration of economic resources among the elites is, in fact, *increasing* over time, due to market rents associated with the accumulation of physical capital. As such, the prevalence of the alternative mechanism associated with labor scarcity only serves to introduce *downward* bias to the estimates associated with the proposed mechanism.

stock of relevant fixed capital and the intensity of *de facto* serf emancipation by the mid-nineteenth century. First, exploiting heterogeneity across counties in the average cost of redemption per emancipation case (i.e., the negotiated emancipation "price" between the manorial landlord and the serf), the analysis finds that the prevalence of water mills in 1819 is negatively associated with the average cost of redemption per emancipation case as of 1848. This result is in accordance with the notion that landlords with increasing stakes in skill-complementing physical capital were more willing to accept lower redemption costs and, thus, hasten the process of serf emancipation. Second, consistent with an *indirect* outcome of the proposed hypothesis, the rate of serf emancipation as of 1848 is shown to be positively associated with the subsequent rate of human capital accumulation, as reflected by either the enrollment rate in public primary schools in 1864 or the literacy rate amongst the population aged 10 and above in 1871.[11] Moreover, in line with the historical narrative of the Prussian labor emancipation experience, the analysis provides *prima facie* empirical evidence that labor markets were highly segmented across Prussian counties in the early nineteenth century, suggesting that the *de facto* serf emancipation process primarily reflected *local* labor market conditions. Specifically, the presence of relatively autarkic market conditions at the county level makes the observed variations across Prussian counties in initial capital abundance and subsequent emancipation and human capital formation suitable for empirically examining the proposed hypothesis.[12]

This paper contributes to both sides of the broader debate on the causes of institutional change in societies. On the one hand, the proposed hypothesis advances modernization theory (Lipset, 1959; Barro, 1999; Glaeser et al., 2004; Glaeser, Ponzetto and Shleifer, 2007), highlighting structural economic transformation, particularly the rise in the importance of human capital in the process of development, as a catalyst of institutional change. On the other hand, in light of the fact that the "defensive modernization" of Prussia, comprising the *de jure* agrarian and emancipation reforms of the early nineteenth century, occurred partly as a response to the threat from the militaristic diffusion of the ideas of the French Revolution, the empirical findings highlight modernization as a driver of *de facto* changes in local institutions, following the "critical juncture" (Acemoglu and Robinson, 2012) of a *de jure* change in centralized state institutions.

The emphasis of the proposed hypothesis on capital-skill complementarity and the increased demand for human capital in the process of industrialization relates with previous studies that have highlighted the importance of this phenomenon for understanding the emergence of support for universal public schooling by the elites (Galor and Moav, 2006; Galor, Moav and Vollrath, 2009). In contrast to these contributions, this paper advances the fundamental insight that, by itself, the provision of universal public education by the elites is insufficient to guarantee investments in human capital by the masses, particularly when the skill premium may be subject to expropriation

[11] It is crucial to note, however, that the proposed hypothesis employs a broad interpretation of investments in human capital, reflecting any private effort undertaken to increase effective labor, encompassing skill acquisition through not just formal education but also occupational training and experience, as well as improvements in health.

[12] In addition, the proposed hypothesis suggests that the elites within a given county did not need to solve a collective action problem, in terms of coordinating on the timing of emancipation of their respective serfs. In particular, according to the posited mechanism, there is no *ex post* threat of labor scarcity to a member of the elite from freeing his serfs, because the complementarity between free workers and the elite's physical capital ensures that, upon being rehired as free workers, his former serfs would earn wage rates that are at least as high as any local outside option.

under coercive institutions.[13] Thus, the abolition of coercive institutions by the elites represents a *necessary* precondition for efficient investments in human capital.

Although the focus of this paper is on the *causes* of labor emancipation, it contributes to an emerging literature devoted to the long-run *consequences* of coercive labor institutions. Cinnirella and Hornung (2016) provide supporting evidence that serf emancipation was indeed related to subsequent increases in formal schooling in the Prussian context.[14] Similarly, McElroy (2017) finds that local variation in serf obligations shaped post-emancipation patterns of human capital accumulation in Russia. Markevich and Zhuravskaya (forthcoming) document that serf emancipation was related to subsequent increases in agricultural productivity in nineteenth-century Russia. Relatedly, Nafziger (2012) presents evidence that the abolition of serfdom also affected non-farming activities undertaken by former serfs in the Russian context, whereas Buggle and Nafziger (2017) examine the long-run consequences of the intensity of labor coercion for present-day comparative development across post-Soviet regions. Finally, Acemoglu et al. (2011) document that institutional reforms, including the *de jure* abolition of serfdom, that arose from the diffusion of the French Revolution into European regions occupied by the French are associated with differential patterns of long-run economic development across German polities.

The remainder of the paper is structured as follows. Section 2 provides a basic formalization of the proposed hypothesis. Section 3 discusses the historical and institutional background relevant for the labor emancipation and proto-industrialization experiences in the Prussian context. Section 4 introduces the unique administrative data on *de facto* serf emancipation that is exploited by the empirical analysis, along with the main explanatory variable and various geographical and historical covariates. Section 5 reveals and discusses the empirical findings, and finally, Section 6 concludes.

2 Conceptual framework

In this section, we present a basic model that highlights our novel mechanism underlying the emancipation of labor. Specifically, the model demonstrates how the accumulation of physical capital raises the demand for human capital due to the complementarity between these factors in the production process, thereby incentivizing landowning capitalist elites to grant freedom to laborers, in order to encourage the latter to undertake costly investments in pertinent skills. The purpose of our model is to highlight this particular channel, emphasizing the role of skill-intensive industrialization in driving the abolition of serfdom. Thus, we intentionally abstract from a variety of complementary theories of the evolution of coercive labor institutions that have been examined previously in the literature. We also discuss how our model can be integrated into a richer (and, admittedly, more realistic) framework without altering the fundamental insight.

[13] Furthermore, because educational investments require private effort that is costly to monitor, compulsory schooling in the presence of expropriation would not ensure the first-best outcome, in terms of the effort exerted by the masses towards the accumulation of human capital.

[14] A related literature (e.g., Sacerdote, 2005; Bertocchi and Dimico, 2014; Bobonis and Morrow, 2014) has explored the relationship between slavery in the Americas and the accumulation of human capital.

2.1 The basic model

Consider a society comprising two classes of individuals: landowning capitalists (elites) and coerced laborers (serfs). Their respective population shares are $\lambda \in (0,1)$ and $1-\lambda$. Rather than drawing an explicit distinction between landowners and capitalists (e.g., Doepke and Zilibotti, 2008; Galor, Moav and Vollrath, 2009), we portray the elites as a single class. The elites in our model may therefore be viewed as the landowners from Galor, Moav and Vollrath (2009) that have already gained sufficiently large stakes in industry from their accumulation of physical capital – an outcome that occurs inevitably in the process of economic development. As explained in Section 3.3 below, our modeling choice is also consistent with the historical reality of nineteenth-century Prussia, where landowners were amongst the most active early capitalists, establishing industrial methods of production on their own estates. For simplicity, we assume that the initial economy-wide capital stock, K_0, is uniformly distributed amongst the elites. In addition, assuming a uniform distribution of (implicit) landownership rules out any conflict of interest between landowning and capitalist elites in our model.

The economy lasts for two periods. At the beginning of the first period, the elites – who hold all the political power in this economy – decide on the status of the laborers; namely, whether they should be coerced or granted economic freedom in the second period. We assume that the elites can credibly commit to enforcing such a decision by enacting the legislation sufficient for the abolition of serfdom.[15] After learning about their status, the laborers decide whether to undertake costly investment in their human capital. Production occurs in the second period, in which the laborers and the elites inelastically supply human and physical capital, respectively.

Output, Y, is produced according to a standard Cobb-Douglas production function, using physical and human capital, K and H, as inputs:

$$Y = AH^{1-\alpha}K^{\alpha}, \quad \alpha \in (0,1),$$

where A is the index of technological advancement, or total factor productivity (TFP). Since the objective of our basic model is to distill the role of industrialization in transforming coercive labor institutions, we abstract away from explicitly including land as factor of production, thus focusing squarely on the key complementarity between physical and human capital in the production process. As mentioned earlier, we consider capital-owning elites that are deciding for or against employing serf labor in industrial or proto-industrial production, rather than in agriculture. It is also worth noting that we adopt a broad definition of human capital that goes beyond just formal schooling, including occupational skills that require costly effort and learning to acquire, as well as worker characteristics that contribute to labor productivity such as better health. Thus, the stock of human capital in our model economy may be viewed as the supply of effective rather than raw labor.

[15] According to Ogilvie and Carus (2014), the economic history of Prussian serfdom provides "arguably the best example" of how the state was instrumental for solving the credible commitment problem, by devising and enacting a clear set of rules for serf emancipation. Unlike our framework, however, these authors view the abolition of serfdom as a zero-sum event wherein the serfs were the only winners from the emancipation reforms. As such, to ensure that the reforms would not be blocked by the losing elites, the commitment of the reforms to adequately compensate the landlords was effectively enforced by the accompanying legislation.

In the state of the world with freed labor, factors earn their marginal products, i.e.,

$$r = \alpha A k^{\alpha-1}, \quad w = (1-\alpha)Ak^{\alpha}, \quad k \equiv K/H,$$

where r and w are, respectively, the rate of return to physical capital and the wage rate under perfectly competitive factor markets in this economy.[16] Under serfdom, the rich appropriate all of the output after providing a "subsistence" level of consumption, $\tilde{c}$, to each laborer.

At the beginning of the first period, should the elites decide to maintain serfdom, the laborers will not have any incentive to undertake the costly acquisition of human capital, because in the second period, they would invariably receive only $\tilde{c}$. In addition, we assume that the elites cannot effectively force their serfs to acquire human capital and/or supply it without moral hazard to the production process. The underlying argument here is that it is much more difficult to monitor both the acquisition and the application of skills, in comparison to the monitoring of raw labor. In contrast to simple agricultural production, the effort, attentiveness, and quality of workers in skill-intensive production are observed much more noisily, thus making both monitoring compliance and the setting of output targets exceedingly costly and ineffective.[17] We consider an extreme case in which the extraction of skills by force is completely infeasible and/or the costs of effectively monitoring the application of skills are prohibitively high. As such, the laborers will only consider investing in human capital if they are granted the economic freedom to secure the perfectly competitive rate of return from that investment.[18] Specifically, under freedom they choose their effort level, e, in order to maximize the following utility function:

$$wh(e) - v(e) = w(1+e)^{\phi} - e,$$

[16]For simplicity, we assume that physical capital depreciates fully in each period, so that the gross and net returns to physical capital are identical.

[17]This argument goes back at least to Fenoaltea (1984), who considered the relative effectiveness of pain incentives and monitoring in land- or labor-intensive versus capital- or "care-intensive" production. As he points out, "human capital – the exercise of skill – is particularly subject to covert sabotage," and in the limit, it can take "the full time of one skilled supervisor to monitor one skilled worker" (pp. 639–640). As a result, increasing the complexity and skill-intensiveness of the production process lowers the effectiveness of pain incentives and raises the cost of administering them. A related argument has been made by Millward (1984), who in rationalizing the adoption of serf-labor quitrent systems amongst the serfowning nobility in Eastern Europe, contends that "[t]he more uncertain the production venture and the smaller was the scope for scale economies in supervising groups of serfs the more profitable was it for the noble to avoid setting predetermined performance levels and to give the serf economic incentives to raise output" (p. 425). Indeed, as noted by Schlumbohm (1981), the German nobility withdrew from their attempts to organize industrial production under the feudal system after early trials were overwhelmingly unsuccessful, primarily due to the fact that "industrial products demanded a higher quality of workmanship than could be enforced under feudal relations" and because "differences in quality seem to have affected the marketability of industrial goods to a much greater extent than that of standard agrarian products" (pp. 96–97).

[18]Although, for simplicity, we abstain from explicitly modeling micro foundations, our reasoning is motivated by the theory of incomplete contracts (Grossman and Hart, 1986; Hart and Moore, 1990) in recognizing that the severity of the hold-up problem increases in the skill-intensity of production. In particular, investment into production-specific skill formation by the serfs loses value when the relationship breaks up, giving full coercive power to the elite. Consequently, as long as serfdom is in place, the elite cannot specify a contract that incentivizes the serfs to undertake the necessary investment in skills and, thus, ensure the desired quality of output. The suboptimal level of relationship-specific investment could be mitigated or avoided, however, by emancipating the serfs – namely, lifting the institutionalized restrictions on their mobility and granting the impartial enforcement of contracts (see, e.g., Nunn, 2007).

where w is the perfectly competitive wage rate in the second period; $h(e) = (1+e)^{\phi}$, $\phi \in (0,1)$, is the human capital production function, which is increasing and concave in the amount of effort, e; and $v(e) = e$ is the disutility of this effort. Further, $h(0) = 1$, so each laborer is endowed with a basic unit of human capital (raw labor) to be supplied in the second period. Utility maximization by a laborer then yields the following optimal level of effort under freedom:

$$e^* = \max\left\{(\phi w)^{\frac{1}{1-\phi}} - 1, 0\right\} = \max\left\{(\phi(1-\alpha)Ak^{\alpha})^{\frac{1}{1-\phi}} - 1, 0\right\}.$$

It therefore follows that under serfdom, the total stock of human capital (raw labor) is equal to $(1-\lambda)h(0) = (1-\lambda)$, whereas under freedom, it is $(1-\lambda)h(e^*) = (1-\lambda)(1+e^*)^{\phi}$. For simplicity, we assume that the elites do not participate in the labor market, so they depend entirely on their capital rents.

At the beginning of the first period, the capitalists make their decision regarding the status of the laborers, passing the corresponding legislation if they choose to abolish serfdom. The elites make this choice in order to maximize their second-period income. Under freedom, this income is simply rK_0, the total competitive-market return to physical capital, whereas under serfdom, it is $Y - (1-\lambda)\tilde{c}$, the total output of the economy after providing for the subsistence consumption of all the laborers.

Should the laborers find it optimal to invest a positive amount of effort in human capital acquisition under freedom (i.e., when $e^* > 0$), the equilibrium level of capital per effective worker, k, would be given by

$$k = \frac{K}{H} = \frac{K_0}{(1-\lambda)\left(\phi(1-\alpha)Ak^{\alpha}\right)^{\frac{\phi}{1-\phi}}} \quad \Longrightarrow \quad k = \left(\frac{K_0}{1-\lambda}\right)^{\frac{1-\phi}{1-\phi(1-\alpha)}} \cdot (\phi(1-\alpha)A)^{\frac{\phi}{\phi(1-\alpha)-1}}.$$

Alternatively, under serfdom, or if $e^* = 0$ under freedom, then $k = K_0/(1-\lambda)$. Along with the function for the optimal level of effort, this implies that the laborers will invest a positive amount of effort in human capital acquisition if and only if they are free and the following condition holds:

$$\kappa \equiv \left(\frac{K_0}{1-\lambda}\right)^{\alpha} > \frac{1}{\phi(1-\alpha)A} \equiv \hat{\kappa}.$$

In other words, investment in human capital is more attractive to freed laborers when the perfectly competitive wage rate is high – i.e., when the stock of complementary physical capital is large and/or the economy's technological level is more advanced.

In the second period, under freedom, the income of the elites is given by $rK_0 = \alpha Ak^{\alpha-1}K_0$, and it is strictly increasing in the stock of human capital acquired by the laborers, as the latter augments the rate of return to physical capital due to the complementarity between the two factors in the production process. Under serfdom, however, since $K = K_0$ and $H = 1-\lambda$, the second-period income of the elites is equal to $A(1-\lambda)^{1-\alpha}K_0^{\alpha} - (1-\lambda)\tilde{c}$. In order to realistically model the process of labor emancipation, we only consider the range of K_0 values for which serfdom is initially profitable for the elites, in the sense that the marginal product of labor is sufficiently large to cover the level of subsistence consumption per worker:

$$(1-\alpha)A\left(\frac{K_0}{1-\lambda}\right)^{\alpha} > \tilde{c} \iff \kappa > \frac{\tilde{c}}{(1-\alpha)A} \equiv \bar{\kappa}. \tag{A1}$$

Otherwise, it would be too costly for the elites to meet the subsistence consumption requirement of the laborers, thereby making the elites unconditionally better off by immediately granting freedom to the laborers, even if no effort will be made to acquire human capital. Therefore, to ensure the historical presence of serfdom prior to the advent of emancipation reforms, we assume that (A1) holds, which then implies that enacting emancipation reforms would not be optimal for the elites if the freed workers do not end up investing a positive amount of effort in the acquisition of human capital.[19] In addition, we assume that $\bar{\kappa} < \hat{\kappa}$, which holds if and only if

$$\phi\tilde{c} < 1. \tag{A2}$$

This ensures that for small enough levels of K_0 satisfying (A1), the laborers would not invest in human capital under freedom, so maintaining serfdom in the second period is more profitable from the viewpoint of the capitalists.

The elites will choose to abolish serfdom if and only if their second-period income under freedom exceeds that under serfdom; i.e., if and only if

$$rK_0 = \alpha A\left(\frac{K_0}{1-\lambda}\right)^{\frac{(1-\phi)(\alpha-1)}{1-\phi(1-\alpha)}} \cdot (\phi(1-\alpha)A)^{\frac{\phi(\alpha-1)}{\phi(1-\alpha)-1}} \cdot K_0 > A(1-\lambda)^{1-\alpha}K_0^{\alpha} - (1-\lambda)\tilde{c},$$

which upon rearrangement yields

$$\alpha A\kappa^{\frac{1}{1-\gamma}} \cdot (\gamma A)^{\frac{\gamma}{1-\gamma}} > A\kappa - \tilde{c}, \quad \gamma \equiv \phi(1-\alpha) \in (0,1).$$

Under assumptions (A1) and (A2), there exists a unique level of κ, κ^*, such that labor emancipation occurs if and only if $\kappa > \kappa^*$, as shown in Figure 1. It follows immediately that there exists a unique level of capital per unit of raw labor, $k_0^* = K_0^*/(1-\lambda) = (\kappa^*)^{1/\alpha}$, such that labor emancipation occurs if and only if $k_0 > k_0^*$. It is also worth noting that the profitability of serfdom from the viewpoint of the elites clearly increases in K_0, given that subsistence consumption per worker is fixed. Nevertheless, due to the boost in the acquisition of human capital by the laborers under freedom, the profitability of freedom rises even more strongly, ultimately making it incentive compatible for the elites to abolish serfdom. In sum, our basic model suggests that, all else equal, a larger stock of physical capital per worker contributes to the process of labor emancipation. In particular, the initial abundance of elite-owned physical capital that became associated with skill-intensive industrialization is expected to be positively linked, *ceteris paribus*, with the subsequent rate of labor emancipation.

[19] Clearly, (A1) also implies that the laborers are unconditionally better off under freedom, while a violation of (A1) implies that free laborers would rather be enserfed and provided a subsistence level $\tilde{c}$ by the elites.

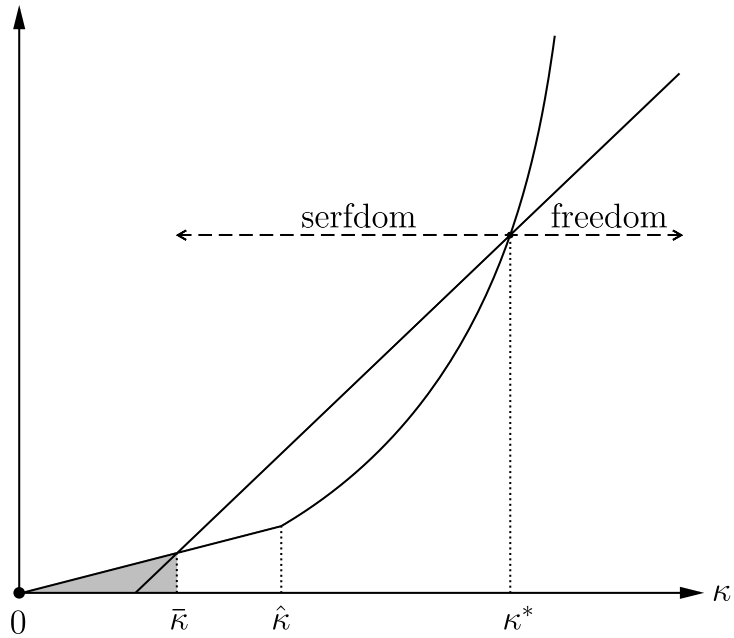


FIGURE 1: Physical capital and labor emancipation

Notes. This figure graphically depicts how the second-period income of the elites compares under serfdom versus freedom of the laborers for different values of $\kappa \equiv (K_0/(1-\lambda))^{\alpha}$, which is an increasing function of the initial stock of physical capital per unit of raw labor. For $\kappa < \bar{\kappa}$, serfdom is never profitable for the elites, so this region is disregarded. For $\kappa \in [\bar{\kappa}, \kappa^*]$, maintaining serfdom is more profitable than granting freedom, even though for $\kappa > \hat{\kappa}$, the laborers would actually invest in human capital if freed. Finally, for $\kappa > \kappa^*$, freedom is more profitable for the elites than serfdom.

2.2 Extensions of the framework

Our basic model can be extended along several dimensions to incorporate a more realistic set of assumptions without qualitatively altering the key insight. First, although in the interest of clarity, we opted to present our main argument in a two-period setting, our model can be seamlessly integrated into a standard overlapping-generations framework à la Galor and Moav (2004, 2006) or Galor, Moav and Vollrath (2009), incorporating endogenous physical capital accumulation. In such a dynamic model, capital accumulation would be driven by either the bequest or the standard saving motive, and the choice between the preservation and the abolition of serfdom would be made by each generation of the elites. Prior to the emancipation of labor, the growth process would be driven purely by the accumulation of physical capital by the elites, but following emancipation, the former serfs would also contribute to this process, initially through their accumulation of human capital alone and eventually through their accumulation of physical capital as well (see, e.g., Galor and Moav, 2006). The value added of such a dynamic framework is that by making the process of physical capital accumulation more explicit, it would demonstrate more evidently that the abolition of serfdom occurs as a natural by-product of the process of economic development. Relatedly, technological progress in such a model, as reflected by a gradual rise in the level of productivity, A, would produce a similar effect as physical capital accumulation, because in light of technology-skill complementarity, TFP growth will not only raise the elites' demand for mass investments in human capital but also encourage skill acquisition by the freed laborers.

Second, relaxing the simplifying assumption that the elites do not participate in the labor market and, thus, do not engage in human capital accumulation would have the following implications. Naturally, the elites would initially invest in their own human capital when the rate of return from this investment becomes sufficiently high – i.e., when there is a large enough stock of physical capital. Although this process is likely to delay the emancipation of the class of coerced laborers, diminishing returns to human capital accumulation at the individual level will ensure that, sooner or later, continued skill formation by the elite minority will cease to support a high rate of return to physical capital. Thus, akin to our basic model, the anticipated expansion in economy-wide human capital generated by large-scale skill acquisition on part of the freed laborers would eventually make it incentive-compatible for the elites to abolish serfdom.[20]

Third, although our basic model assumes that the acquisition of human capital by the freed laborers does not involve any fixed cost in terms of output (or the consumption good), relaxing this assumption and even introducing the more realistic feature of credit market imperfections (e.g., Galor and Zeira, 1993; Galor and Moav, 2004, 2006; Doepke and Zilibotti, 2008; Galor, Moav and Vollrath, 2009) would again merely serve to delay the abolition of serfdom by the elites. In particular, under binding constraints on the ability of the former serfs to obtain credit, the elites would have to tax themselves in order to finance the real cost associated with the acquisition of human capital by the masses (e.g., through public schooling), and as such, the profitability of granting freedom from the viewpoint of the elites would become conditioned by the amount of this fixed tax burden. Nevertheless, once the elites' demand for mass acquisition of human capital becomes sufficiently high due to a large enough stock of physical capital, they will find it incentive-compatible to financially support large-scale emancipation and the concomitant acquisition of human capital by the freed laborers, as the profitability of granting freedom net of the fixed tax burden inevitably rises above the profitability of maintaining the status quo with serfdom.

Fourth, as discussed earlier, our basic model abstracts from the potential conflict of interest between landowners and capitalists in the decision to maintain or abolish serfdom, choosing instead to treat the elites as a single class of "landowning capitalists" with equal stakes in the economy's assets. The implications of relaxing this assumption, however, can be readily inferred from the findings of Galor, Moav and Vollrath (2009), who examine the role of landownership inequality in delaying the emergence of human-capital promoting institutions, such as public schooling. A central feature of their argument is that human capital is less complementary to land than it is to physical capital and, therefore, as long as their stakes in industrial production are small, the landed aristocracy has little economic incentive to financially support the advent of universal education, which would not only require taxing themselves explicitly but would also divert workers away from the agricultural sector, thereby raising wages and lowering the return to land. Therefore,

[20]It may be noted that in such an extension of the model, wherein the elites are allowed to engage in human capital accumulation, the decision to maintain or abolish serfdom will be conditioned by a secondary effect of emancipation on the profitability of freedom from the viewpoint of the elites. Namely, the subsequent increase in the economy-wide supply of human capital will tend to depress the wage income of the elites, thereby serving to delay their support of large-scale emancipation reforms. Because this general equilibrium effect simply obfuscates our main mechanism and unnecessarily complicates the analysis, we choose to model the elites as a purely rentier class.

to the extent that the landowners affect the political process, this consideration would impede the introduction of public schooling. For precisely the same rationale, if our basic model were extended to incorporate the two-sector structure of Galor, Moav and Vollrath (2009), the abolition of serfdom would, yet again, be merely delayed by the presence of politically influential landowning elites, at least until their stakes in industrial production become sufficiently large so as to align their economic interests with those of the capitalist elites.[21]

Finally, consider the possibility that there exists an external urban industrial sector that always offers a higher wage to workers relative to what free laborers could earn in the rural industrial sector. Our main mechanism would indeed be operative in the presence of such an outside option for emancipated serfs, so long as the *ex ante* probability of their reallocation to the urban sector upon gaining freedom is less than one. This would be the case if there are significant impediments to labor mobility across space, due to geographically or institutionally imposed mobility costs, and there is heterogeneity across workers in their willingness or ability to absorb such costs. Common knowledge regarding the presence of such impediments, combined with access to private information on their serfs, would be sufficient for capitalist landowners to realize that a significant portion of their emancipated peasants would continue to remain employed in the rural industrial sector as freed workers. Indeed, as discussed in the next section, such an outcome appears to have been typical in our particular historical setting.[22]

Overall, our fundamental insight regarding the influence of physical capital accumulation by the elites in society on their decision to support large-scale labor emancipation remains qualitatively unchallenged by these additional considerations.

3 Historical background

3.1 Agrarian reforms, *de facto* emancipation, and elite class structure

The Prussian agrarian (Stein-Hardenberg) reforms of the early nineteenth century provide a historical setting that is particularly well-suited for empirically examining our hypothesis regarding the role played by industrialization and the associated economic interests of capitalist elites in driving the decline in coercive labor institutions. In what follows, we briefly discuss some of these key reforms and how they served to generate rich heterogeneity in the pace and extent of *de facto* labor emancipation across regions of Prussia over the course of the nineteenth century.[23] We also discuss how these reforms served to shift the composition of the class of rural elites to incorporate landed manorial entrepreneurs with bourgeois orientations towards industrial production methods. To be

[21] We relax our theoretical assumption in our empirical analysis, where we account for the potential role of "conservative" landowners by including a measure of concentration in landownership in our estimating equation.

[22] In addition, our empirical analysis in Section 5.2.5 uncovers evidence that although urbanization is indeed positively associated with day-laborer wages, accounting for this association does not qualitatively alter the role of capital-ownership by the nobility as a contributing force in the emancipation of serfs.

[23] Appendix D provides some additional details, summarizing the heterogeneity in the *de jure* emancipation process across different categories of the enserfed peasant population, both in the Prussian territories that were not ceded to France in the Second Treaty of Tilsit (1807) as well as in those territories that were annexed or regained by Prussia following the Congress of Vienna (1815).

clear, we view these outcomes of the reforms as important for producing the variation necessary for the falsification of our hypothesis.[24]

As of the late eighteenth century, peasant labor coercion associated with feudal political authority had been practiced for centuries by Prussian Junkers (the landed aristocracy) at varying levels of intensity throughout the Kingdom of Prussia (see, e.g., Ogilvie and Carus, 2014). A marked change in *de jure* institutions, however, occurred in the early nineteenth century, following the defeat of Frederick William III of Prussia by Napoleon's forces at the Battle of Jena-Auerstedt in 1806 and the ensuing Second Treaty of Tilsit, in which Prussia ceded about half of its territories and was forced to make substantial tribute payments to France. This adverse shock to the political economy of the region triggered the so-called "defensive modernization" of Prussia, based on Frederick William III's position that the Prussian state and Prussian society could not survive unless progressive reforms were enacted. Thus, for a short period of time, the balance of power in Prussian society shifted away from the landed nobility to a group of progressive bureaucrats that enacted various *de jure* institutional reforms based on the principles of economic liberalism, including the granting of equality before the law and freedom from personal subjection to the entire population of Prussia from 1810 onwards, as per the "October Edict" of 1807. Although the October Edict did not necessarily dissolve the bonded servile duties owed to the nobility by the peasantry, or even specify how peasants could redeem their lifetime labor dues, it ended the nobility's *de jure* monopoly over the ownership of large manorial (knight) estates. This was followed by the "Regulation Edict" (*Regulierungsedikt*) of 1811, which granted peasants holding weak (i.e., non-hereditary) land tenure the legal right to ownership of the lands that they farmed as well as the ability to redeem their lifetime servile dues, but only upon handing over between a third and two-thirds of these lands to their former manorial lords as compensation.[25]

The process leading up to the full *de facto* emancipation of the peasantry, however, extended well into the final decades of the nineteenth century, as the balance of power shifted back towards the conservative landowning nobility, in the aftermath of the German Campaign of 1813 that effectively ended the short-lived domination of Prussia by the French with Napoleon's defeat at the Battle of Leipzig. Following the Congress of Vienna in 1815, the Kingdom was established within

[24]Our hypothesis is broadly consistent with various elements of the Prussian historical narrative regarding emancipation and industrialization. For instance, Pierenkemper and Tilly (2004) have described the Prussian peasant emancipation process (*Bauernbefreiung*) as a prerequisite for the widespread adoption of industry, arguing that labor productivity increased over the course of the reform period. Nevertheless, the historical literature on peasant emancipation in Prussia has generally tended to focus either on the redistribution of resources from peasants to the nobility (e.g., Schissler, 1978; Dipper, 1980; Harnisch, 1984; Pierenkemper, 1989) – i.e., as a result of the compensation payments from the former to the latter for the commutation or redemption of labor dues – or on the economic conditions of those peasants who remained attached to agriculture following their emancipation (e.g., Knapp, 1887; Böhme, 1902; Berthold, 1978). Ignoring the emancipation-oriented incentives associated with the emergence of capital-ownership amongst the landed nobility, this literature has tended to highlight other complementary forces underlying the nobility's rationale to ultimately agree to the emancipation reforms, including changing market conditions in agricultural free-labor and goods markets, the temporary decline in political power amongst the nobility in the aftermath of Prussia's defeat by Napoleon in 1806, and the allocation of compensation payments to overcome debts associated with noble estates.

[25]Interestingly, the anecdotal evidence from historians suggests that at least part of the motivation for these reforms amongst the reformers themselves was the attainment of higher economy-wide productivity. For instance, as Reddy (1987, p. 84) notes, "Hardenberg had promised in 1811 that "the state would thus acquire a new, estimable class of motivated property owners" and that "through the desire to enter this class, the cultivation of the soil would profit from more hands, and through their greater effort, because freely given, more work as well.""

new borders, regaining most of its territories lost during the Napoleonic wars and annexing new territories in the western regions of the former Holy Roman Empire (Rhineland and Westphalia) and in Saxony. As a result of conservative opposition to the reforms from a rehabilitated landed aristocracy, the Regulation Edict (as it applied to both landownership and emancipation reform) was amended by the "Declaration" of 1816 to exclude peasants residing on small parcels of land (*nichtspannfähige Nahrungen*) from acquiring allodial title rights and, thus, from also redeeming their lifetime servile dues to the nobility.

A further step towards increased *de facto* emancipation of the peasantry occurred in 1821, when the "Dissolution Ordinance" (*Ablösungsordnung*) clarified how peasants holding strong (i.e., hereditary) land tenure could terminate their feudal labor relations; namely, by compensating their manorial lords with 25 times the annual value of forgone services and labor dues in either money or land. Thus, in spite of *de jure* emancipation, the obligation borne by the peasants to substantially compensate their manorial lords, combined with the bargaining power of the landed nobility over certain terms of redemption process (to be discussed below), effectively stretched *de facto* emancipation into a long and heterogeneous process across regions and even estates throughout nineteenth-century Prussia.[26] Moreover, it was only after the passage of the "Commutation Law" of 1850, adopted by the new parliament in the aftermath of the German Revolution of 1848–1849, that surviving servile duties, particularly those associated with peasants residing in the small land parcels that were excluded from emancipation by the Declaration of 1816, could be *de jure* liquidated via redemption payments to the nobility.

In addition to generating heterogeneity in the *de facto* emancipation process across Prussia, the agrarian reforms of the early nineteenth century served to alter the composition of the landed nobility towards an ever increasing representation of the bourgeoisie. As mentioned previously, a significant aspect of the October Edict of 1807 was the termination of the nobility's monopoly over manorial landownership, thereby permitting the free trade of noble estates. Following Prussia's defeat to Napoleon in 1806, the market for noble estates was opened to commoners as part of an effort to recapitalize the economy, which was now overburdened by its enormous reparations to France. Consequently, the capital market witnessed an increase in the trade of manorial estates and, according to Schiller (2003, p. 477), the replacement of less productive noble estate owners. Once the market became accessible to commoners, the early purchasers of knight estates were primarily merchants and industrialists from Berlin, but the group included mill owners and master masons as well (Schiller, 2003, p. 259). By the mid-nineteenth century, however, a significant share of manorial estates were owned by the non-nobility, and the sizable representation of the bourgeoisie in this group led to a "socially mixed elite of landed businessmen" (Bowman, 2011, p. 33).[27]

3.2 Redemption of servile dues and peasant mobility

As mentioned previously, despite the *de jure* emancipation of the peasantry under the October Edict, the rehabilitation of the landed nobility in the period following the Congress of Vienna

[26]For a nuanced picture of the emancipation process in Prussia, see Eddie (2013).

[27]Indeed, as Bowman (2011, p. 32–33) affirms, "[t]he influx of commoners into the ranks of Junkerdom spurred what Reinhard Koselleck calls "the creeping transformation of the landed nobility (*Ritterstand*) into an entrepreneurial class of manorial lords (*Gutsherren*).""

permitted them to exert substantial control over the pace of the *de facto* emancipation process, by conditioning the terms associated with the redemption of lifetime servile dues to reflect their own economic interests. This is an important aspect of the Prussian peasant emancipation experience as it suggests that the progressive nobility and the landed bourgeoisie may have been willing to accelerate emancipation by settling for terms that were more favorable to their peasants.[28] We provide a brief narrative below on the redemption process itself and how the elites came to exert their authority over this process, thereby influencing the pace of *de facto* emancipation following the Prussian agrarian reforms.

The redemption process (*Reallastenablösung*) associated with each emancipation case was overseen by the General Commission (*Auseinandersetzungsbehörden*), staffed with public officials possessing legal training and knowledge of agricultural markets. At the highest level of administration, the Commission comprised a total of 6 agencies, each holding jurisdiction over several districts. At the lowest administrative level, the county mediation agency (*Kreisvermittlungsbehörde*) was staffed with 2-6 local officials that were elected by the county assembly and worked closely with the county supervisor (*Landrat*). Importantly, because the county assembly was predominantly composed of noble landowners, officials at the county mediation agency were typically strongly aligned with entrenched members of the local nobility.

The settlement (*Auseinandersetzung*) between a manorial lord and his serf peasants was triggered by the so-called "provocation of the redemption" (*Provozierung der Ablösungen*) and was to be filed with the General Commission.[29] Either party could initiate the process, resulting in a formal hearing where the exact amount of the compensation payment was to be determined by the parties and arbitrated by an expert.[30] Contemporary observers from the period acknowledge that forgone labor services were extremely difficult to value, so "norms" for the valuation of compensation payments to the nobility had to be set by central authority (Eddie, 2013, p. 211). Consequently, redemption values were based on either "normal prices" (*Normalpreise*) or expert judgment.

As noted by Berdahl (1988), following the passage of the Dissolution Ordinance, "tempering of the moderate reforms had begun in the interest of the landowning nobility" (p. 269). The nobility protested against the bureaucratic intrusion into what they deemed to be a "happy patriarchal relationship" on their lands and appealed to the Crown to leave the settlements for the lords to work out with their peasants (Berdahl, 1988, p. 281). In response to these appeals, the General Commission in Königsberg was "ordered to reduce its staff and to plan intentionally for a slower pace of work. Aware of the effects that this order might have on the peasantry, the ministry instructed the commission to keep it secret" (Berdahl, 1988, p. 269). Beyond this growing influence of the nobility on the Crown, the fact that county commissioners were aligned with the nobility meant that the settlement of emancipation cases became subject to the will of the landowners,

[28] Historical accounts of the time are suggestive of the prevalence of such incentives amongst the elites. Specifically, Schissler (1978, p. 126) discusses how noble estate owners in Pomerania renounced some of the land they were entitled to as compensation for forgone servile dues. The estate owner, Ernst von Büllow-Cummerow, for example, welcomed the abolition of serfdom, based on the idea that free labor would serve to increase land and worker productivity.

[29] Hagen (2002) provides some detailed micro-historical examples of the redemption process at the noble lordship of Stavenow in the central Prussian province of Brandenburg.

[30] In the event of a dispute where official mediation was required, the local commissioner's job was to determine which land belonged to which party and what the legal status of each landowner was, whether peasant tenancy was hereditary (i.e., if the peasant had strong tenure rights), and whether the peasant landowner was eligible for settlement under the regulation.

who often challenged the legal status of the peasants or their eligibility under the regulations with respect to their tenancy rights.[31]

In addition to the considerable influence exerted by the elites on the redemption process, the historical evidence further suggests that they were able to exploit idiosyncrasies in the structure of the reforms to ensure the limited mobility of labor even after the *de facto* emancipation of their serf peasants. For instance, Skocpol (1979, p. 109) writes that "when serfdom was abolished, the landlords influenced the process in ways that ensured as far as possible the maintenance of their accustomed economic hegemony in new forms. Prussian peasants were forced to cede to the large, Junker-owned estates one-third to two-thirds of the holdings they had worked for themselves under serfdom, in order to gain property title to the lands that remained. This meant that the vast majority were left with inadequate land to support themselves, thus ensuring that they would continue to work on the Junker estates, henceforth, as wage laborers."

This is a critical aspect of our empirical setting for three reasons. First, it mollifies the potential concern that the economic incentives of the elites to hasten or delay the *de facto* emancipation of their serfs, as per our hypothesis, would not have been mobilized unless the elites had prior knowledge of (their ability to ensure) a high degree of spatial segmentation of labor markets for their freed peasants. Second, it suggests that the threat of local labor scarcity arising from peasant workers exploiting potentially better outside options was likely not a primary concern underlying the decision of the elites to accelerate *de facto* emancipation in order to retain their former serfs under competitive market wages. Finally, it implies that even if better outside options existed for the peasants that initiated the redemption process, they were not necessarily able to exploit these opportunities to expedite the redemption of their lifetime servile dues via compensation payments to their landlords. We will revisit the evidence on the segmentation of labor markets more systematically in our empirical analysis in Section 5.2.

3.3 Industrialization of the estate economy

The stereotypical view of the Prussian landowning nobility (*Ritterstand*) has been one in which the Junkers are seen as a highly conservative reactionary group, strongly attached to class habits and a traditional lifestyle, and focusing almost exclusively on agricultural economic activities. Although the historical literature on the period leading up to and following the agrarian reforms generally acknowledges an increasingly capitalist organization of the estate economy, reflecting advances in crop rotation and agricultural productivity whenever grain prices increased due to high demand, the Junkers are usually not described as being progressive (Rosenberg, 1978; Bowman, 2011; Schiller, 2003; Wehler, 2006).

However, according to Eddie (2008, p. 177), "a mostly overlooked feature of the nineteenth-century economy of eastern Germany is the significant role that industrial production on agricultural estates played in that economy." Based on information from industrial censuses in the latter half of the nineteenth century, the author affirms the existence of a dense and heterogeneous network of rural-based industrial establishments on large manorial estates (averaging about one establishment for every 2.5 square kilometers), concluding that "the stereotypical picture of Junkerland as being

[31] The baseline year for the determination of peasant land tenancy was 1752, and written records from that time were sparse.

a vast expanse of extensively cultivated estates with almost no industry is clearly wrong" (Eddie, 2008, p. 180). Thus, although the Junkers are not considered to have held any immediate stakes in the proto-industrial economy of pre-reform Prussia (e.g., Carsten, 1988, p. 51), due to the fact the nobility were excluded from bourgeois occupations prior to the October Edict of 1807, the historical evidence clearly suggests that production activities in Junkerdom underwent considerable structural change once these institutional constraints were removed.

Furthermore, the nineteenth-century industrialization of the Prussian estate economy additionally reflects the infiltration of the bourgeoisie into the class of landowning elites in the period following the agrarian reforms. The case of Johann Gottlob Nathusius (1760–1835) provides a prominent illustration of this phenomenon. Nathusius became the richest man in Magdeburg as the first tobacco-factory owner in Prussia in 1787. In 1810/11, he purchased three manorial estates to grow his own tobacco and eventually developed the estates into the first industrial conglomerate in Prussia (*Nathusius'sche Gewerbeanstalten*), including a porcelain factory, a machine factory (involved in the building of hydraulic presses and steam engines), a sugar refinery, and several distilleries, brick works, and grain mills (Görlitz, 1981). The Nathusius conglomerate eventually gave rise to several spin-off enterprises by former employees and is considered to have strongly influenced the intensity of local industrialization.

In sum, the historical narrative of nineteenth-century Prussia indicates the emergence of significant stakes in industrial production amongst the rural landowning elites, encompassing both the nobility and the bourgeoisie. An integral part of our thesis is that, in the presence of capital-skill complementarity, this process contributed to the mobilization of the emancipation-oriented incentives of the capital-owning elites.

3.4 Emancipation and worker productivity

In our conceptual framework, the elites choose to emancipate their serf peasants because they rationally expect worker productivity to be higher for freed labor. Indeed, the evidence from historians suggests a keen awareness amongst members of the Prussian nobility, both in the period leading up to and following the agrarian reforms of the early nineteenth century, that serf emancipation would ultimately serve to raise worker productivity.

The fact that such awareness existed amongst the nobility as early as the mid-eighteenth century is exemplified by the case of Ernst Wilhelm von Schlabrendorff (1719–1769), the son of a knight estate owner, who was appointed minister of Silesia in 1755. According to Melton (1988), Schlabrendorff's emancipation-oriented outlook as Silesia's minister was inspired by his exposure to the experience in the province of Magdeburg, where landlords had already started the process of commutating peasant labor services into quitrents on their own initiative. Specifically, upon returning from an inspection tour of Upper Silesia, where labor coercion of the peasantry was particularly intense, Schlabrendorff wrote to the King recommending the commutation of the peasantry's labor obligations into quitrents, insisting that excessive labor services and the insecurity of peasant land tenure bred discontent and were a barrier to worker productivity. Indeed, Schlabrendorf is quoted by Melton (1988, pp. 154–155) as stating: "It is beyond question that the peasant who works on his own property will labor far more enthusiastically." Another example of early progressivism is the case of Friedrich Eberhard von Rochow (1734–1805), who introduced a small-scale agrarian reform on his own manorial estates in Brandenburg well before the Prussian reforms of the early nineteenth century. Specifically, he enclosed the commons on his estates, turned them into private peasant holdings, and commutated the feudal labor services of his serfs into quitrents. As discussed by Melton (1988, p. 167), von Rochow's local reforms followed a period of intense pedagogical activity, based on the nobleman's prior belief that his institutional changes, aimed to increase peasant labor productivity, would be ineffective unless the peasants were sufficiently educated.[32]

Beyond associating labor coercion with reduced worker productivity, the evidence from historians further suggests that some members of the nobility even considered freed workers to be more "appropriate" for the adoption of innovative agrarian production techniques. For instance, according to Carsten (1988), the *Geheime Oberfinanzrat* von Ernsthausen wrote in 1788 that because peasant labor services were only ever provided with reluctance, labor coercion "had produced major disruptions [to productivity] for centuries" and "choked all engines of invention and improvement." As noted by Carsten (1988, p. 67), "insightful nobles in the late eighteenth century therefore allowed peasant services to be commutated into quitrents and ultimately released their peasants from serfdom. [...] The landlords realized that coerced labor services had lost their value, and for the new agricultural methods, wage workers were more suitable than reluctantly serving peasants." In a similar vein, Berdahl (1988, p. 88) asserts that "many agricultural innovators considered serfdom a major obstacle to the improvement of agricultural productivity. Serfdom came to be seen by many as too inefficient. Albrecht Thaer, the most important proponent of new agricultural methods in Prussia, advocated the emancipation of the serfs; [...] A few estate owners liberated their serfs and adopted a system of wage labor; others reduced the work obligations in exchange for increased rents." Interestingly, echoing the case of von Rochow, the historical narrative also indicates cognizance amongst the nobility in the mid-to-late eighteenth century that the reduction of peasant labor services, or their commutation into quitrents, would by itself not be sufficient to increase labor productivity, because such transformation required that peasants gain "self-awareness" as workers through education (Melton, 1988, p. 156–158).[33]

Finally, both the historical narrative and anecdotal evidence attest to the fact that many landlords in the period following the agrarian reforms of the early nineteenth century actually benefited from higher worker productivity, especially from the application of freed labor to new production techniques. In particular, Skocpol (1979, p. 109) states that "once the Prussian reforms had both abolished serfdom and opened the market for noble estates to all well-to-do investors, Prussian landlords [...] could begin to adopt innovative techniques that required "free" wage labor." Furthermore, in discussing the socioeconomic transition from feudal to "capitalist" labor institutions following the agrarian reforms, Biernacki (1995, p. 305) provides anecdotal evidence

[32] As part of his educational program, von Rochow built schools on each of his three estates (all of which subsequently became well-regarded model schools throughout Europe), wrote a textbook for the teaching of basic arithmetic and economic thinking (next to the usual religious and moral content), and increased the salary of teachers in his schools to ensure that they would not have to assume secondary occupations.

[33] For instance, Melton (1988, p. 158) notes that "[t]he *Schlesische Oeconomische Sammlungen* (1755–62), an economic journal to which progressive landowners, estate managers, and agronomists submitted practical articles on estate improvement, proposed creating an economic society devoted to peasant education," with the goal of raising peasant productivity. The historian further highlights the case of Johann Georg von Dresky, an enterprising Silesian landowner and a member of the Silesian Economic-Patriotic Society, arguing that the nobleman "considered the peasantry's lack of education to be the major barrier to increased agricultural productivity."

on how the transformation was viewed by the workers themselves, in the form of a quote from Adam Heuss, who worked for a small hand smith in Nürnberg and published his observations in 1845. Heuss remarks that in his "age of mighty advance," it was considered "advantageous" to have "tradable wares manufactured in factories with machines." He additionally illustrates the incentives of the elites, citing the case of the "Mecklenburger estate lords [*Gutsherren*] who released their subject peasants and turned them into day laborers."[34]

Indeed, the changing incentives of the elites are perhaps best exemplified by the aforementioned case of the rural industrialist Nathusius. Specifically, in discussing the status of peasants on the manorial estates that he purchased, his daughter and biographer writes: "at first the peasants served him, but he soon insisted on a *cheap* [emphasis added] redemption for them" (von Nathusius, 1915, p. 239). Moreover, in line with the increased demand for skilled workers by capitalist elites, Nathusius' biography (p. 237) further states that "[h]e vigorously advocated for better instruction in the schools, especially for the practical sciences, and also in rural schools, which represented the best means of uplifting industry." Thus, it is evident that landlords not only perceived freed workers to be more productive but actually reaped these benefits by facilitating the emancipation of their serfs, employing them as free workers in more innovative production activities, and encouraging their acquisition of complementary skills.

4 Data

Our empirical analysis aims to document reduced-form patterns that are consistent with our hypothesis regarding the decline of serfdom in nineteenth-century Prussia. Specifically, we link the initial abundance of a relevant form of physical capital (i.e., elite-owned proto-industrial capital that also anticipates skill-intensive production) with the subsequent rate of labor emancipation. This section discusses the most germane aspects of our dataset, relegating additional information to Appendix E.

4.1 Serf emancipation

We employ administrative data on *de facto* serf emancipation, obtained from sources published by the Prussian Statistical Office and first presented in Meitzen (1868) for the purposes of documenting the progress achieved by the emancipation process by the mid-nineteenth century.

The dependent variable in our cross-sectional analysis is based on the cumulative stock of emancipation cases (*Rezesse*) settled in a county (*Landkreis*) as of 1848. Thus, we attempt to explain the observed variation in labor emancipation at this lowest of administrative levels in

[34] A prominent example of the "Mecklenburger estate lords" from the reference made by Huess is the nineteenth-century social scientist and experimental agrarian reformer, Johann Heinrich von Thünen (1783–1850), owner of the estate of Tellow. According to Sundberg (2004, pp. 144–145), "von Thünen's innovations were basically aimed at increasing productivity and realizing an optimal use of land resources related to the economic mechanisms of the market economy." Further, the nobleman was concerned about not only "the peasant population's living conditions" but also "the level of education for the children of the common people in Mecklenburg" to the extent that "a village school for the people was built in Tellow during the years 1828–1830." Based on a study of von Thünen's biographical notes, the historian goes on to contend that he "clearly understood that improvement for the farm workers and peasants at Tellow also meant improvement in production and economy at the manor."

Prussian regions east of the river Rhine.[35] The original data tables indicate the specific legislation under which each emancipation case was settled, and we exploit this information to focus our measure on the number of former service and duty payers (*Dienst- und Agabenpflichtige, welche abgelöst haben*) who redeemed their lifetime servile duties under the Dissolution Ordinance of 1821 (*Ablösungsordnung*). This permits us to capture precisely those cases in which, upon settlement, the former serfs were no longer required to provide labor services to their manorial lords. In addition, for each case, Meitzen (1868) reports the number of redeemed days of service as well as the cost of redemption. We use this information in our analysis to account for the average intensity of coercion and, in a different exercise, to explore cross-county variation in the average cost of redemption itself.[36]

In light of the fact that our dependent variable focuses on emancipation cases settled under the 1821 ordinance, it is important to understand the extent to which this legislation influenced the *de facto* peasant emancipation process in Prussia. Recent estimates have placed the number of rural households in early-nineteenth-century Prussia at approximately one million: ca. 710,000 peasant households and 283,000 lodgers (Eddie, 2013). Of these rural households, roughly 11–13 percent held only weak (non-hereditary) rights to land tenure and were thus emancipated under the terms of the 1811 regulation and its 1816 amendment. The remaining majority of households, however, held strong (hereditary) rights to land tenure, and their emancipation was therefore exclusively governed by the terms of the 1821 ordinance.

One shortcoming of our data set is that precise information on the initial population of serfs (i.e., as of the early nineteenth century) is not available. In order to arrive at a measure of the *intensity* of serf emancipation, we must therefore rely on approximations of the initial serf population. Our preferred measure for normalizing the cumulative stock of settled emancipation cases at the county level is the rural population of the county as of 1816, net of the population in small peasant landholdings that were only able to emancipate after the Commutation Law of 1850 was issued.[37]

[35]We structure our county-level data set to consistently link information from different censuses over time. The original sources exclude regions west of the river Rhine, where, due to the Napoleonic occupation, agricultural and emancipation reforms developed in a radically different fashion than in the rest of Prussia. This also applies to the district of Stralsund, where such reforms had been introduced by the Swedish Crown in 1806. Furthermore, no information is available for the city counties (*kreisfreie Städte*), presumably because serfdom was not at all prevalent in these purely urban areas.

[36]The data on Prussian serf emancipation are discussed by Harnisch (1974), who finds inconsistencies in the information for 1838 versus 1848. Although concerns regarding the number of settled cases are not raised, Harnisch questions the reliability of the data on redemption costs reported for 1848. According to Harnisch, the statistics, published shortly after the events of the German Revolution of 1848, may systematically underreport the actual redemption payments. In fact, it is plausible that redemption payments were only applicable to emancipation cases settled under the 1821 ordinance, thus creating the inconsistencies identified by Harnisch, and it is for this reason that we focus only on those cases.

[37]In using this measure, we assume that the entire rural population of a county, including peasant family members, farm hands, and day laborers, were bonded serfs engaged in the provision of servile labor duties. To account for persistent systematic differences across counties in the size of peasant households, our empirical model will include average family size in 1849 as a covariate. To address other potential sources of systematic measurement error in our dependent variable, we will additionally control for heterogeneity in both the prevalence of free peasants and the legal status of serfs across counties. Our main findings prove to be robust to the use of alternative measures for normalizing the stock of settled emancipation cases at the county level, including the total population in 1816, the rural population including peasant landowners of small parcels in 1816, the number of servants in agriculture in 1816, the number of peasant landholdings in 1816, the number of full-time peasants including family and farm hands in

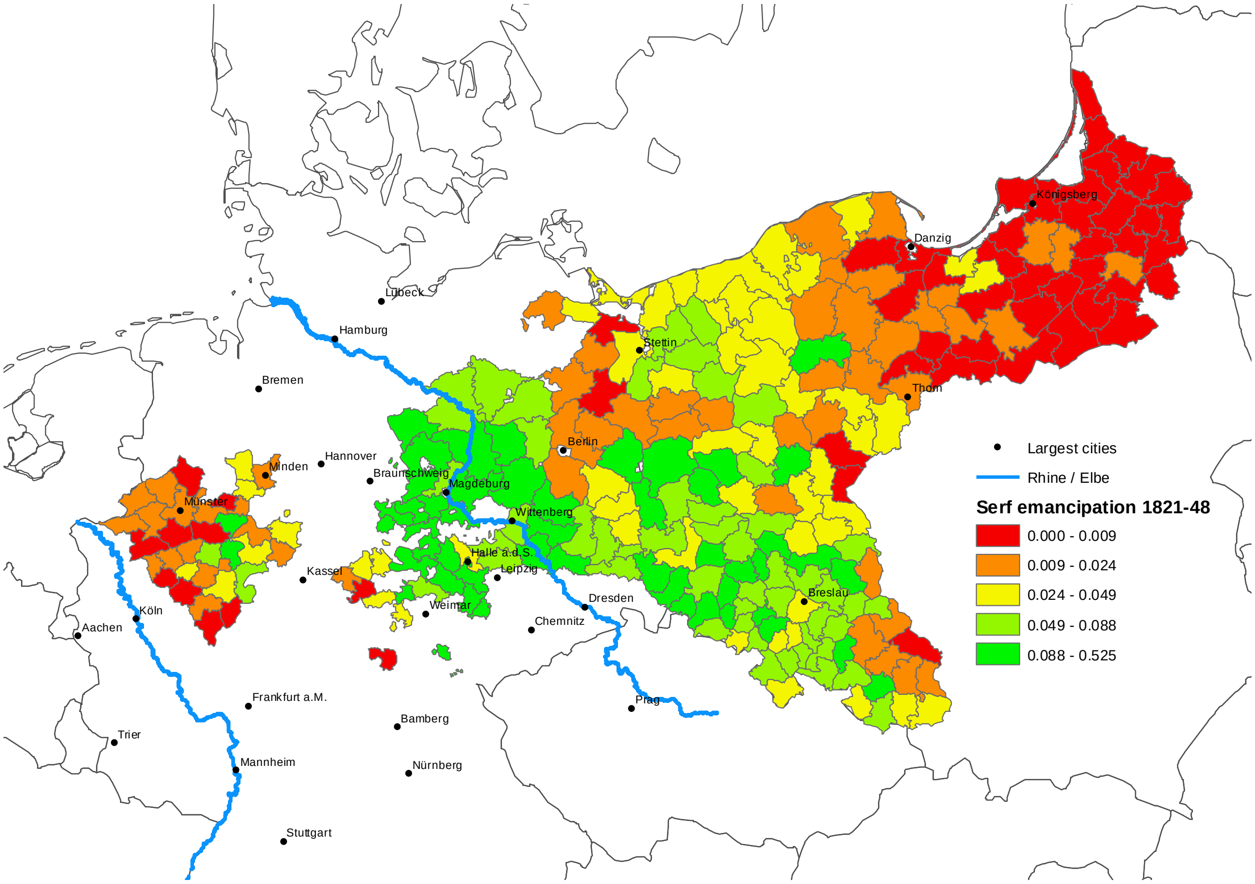


FIGURE 2: Spatial distribution of serf emancipation intensity as of 1848

Notes. This map illustrates the distribution across Prussian counties of the share of emancipated serfs as of the mid-nineteenth century. This variable is measured as the total number of emancipation cases settled in a county (under the 1821 ordinance) as of 1848, expressed as a fraction of the rural population of the county in 1816 (net of the population in small peasant landholdings). See the discussion in the main text and Appendix E for additional details.

As is evident from the map in Figure 2, there is considerable variation across Prussian counties in the intensity of the *de facto* serf emancipation process as of 1848. In particular, the share of emancipated serfs at the county level ranges from 0% to 52% and has a mean of 6%. This distribution reflects a relatively advanced emancipation process in many counties belonging to the central and southeastern provinces of Saxony, Brandenburg, and Silesia, and predominantly low emancipation shares in the eastern regions of Prussia and the western province of Westphalia.

In addition to the cumulative stock of emancipation cases settled in a county by 1848, our historical data sources provide information on the number of cases settled each year during the 1850–1898 time horizon, but only at the higher administrative level of districts (*Regierungsbezirke*). In Section 5.3, we employ these district-level data to conduct a flexible panel analysis of the temporal *flows* of emancipation cases. Importantly, the inclusion of district fixed effects in this analysis implies that it will be able to account not only for the potentially confounding effects of time-

1849, the number of full- and part-time peasants including family and farm hands in 1849, or the number of peasant landholdings in 1849.

invariant geographical, cultural, and institutional characteristics at the district level but also for any measurement issues associated with the absence of precise information on the initial population of serfs.

4.2 Relevant proto-industrial physical capital

The first half of the nineteenth century is generally regarded as the period during which the foundations for Prussian industrialization were laid. The accumulation of physical capital during this period was concentrated in the agricultural sector and was largely driven by investments in livestock, seed, and buildings (Tilly, 1978). Since neither livestock nor seed is directly associated with proto-industrial production, we start by considering only productive structures and devices (e.g., milling facilities, brick and glass factories, and looms) on which data are available for the early nineteenth century at a spatially disaggregated level. Ultimately, our empirical analysis exploits the number of water mills (per 1,000 inhabitants) in 1819 as a proxy measure of the initial abundance of physical capital at the county level. This measure accounts for nearly 40% of all proto-industrial establishments (i.e., different types of milling facilities plus brick and glass factories) in the average county in our sample in 1819. Moreover, as discussed below, unlike other available measures of proto-industrial physical capital, this measure possesses two crucial features that make it particularly relevant for examining our proposed hypothesis.

First, the ownership of water mills in this period was almost exclusively restricted to the nobility, thus ensuring that the rents associated with milling were available for reinvestment and subsequent capital accumulation by the elites. Prior to the agrarian reforms of the early nineteenth century, the construction and operation of a grain mill was a noble prerogative. The seigniorial rights of a feudal lord encompassed the monopoly privilege of grain milling on his estate, including (i) the legal obligation that all local peasants exclusively grind their grain in the mill on their landlord's estate (*Mühlenzwang* or suit of mill); and (ii) the right of the lord to additionally tax the milled grain (*Mahlsteuer* or multure).[38] Historians agree that the seigneurial rights associated with grain milling conferred considerable profits to the landed nobility (e.g., Bloch, 1967; Hills, 1996; Lucas, 2006; van der Beek, 2010). Consequently, the returns from the ownership of water mills not only accrued exclusively to the nobility but were also sufficiently large for exploiting reinvestment opportunities.[39]

Second, the use of water mills in early stages of industrialization arguably foreshadowed the subsequent adoption of a well-known skill-intensive technology during more mature stages of industrialization – namely, the steam engine.[40] In particular, economic historians of the Industrial Revolution have argued that early investments in water mills – the proto-industrial installations most closely related to steam engines because of their reliance on water availability – may well have

[38]The suit of mill was effectively a ban on local peasants to grind their grain using personal hand mills. The multure tax rate was often quoted at 1/16.

[39]Indeed, as claimed by Hills (1996, p. 26–27), "[t]he rights to a watermill were owned by the lord of a manor and, in an age when there were no stocks and shares to provide an income, the corn mill presented one of the few profitable capital investments available. [...] Once the mill was established, it became another potential capital investment and, with the 'soke' or control over the milling rights which the lord of the manor held, the mill became something worthwhile building and owning [...]."

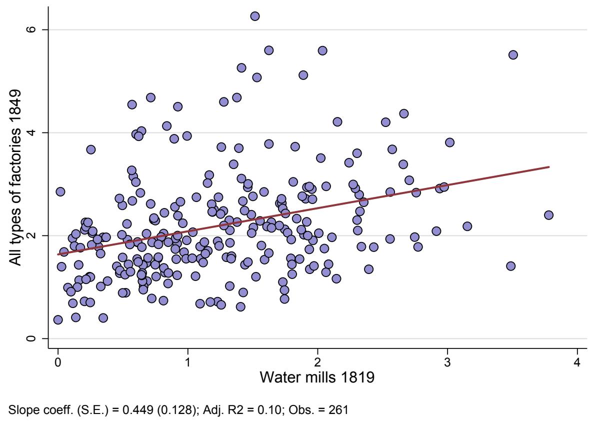
[40]See, for instance, Franck and Galor (2017) for systematic evidence linking the adoption of steam-engine technologies in mid-nineteenth-century France with broad increases in literacy rates and educational attainment.

made the adoption of steam-engine technology more "appropriate" over the course of industrialization. For instance, Mokyr (2002, p. 256) states that "[...] the owner of machines that become obsolete will take a loss on those machines, but he can always buy into the new technology by purchasing new machines that yield higher profits through lower costs. This explains, for instance, the relatively weak resistance to the introduction of steam engines despite the huge locational rents that were being secured by the owners of water mills sites. Industrialists using water power might have been losing when their mills fell into disuse, but they could make up for those losses by buying into steam technology themselves, which is precisely what happened in Lancashire during the British Industrial Revolution." Furthermore, because steam engines were initially only water-pumping engines (e.g., the Savery and Newcomen variants) and were unable to convert steam power into a steady rotary motion by themselves, early industrial production sites often exploited steam power in conjunction with water wheels, employing the engine to pump water up into an elevated reservoir, which then supplied hydraulic power to an existing overshot water wheel (see, e.g., Reynolds, 1983, pp. 322–323).[41] Thus, even from an applied engineering standpoint, steam engines naturally possessed a temporally sequential relationship with respect to water mills.

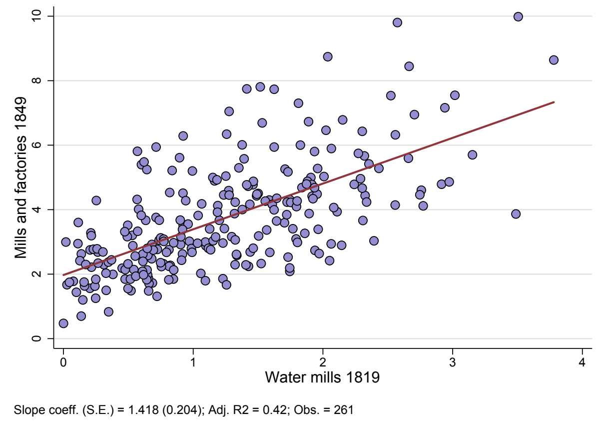
In the context of nineteenth-century Prussia, the prior that the early use of water mills foreshadowed skill-intensive industrialization later on is empirically vindicated by the scatter plots in Figure 3. To start, panels (a) and (b) document statistically significant positive associations across counties between the prevalence of water mills (per 1,000 inhabitants) in 1819 and measures of *broad-based* industrialization (per 1,000 inhabitants) in 1849, as reflected by not only the number of factories but also the total number of factories and mills. We interpret these associations as providing the *intermediate* temporal link between the prevalence of water mills in 1819 and the eventual adoption of more *skill-intensive* technologies in the latter half of the nineteenth century. Indeed, as shown in panel (c), the statistically significant positive association between the prevalence of water mills in 1819 and the adoption of steam engines (per 1,000 inhabitants) in 1875 confirms the posited path dependency in the emergence of skill-intensive industrialization over the long run. Furthermore, as shown in panel (d), the connection between our measure of proto-industrialization and the future use of advanced technologies in industrial establishments is in fact more general, extending to all types of motorized engines in 1875.

As mentioned earlier, the two crucial features that make water mills particularly relevant for examining our hypothesis are either partly or entirely absent from other available measures of proto-industrial structures and devices in the early nineteenth century. Corroborating the notion that, among extant milling technologies, only the water-powered ones were "appropriate" for subsequent industrialization, panels (a)–(d) of Figure 4 illustrate relevant "placebo tests" using measures of "dead end" milling technologies. They document that the prevalence of neither wind-powered nor animal-powered mills (per 1,000 inhabitants) in 1819 bears any systematic association with either broad-based industrialization in 1849 or skill-intensive industrialization in 1875, reflecting the fact that these "dead end" milling technologies eventually fell into disuse because of their dependence on energy sources that were, relative to water power, naturally less predictable/reliable (e.g., wind) or more costly (e.g., animals that could have been more efficiently allocated to other activities). Thus, although both wind- and animal-powered mills fulfill our first criterion of exclusive ownership by the

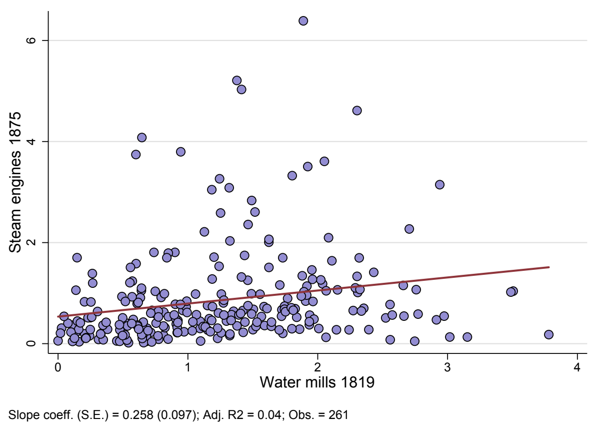
[41] See also Nuvolari, Verspagen and von Tunzelmann (2011, p. 294 and p. 309) and references cited therein.



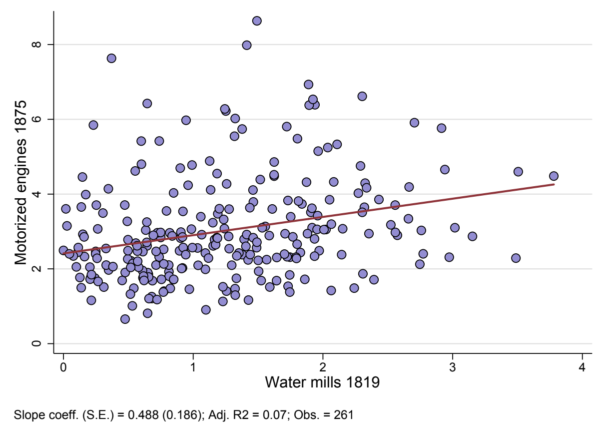
(a) Factories in 1849



(b) Mills and factories in 1849



(c) Steam engines in 1875



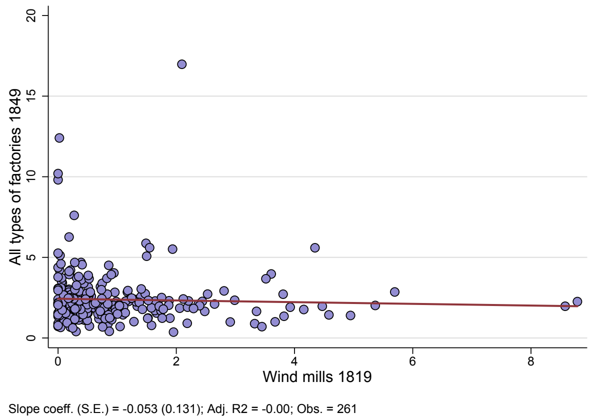
(d) Motorized engines in 1875

FIGURE 3: Water mills in 1819 versus industrialization in 1849 and 1875

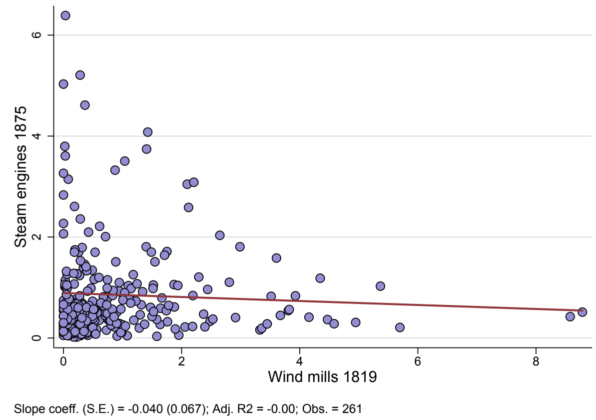
Notes. These scatter plots illustrate the significant positive relationship across Prussian counties between the number of water mills in 1819 and each of four different measures of subsequent industrialization, including (i) the total number of factories across manufacturing sectors (textiles, metals, paper, chemicals, food-processing, etc.) in 1849 (panel (a)); (ii) the total number of all types of mills (excluding wind- and animal-powered mills) in 1849 plus the preceding measure of the total number of factories in 1849 (panel (b)); (iii) the total number of steam engines across manufacturing establishments in 1875 (panel (c)); and (iv) the total number of all types of motorized engines across manufacturing establishments in 1875 (panel (d)). The measure of water mills for a given county in 1819 is divided by the county's population (in thousands) in 1821 (the population census year closest to 1819). Each measure of subsequent industrialization for a given county and year is divided by the county's population (in thousands) in that very year. See the discussion in the main text and Appendix E for additional details.

nobility, they fail to satisfy the second criterion of being associated with the subsequent emergence of skill-intensive industrialization.

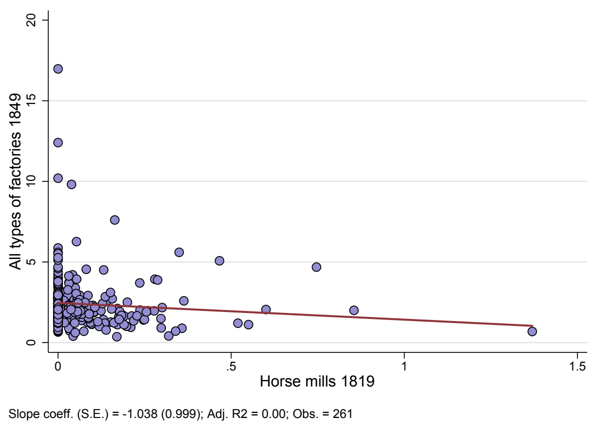
On the other hand, panels (e) and (f) of Figure 4 indicate that the prevalence of "other" (i.e., non-grain-processing) mills (per 1,000 inhabitants) in 1819 does possess significant positive associations with both broad-based industrialization in 1849 and skill-intensive industrialization in 1875. Unfortunately, however, our data source classifies these "other" types of mills only according



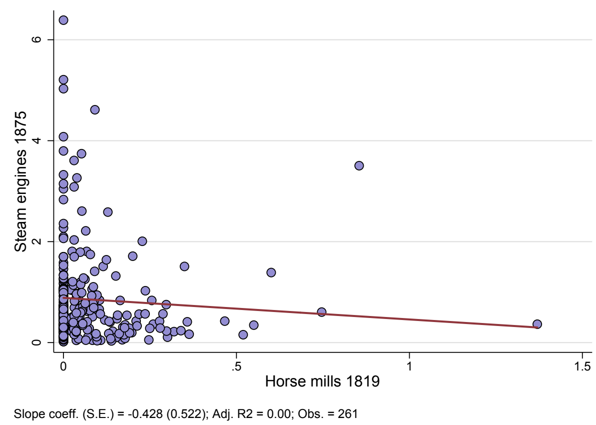
(a) Wind mills in 1819 and factories in 1849



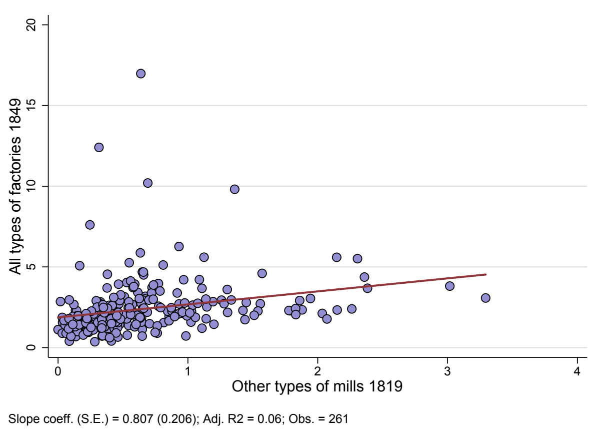
(b) Wind mills in 1819 and steam engines in 1875



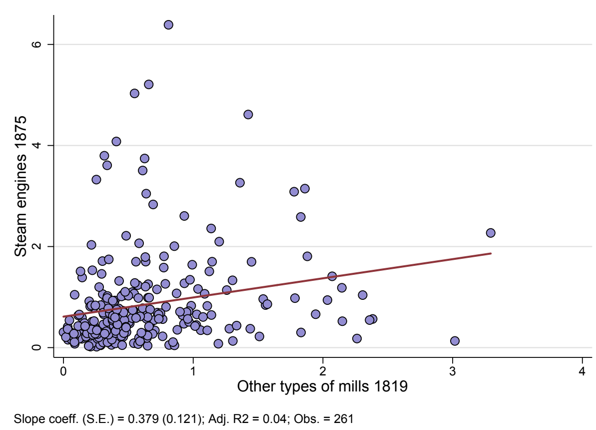
(c) Horse mills in 1819 and factories in 1849



(d) Horse mills in 1819 and steam engines in 1875



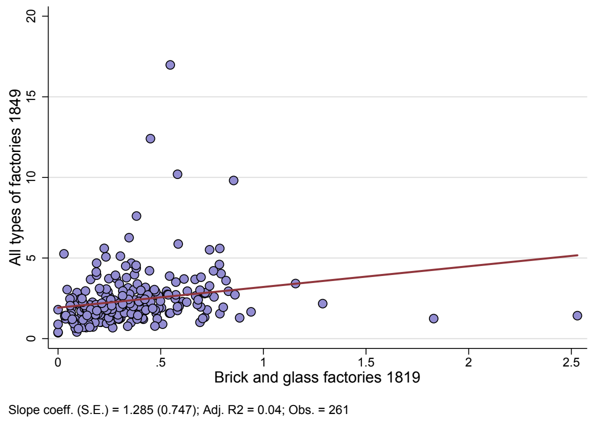
(e) Other mills in 1819 and factories in 1849



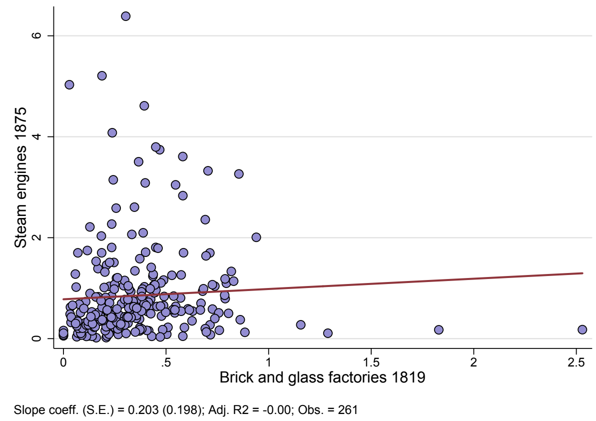
(f) Other mills in 1819 and steam engines in 1875

FIGURE 4: Orthogonality of other forms of proto-industrial capital in 1819 with subsequent industrialization

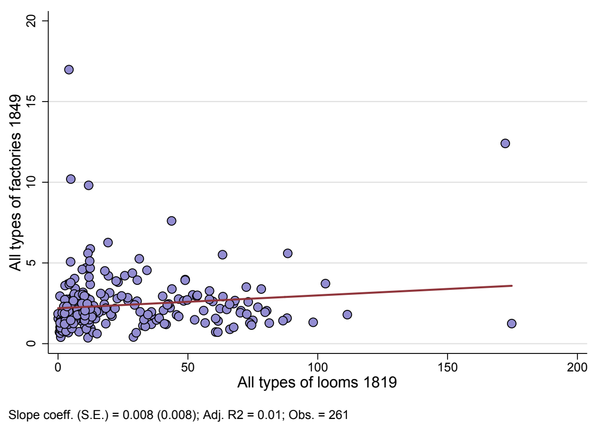
Notes. This figure continues on the next page. See the notes provided at the end of the resumed figure.



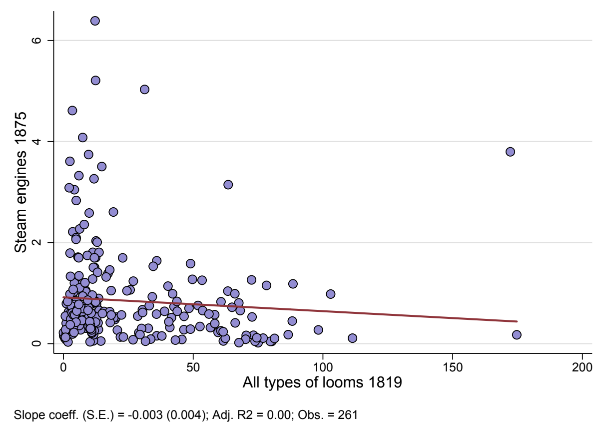
(g) Factories in 1819 and factories in 1849



(h) Factories in 1819 and steam engines in 1875



(i) Looms in 1819 and factories in 1849



(j) Looms in 1819 and steam engines in 1875

FIGURE 4: Orthogonality of other forms of proto-industrial capital in 1819 with subsequent industrialization (cont.)

Notes. These scatter plots illustrate the relationship (if any) across Prussian counties between each of five different measures of proto-industrial physical capital in 1819, on the one hand, and each of two different measures of subsequent industrialization, on the other. The measures of proto-industrial physical capital in 1819 consist of (i) the total number of wind mills, including post and smock mills (panels in the first row); (ii) the number of horse mills (panels in the second row); (iii) the total number of other (i.e., non-grain-processing) types of mills, including oil, fulling, saw, and paper mills (panels in the third row); (iv) the total number of construction factories, including brick works, lime kilns, and glass works (panels in the fourth row); and (v) the total number of (hand-powered) looms, including looms for the weaving/knitting of silk, cotton, wool, linen, hosiery, band, shag, and other fabrics (panels in the fifth row). The measures of subsequent industrialization consist of (i) the total number of factories across manufacturing sectors (textiles, metals, paper, chemicals, food-processing, etc.) in 1849 (panels in the left column); and (ii) the total number of steam engines across manufacturing establishments in 1875 (panels in the right column). Each measure of proto-industrial physical capital for a given county in 1819 is divided by the county's population (in thousands) in 1821 (the population census year closest to 1819). Each measure of subsequent industrialization for a given county and year is divided by the county's population (in thousands) in that very year. See the discussion in the main text and Appendix E for additional details.

to their milling purpose (sawing of lumber, extraction of vegetable oils, pulping of wood for paper-making, etc.) and not by their power source (i.e., water, wind, or animals). Thus, although we contend that the associations depicted in panels (e) and (f) predominantly reflect "agglomeration" effects due to unobserved non-grain-processing mills that were *water-powered*, the overall measure is likely also contaminated by information on the aforementioned "dead end" milling technologies.

Finally, the remaining available measures of proto-industrial structures and devices in the early nineteenth century – namely, the number of brick- and glass-producing factories and the number of hand-driven looms (both in per 1,000 capita) in 1819 – capture forms of fixed capital that were overwhelmingly owned by the bourgeoisie rather than the serf-owning landed nobility, reflecting the legacy of institutional restrictions that prevented the nobility from engaging in bourgeois occupations at least until 1807. These measures therefore fail to properly satisfy the first criterion of exclusive ownership by the nobility. Moreover, as shown in panels (g)–(j) of Figure 4, neither of these measures of proto-industrialization appear to possess relationships with the measures of subsequent industrialization (either broad-based or skill-intensive) that are statistically distinguishable from zero.

In sum, with the exception of water mills, none of the alternative forms of proto-industrial structures and devices in the early nineteenth century fulfills the features necessary for making them relevant for examining our hypothesis of emancipation from serfdom. Indeed, in Table A.1 in Appendix A, we show that due to their conceptual deficiencies, these alternative available measures of proto-industrialization are either not associated at all with subsequent emancipation, or when they are, the association is either attenuated (due to noisy measurement) or qualitatively different than what our framework predicts.

Henceforth, our analysis of the determinants of serf emancipation adopts water mills (per 1,000 inhabitants) in 1819 as the relevant explanatory measure of proto-industrial physical capital. The map in Figure 5 illustrates the spatial distribution of this measure across Prussian counties. The measure itself has an average value of 1.2 and ranges from 0 to 3.8, reflecting higher capital abundance in Westphalia and in the central regions of Saxony and Silesia, relative to Brandenburg and the eastern provinces of Prussia.

4.3 Control variables

Our empirical analysis accounts for a sizable set of potentially confounding factors at the county level that may have not only affected the pace of industrialization but also influenced the bargaining power of peasants and the incentives of the elites to relinquish labor coercion, thereby conditioning the rate of serf emancipation. The first set of control variables is aimed at accounting for spatial heterogeneity in geographical endowments that can directly influence agricultural productivity and access to markets and can also indirectly affect cultural and institutional characteristics through various mechanisms. Specifically, our geographical control variables include temperature, precipitation, soil suitability for cereal crops, the share of sand in the top soil, and distance to navigable rivers. We also include an indicator for counties east of the river Elbe, where both coercive labor institutions and dependence on large-scale agriculture are known to have historically evolved in a characteristically different fashion than in the western regions of Prussia (see, e.g., Harnisch, 1986; Melton, 2000).

Our second set of control variables is intended to capture variations in admittedly less exogenous but more proximate potential confounders. In particular, we introduce controls for

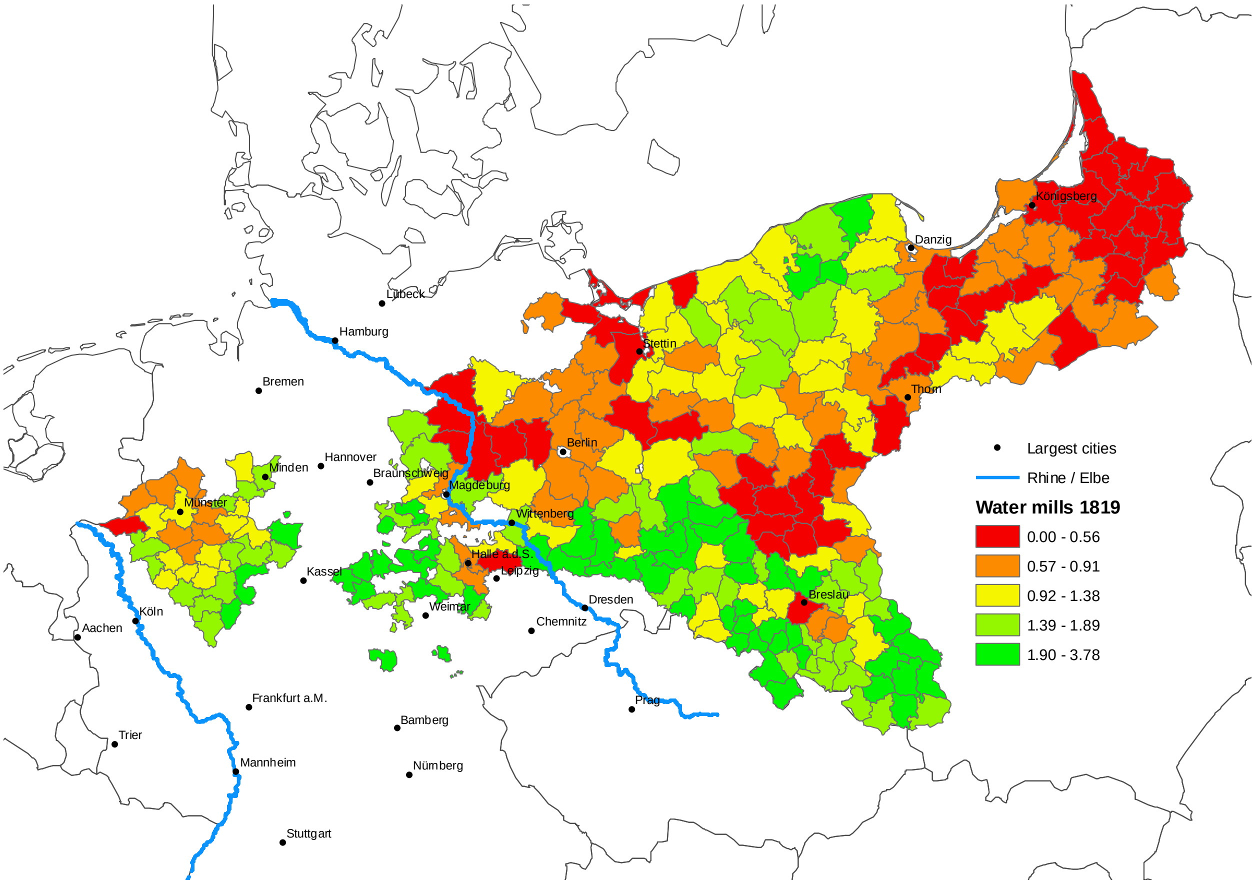


FIGURE 5: Spatial distribution of water mills (per 1,000 inhabitants) in 1819

Notes. This map illustrates the distribution across Prussian counties of our proxy measure of the initial abundance of relevant physical capital. This variable is measured as the number of water mills in a county in 1819, divided by the county's population (in thousands) in 1821 (the population census year closest to 1819). See the discussion in the main text and Appendix E for additional details.

population density and urbanization rate in 1816, in order to account for heterogeneity across counties in initial development, labor abundance, and access to urban markets. Peasant-household demographic factors and the initial intensity of investments in human capital, both of which can influence the incentives of the elites to emancipate while also affecting industrialization, are accounted for by measures of average family size (only available from the 1849 census onward) and the enrollment rate in public primary schools in 1816. Differences across counties in the cultural propensity to emancipate and/or industrialize (as well as the correlated tendency to attract immigrants) are captured by controls for the share of Protestants in the population in 1816 and the share of individuals of non-Germanic (mostly Slavic) ancestry in the population (only available from the 1861 census onward).

In addition, our second set of covariates includes two measures that account for institutional differences across counties in the structure of peasant and noble landholdings. Such distinctions could have influenced the ability of the peasantry to compensate the landlords for the redemption of lifetime servile dues as well as the incentives of the elites to delay both serf emancipation and the adoption of industrial production techniques. Our first measure is an indicator for the predominant law of succession that governed the inheritance of peasant landholdings in a county; namely, partible inheritance (*Realteilung*), characterized by the equal division of land across heirs, versus impartible inheritance (*Anerbenrecht*) or primogeniture. This indicator is aimed at capturing the potentially confounding demographic and economic effects associated with the larger average size of peasant landholdings in counties that overwhelmingly practiced impartible inheritance.[42] Our second measure captures the share of all landholdings in a county that were designated as knight estates (*Rittergüter*). These sizable manorial estates were associated with stronger feudal institutions and, thus, stronger vested interests of the landed aristocracy in the appropriation of serf labor for large-scale farming activities (Cinnirella and Hornung, 2016).

The final set of covariates considered by our analysis includes additional proxy measures capturing some of the alternative mechanisms mentioned above as well as other potential confounders. Specifically, omitted variable bias due to heterogeneity across counties in access to external (urban) markets or "outside" employment options for the enserfed population is further addressed by the inclusion of three dummy variables, indicating (i) the presence of at least one main road (on which the earliest reliable information is for 1848); (ii) the presence of a railway line (also in 1848, noting that railroad development in Prussia began in 1838); and (iii) the presence of coal mining. Relatedly, we also control for the share of the population born outside the county (available from the 1871 census), employing this *ex post* realization to partly account for the *ex ante* possibility that upon emancipation (and in the absence of labor market segmentation), former serfs could have migrated away to seek employment in external markets offering better opportunities.

Furthermore, differences in the economic incentives of the elites to prolong the use of serf labor as well as variation in the ability of the enserfed population to redeem their lifetime servile duties (following *de jure* emancipation) are accounted for by a measure of prevailing coercion intensity, reflected by the average number of days of labor services per emancipation case for which the landlords required compensation under the redemption agreement.[43] We also control for the number of social uprisings during the 1816–1847 time period, in an attempt to account for differences across counties in the strategic incentives of the elites to grant emancipation when faced with a credible threat of mass revolts.[44] Such perceived threats could have been either suppressed

[42]For instance, historians have associated impartible inheritance not only with peasant demographic outcomes like lower fertility and marriage rates, smaller family size, and higher out-migration from rural areas but also with structural economic outcomes like the persistence of large-scale agriculture and the late emergence of concentrated industrial activities (see, e.g., Habakkuk, 1955; Rudolph, 1995; Grant, 2005).

[43]As explained in Appendix E, we construct this measure by extracting the first principal component of the average amounts associated with two different types of labor services that peasants needed to redeem as part of their settlements with the landlords.

[44]Our measure includes not only peasant rebellions but also uprisings involving commoners. In fact, peasant uprisings in Prussia were virtually nonexistent in the period following the introduction of the agrarian reforms and until the German Revolution of 1848–1849. Specifically, the historical evidence (e.g., Carsten, 1988, p. 82) indicates that peasant rebellions in early nineteenth-century Prussia occurred predominantly in the province of Silesia between 1809 and 1811, and even these were primarily due to a misunderstanding of the October Edict by the enserfed Polish-speaking population of the region (which had misinterpreted the legislation as abolishing not just the personal subjection of peasants but their servile duties as well). These uprisings, however, are the only known peasant rebellions of the period during and following the reforms, an outcome partly attributable to the economic recovery of Prussia in the 1820s and the fact that, because the Dissolution Ordinance granted serfs the right to initiate the redemption process, revolts for the purpose of instigating the elites to emancipate were not necessary. Nevertheless, our measure

in regions where the elites owned more resources to counter social unrest or intensified by the greater attractiveness of these resources for mass appropriation.

The opening up of the market for noble estates to commoners from 1810 onwards may have resulted in the purchase of demesnes with established cottage industries by urban industrialist elites who also happened to possess emancipation oriented social preferences. In addition, to the extent that proto-industrialized manorial estates were also the ones that were most in need of recapitalization following the Napoleonic Wars, the noble landlords of these estates may have been compelled to sell their assets relatively quickly to avert or mitigate delinquency, emancipating some of their serfs at lower redemption costs as part of this process. To account for these sources of omitted variable bias in our coefficient of interest, we control for the share of noble estates in a county that came to be owned by commoners (*Bürgerliche*) as of 1856.

Our final set of covariates additionally includes two variables aimed at capturing the non-uniform distribution of free peasants in the population across counties prior to the *de jure* abolition of serfdom. This allows us to account not only for differential incentives of the elites to grant emancipation in the presence of free peasants (e.g., delaying emancipation by allocating serf labor to agriculture and hiring free labor for industrial production) but also for differential convergence across regions to a state of full emancipation (i.e., counties with a larger initial share of free peasants emancipated less because they had smaller enserfed populations to begin with). At the turn of the nineteenth century, certain peasant groups like *Schulzen* and *Köllmer* accounted for only about 4% of rural households across Prussia, but they enjoyed personal freedom and were required to provide only minor dues in quitrents or labor services to the nobility (Eddie, 2013). Although county-level data on the population of free peasants during this period is unavailable, we exploit two relevant proxy measures. The first measure captures the share of estates in a county that operated under the so-called Kulm law, a legacy of the Monastic State of the Teutonic Knights (1230–1525). These *Köllmer* estates, mostly prevalent in the areas surrounding the towns of Kulm and Thorn, were established during the era of the Teutonic Order and provided the settled peasant population with long-term legal protection from landownership exclusion and enserfment. Our second measure reflects the share of land in a county owned initially by the Prussian Crown and later on by the state. Peasants residing in these royal domains were granted personal freedom as early as 1799 and were subsequently able to engage in the commutation of dues and labor services into cash rents, with about one-third of these peasants attaining full redemption of lifetime servile duties and about one-tenth purchasing their lands by 1806 (Eddie, 2013, p. 185).

Lastly, in order to account for heterogeneity across counties in their historical exposure to the Commercial Revolution of the early modern period, we include an indicator for whether a county harbored a university in 1517 or a commercially vibrant urban center, as reflected by its status as an Imperial City (*Reichsstadt*) or a member of the Hanseatic League (*Hansestadt*), in 1517.[45] In particular, the landowning nobility in these counties may have historically benefited from access to

of social uprisings is intended to control for the possibility that the elites may have perceived non-peasant uprisings as potential triggers for more widespread revolts.

[45]The importance of late medieval universities and of early modern cities participating in Imperial or Hanseatic Diets as factors contributing to the Commercial Revolution has been noted by several papers in the recent empirical literature on German economic history (see, e.g., Becker and Woessmann, 2009; Cantoni, 2012; Cantoni and Yuchtman, 2014; Jedwab, Johnson and Koyama, 2016).

long-distance trade in staples, through an established network of merchant guilds, thus becoming more entrenched over time in large-scale serf-intensive agricultural production. Complementarily, craft guilds with vested interests in blocking the widespread adoption of skill-intensive industry may have come to possess greater bargaining power in strategic interactions with the nobility in these counties, thus undermining the ability of the landlords to diversify their production activities (see, e.g., Desmet, Greif and Parente, 2017) and, thereby, retarding labor emancipation.

4.4 Other outcomes

To provide corroborating evidence in support of our interpretation of the reduced-form association between the initial stock of relevant (i.e., elite-owned and skill-complementing) physical capital and the subsequent *de facto* emancipation of labor, our empirical analysis additionally explores the links between (i) relevant fixed capital abundance in the early nineteenth century and the willingness of the elites to settle for lower compensation payments in redemption agreements with their serfs, conditional on the prevailing intensity of labor coercion; and (ii) the intensity of *de facto* serf emancipation as of the mid-nineteenth century and the subsequent accumulation of human capital by the masses, conditional on the initial abundance of relevant capital.

Our outcome measure for exploring the first link is based on the average compensation payments made to the landlords (for redeeming lifetime labor services) per emancipation case settled in a county by 1848, under the Dissolution Ordinance of 1821.[46] For examining the second link, we employ two different outcome measures. The first measure captures the enrollment rate in primary schools in 1864, based on county-level census information on both total attendance across primary schools and the population of children of recommended school age (6 to 14). The second measure reflects the literacy rate amongst the population aged 10 and above in a county, based on information available from the 1871 census.

Table E.1 in Appendix E provides the descriptive statistics for all variables considered by our cross-sectional analysis, including terrain slope (to be introduced in the next section), which we exploit as a plausibly exogenous source of variation across counties in our proxy measure of the initial stock of relevant physical capital.

5 Empirical analysis

5.1 Cross-sectional specification and reduced-form identification

5.1.1 The empirical model

Our conceptual framework suggests that the historical decline of serfdom in nineteenth-century Prussia can be partly explained by the emergence of capital-ownership amongst the class of manorial lords, which served to mobilize their incentives to emancipate labor in order to reap higher returns to physical capital arising from the nascent complementarity between capital and free workers over the course of industrialization. In empirically exploring our hypothesis, we therefore exploit

[46] To be precise, it is the first principal component of the average amounts associated with four different types of compensation payments made by peasants in their settlements with the landlords. See Appendix E for additional details.

variations in a cross-section of Prussian counties, aiming to establish a robust positive link between the initial abundance of elite-owned physical capital that came to be associated with skill-intensive production, on the one hand, and the subsequent intensity of *de facto* serf emancipation, on the other. Specifically, we estimate the following linear model using ordinary least squares (OLS):

$$\text{Emancipation}_{i,1821-48} = \alpha + \beta \cdot \text{Mills}_{i,1819} + \mathbf{X}_i' \cdot \boldsymbol{\Lambda} + \mathbf{Z}_i' \cdot \boldsymbol{\Theta} + \varepsilon_i,$$

where, as discussed earlier in Section 4.3, the vector $\mathbf{X}_i$ represents our first set of covariates, capturing exogenous geographical characteristics of county i, the vector $\mathbf{Z}_i$ includes our second and third sets of covariates, comprising less exogenous but more proximate potential confounders of the relationship between initial capital abundance and subsequent serf emancipation, and ε_i is a county-specific disturbance term.

The coefficient of interest, β, relates our proxy measure of vested economic interests of the landowning capitalist elites, arising from their increasing stakes in skill-complementing physical capital, with the intensity of *de facto* serf emancipation, after the potentially confounding effects of $\mathbf{X}_i$ and $\mathbf{Z}_i$ have been partialled out. Under the "reduced form" interpretation of our hypothesis, β is expected to enter our regressions positively and significantly. In our empirical analysis, we will begin by estimating the bivariate relationship of interest and will then incrementally add control variables from $\mathbf{X}_i$ and $\mathbf{Z}_i$ to our estimating equation, in the build-up towards our full empirical model. This will facilitate an assessment of the stability of our coefficient of interest when conditioned on different (sets of) covariates, thus permitting a proper evaluation, based on selection on observables, of potential bias arising from selection on unobservables (Altonji, Elder and Taber, 2005). Finally, to account for possible interdependence of error terms across counties within larger administrative units, we cluster the standard errors at the district level. Overall, the 261 counties in our full sample belong to nineteen districts.[47]

5.1.2 Mitigating endogeneity

Since our explanatory variable of interest, that is, the number of water mills (per 1,000 inhabitants), corresponds to a census year that precedes the time horizon over which the intensity of *de facto* serf emancipation is measured, reverse causality is not likely to be a major source of concern. On the other hand, although our estimating equation includes a considerable set of potentially confounding factors, the prevalence of water mills in 1819 may still be correlated with the error term due to omitted variables. In particular, heterogeneity across counties in unobserved mechanisms that may have contributed to both initial capital abundance and subsequent labor emancipation would bias our coefficient of interest in favor of rejecting the null hypothesis. We attempt to mitigate this issue by exploiting an exogenous (and, arguably, conditionally excludable) source of variation across counties in the prevalence of water mills in the early nineteenth century.

[47] Alternatively, to allow for a more general form of spatial correlation in error terms across counties, we implemented the "Conley correction" for all of our main specifications, using various spatial cutoffs in the range of 200 to 500 kilometers. Table C.2 in Appendix C shows that the resulting standard errors are indeed very similar to their baseline estimates (as reported in the main text below), and the statistical significance of the relationship of interest remains largely unaffected.

There are two apparent forces that determined the spatial distribution of water mills across counties in nineteenth-century Prussia. First, as mentioned in Section 4.2, a water mill could only be operated on a manorial estate if the lord was licensed to do so under a suit of mill granted by the King, but this institutional constraint on the prevalence of water mills in a given region was likely endogenously determined with other forces that shaped the historical evolution of both coercive labor institutions and capital-ownership by the elites in that region. Second, certain features of the physical environment determined the suitability of a region for the effective operation of water mills. Specifically, because terrain undulation affects the natural speed of running water (and, thus, the hydraulic energy potentially harnessable by water mills at the time), the average slope of the terrain in a region had a non-monotonic influence on the region's suitability for operating water mills. At one end of the spectrum, terrains that are too flat did not permit the natural movement of water to be associated with a sufficient amount of kinetic energy. At the other end, however, in terrains that are too steep, such energy could not be feasibly harnessed, given the constraints imposed by the frontier of engineering technology in the early nineteenth century.

In particular, terrain slope is expected to possess a hump-shaped relationship with the suitability of the natural environment for operating a water mill, reflecting a trade-off that captures the influence of terrain slope on the viability of constructing mill *dams*. Historically, the setup of a water mill almost invariably involved the placement of a dam on a natural waterway (a stream or small river) to create an artificial mill pond in an upstream catchment area. From there, the water was conveyed to a water wheel along an artificially constructed channel (i.e., a sluice or leat), fitted with gates for controlling the water current (or mill race) that was supplied to the water wheel. Thus, although a steeper natural gradient conferred the benefit of a stronger *baseline* water current, it also increased the marginal cost of setting up a functional mill site, especially in light of the technological limitations of the nineteenth century: a steeper terrain meant that not only was it more challenging to construct a mill dam for creating a well-contained mill pond, it was also more difficult to engineer the artificial channel to appropriately control the mill race that fed hydraulic energy to the water wheel. Indeed, based on conceptually similar priors, Duflo and Pande (2007) assert that "engineering considerations suggest that river gradient should have a nonmonotonic effect on the likelihood of dam construction" (p. 606), and they empirically document precisely such an effect of river gradient on the prevalence of irrigation dams across districts in modern-day India.[48]

We measure the average slope of a county's terrain using geospatial elevation data at a 30-arc-second resolution by first computing the maximum elevation gradient (in angular degrees) between each grid cell and its eight contiguous neighbors and then calculating the average of this gradient measure across all the grid cells of the county. The scatter plot in Figure 6 depicts the significant non-monotonic influence of terrain slope on the prevalence of water mills in our sample. We exploit this pattern in the first stage of a two-stage least squares (2SLS) estimation framework to mitigate the potential omitted variable bias afflicting our coefficient of interest under OLS.[49]

[48]Specifically, the authors study the productivity and distributional effects of dams, exploiting heterogeneity across Indian districts in the slope of the ground surface as an exogenous source of variation in dam construction.

[49]Notably, the inflexion point of the hump-shaped relationship depicted in Figure 6 occurs in the neighborhood of a terrain slope value of 2.5 angular degrees, which corresponds to a rise-over-run slope ratio of $\tan(2.5) \approx 4\%$. This is, in fact, quite similar to the 3% rise-over-run "cutoff" value for the river gradient in Duflo and Pande (2007,

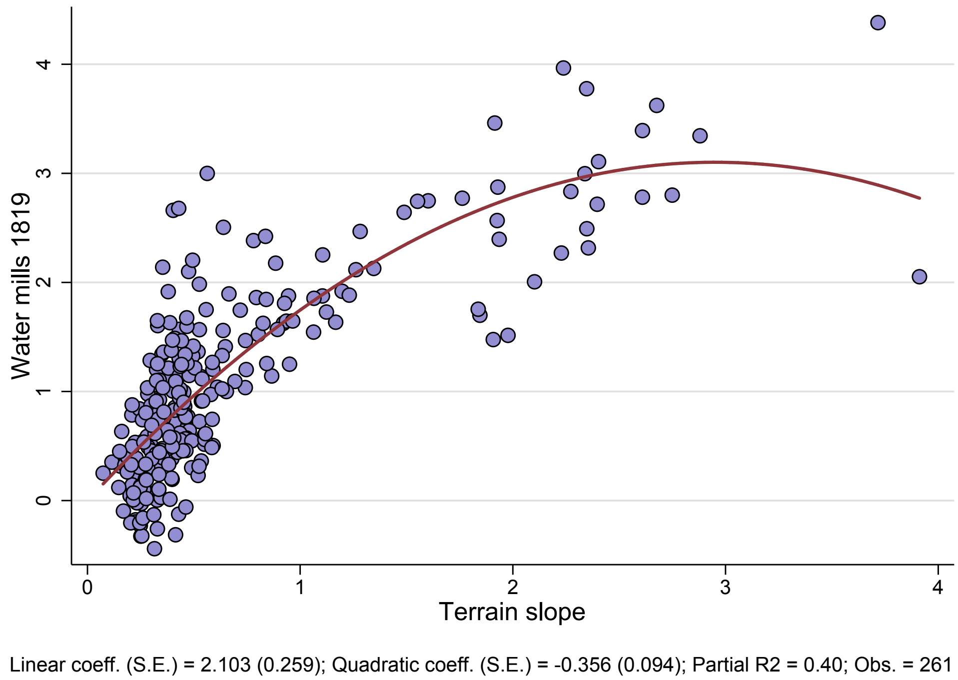


FIGURE 6: Terrain slope and water mills in 1819

Notes. This scatter plot depicts the trade-off associated with the influence of terrain structure on the operability of water mills, illustrating a significant non-monotonic relationship across Prussian counties between average terrain slope and the number of water mills (per 1,000 inhabitants) in 1819. The depicted relationship accounts for heterogeneity across counties in potentially confounding geographical factors. See the discussion in the main text and Appendix E for additional details.

Nonetheless, one may still harbor admittedly valid concerns regarding the excludability of terrain slope from the second stage of our 2SLS framework, namely, the possibility that terrain slope could have influenced the pace of *de facto* serf emancipation through mechanisms other than the prevalence of water mills in the early nineteenth century. Below, we provide several arguments to alleviate such concerns.

First, our analysis directly accounts for the immediately obvious alternative mechanisms through which terrain structure could influence the strength or persistence of coercive labor institutions. Specifically, since average terrain slope could be correlated with local climatological and ecological features that affect the agricultural productivity of land, our analysis controls for variations across counties in temperature, precipitation, and different measures of soil quality. In addition, because terrain undulation is expected to be associated with higher transportation costs and thus weaker integration of goods and factor markets across space, we account for cross-county differences in access to external markets, as captured by distance to waterways and the presence of roads and railways, and in more proximate measures of labor abundance and economic

p. 619, Table 2) – i.e., the value below (above) which river gradient is found to have a positive (negative) effect on the likelihood of dam construction across districts in modern-day India. In light of the fact that their study focuses on a completely different time period and region of the world, this "external validity" result lends further credence to our identification strategy.

development, such as population density and urbanization rate in the early nineteenth century. It is also important to note that although the latter controls may themselves be endogenous in our regression framework, both population density and urbanization rate are observed in a census that preceded the time horizon over which the outcome variable is measured. As such, while the second-stage coefficients associated with these controls may well be afflicted by omitted variable bias, the fact that they are not marred by reverse causation still makes them useful for excluding mechanisms, broadly pertaining to economic development, through which terrain slope could potentially influence the persistence of coercive labor institutions.

Second, had the terrain slope variable been particularly susceptible to the issue of non-excludability from the second stage of our framework, one expects that upon augmenting the specification with additional control variables, there would be considerable instability in the 2SLS estimate of our coefficient of interest. In contrast, as will become evident, we find that conditional on all geographical controls, the 2SLS coefficient associated with the prevalence of water mills remains largely stable when additional covariates are included in the estimating equation. Related to this pattern, we also find that the first-stage coefficients reflecting the non-monotonic influence of average terrain slope on the prevalence of water mills in 1819 remain remarkably stable when additional controls are incorporated in our 2SLS framework. A similar pattern of stability is also observed for the first-stage partial R^2 that captures the explanatory power of the residual variation in terrain slope for the residual variation in the prevalence of water mills across counties.

Furthermore, to the extent that the possible non-excludability of terrain slope from our baseline regressions can manifest itself in a higher 2SLS coefficient estimate for the prevalence of water mills, it may be noted that in our full sample of counties and conditional on our complete set of covariates, we obtain largely similar OLS and 2SLS point estimates. This suggests that insofar as our 2SLS approach is able to credibly mitigate the potential issue of omitted variable bias in our OLS specifications, this bias is inconsequential to begin with.

Lastly, we can show that a conceptually more refined identification strategy, based on *both* the topographic and the hydrological suitability for operating water mills, provides results that are substantively identical to those obtained under our baseline strategy. This is due to the fact that the suitability for operating water mills is overwhelmingly determined by the topographic rather than the hydrological dimension in our data.[50] The alternative identification strategy is explained in detail in Appendix B, with the corresponding results reported in Tables B.1–B.3.

5.2 Cross-sectional findings

5.2.1 Baseline analysis: Controlling for geographical confounders

Table 1 reveals the results from estimating our baseline set of regressions, exploiting variations across Prussian counties to link the prevalence of water mills in 1819 with the share of serfs that were *de facto* emancipated during the 1821–1848 time horizon, conditional on geographical characteristics. In column 1, we report the coefficient estimate for the bivariate relationship between

[50] We measure the hydrological suitability for operating a water mill by aggregating geospatial information on "flow accumulation" at a 30-arc-second resolution. Flow accumulation reflects the potential for surface water presence and is measured as the cumulative number of "upstream" cells from which a given cell can potentially receive water inflows.

our variables of interest. This estimate is statistically significant at the 1% level and implies that an increase in the prevalence of water mills in 1819 by one standard deviation is associated with an average increase in the intensity of *de facto* serf emancipation between 1821 and 1848 by 30% of a standard deviation of this variable in our sample of 261 counties. The scatter plot in panel (a) of Figure 7 depicts the corresponding bivariate relationship between the unstandardized counterparts of our variables of interest.

In columns 2–7, we augment our bivariate specification from column 1 to account for heterogeneity across counties in each of our geographical covariates at a time – namely, average temperature, average precipitation, distance to navigable rivers, two different measures of soil suitability for agriculture, and an "East Elbia" fixed effect. The results indicate that conditional on the prevalence of water mills in 1819, the geographical factors that *individually* matter the most for the pace of *de facto* serf emancipation in the first half of the nineteenth century are temperature, precipitation, and soil suitability for cereal crops, all measured using contemporary high-resolution geospatial data. The significance of the latter two variables potentially reflects the stronger vested interests of the landowning elites in maintaining coercive labor institutions in those locations where, because of the higher agricultural productivity of land (arising from more precipitation and/or better soil quality), the elites could benefit more from the continued use of serf labor in large-scale agricultural production.[51] On the other hand, the positive and significant coefficient estimate for average temperature likely captures the apparent latitudinal gradient in the intensity of emancipation across Prussian counties, particularly in East Elbia, as is evident from the map in Figure 2.

In terms of the other geographical covariates in columns 2–7, their associated coefficients are imprecisely estimated, and they do not necessarily enter their respective regressions with expected signs, as is the case for distance to navigable rivers. In line with priors, however, the regression in column 7 suggests that coercive labor institutions were more persistent in the counties located to the east of the river Elbe, where both industrialization and serf emancipation are known to have been delayed due to the vested interests of the nobility in the continuation of large-scale agriculture (see, e.g., Harnisch, 1986; Melton, 2000; Acemoglu et al., 2011; Cinnirella and Hornung, 2016). Nevertheless, in all specifications corresponding to columns 2–7, our coefficient of interest remains both highly statistically significant and quantitatively rather stable, indicating that a unit standard deviation increase in the prevalence of water mills in 1819 is associated with an average increase of between 27% and 34% of a standard deviation in the intensity of *de facto* serf emancipation during the 1821–1848 time horizon.

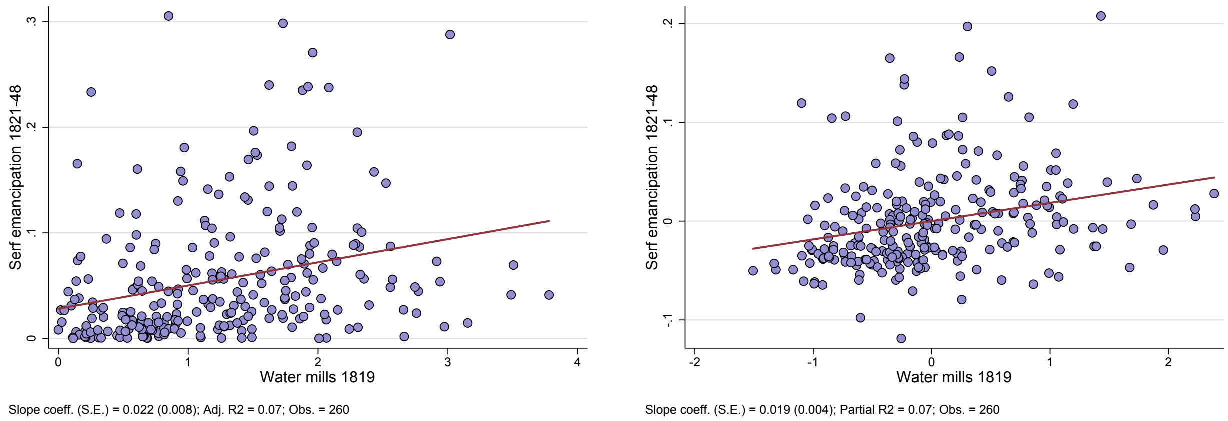
Controlling simultaneously for all geographical covariates, the specification in column 8 yields an estimate for our coefficient of interest that remains highly statistically significant and is only marginally smaller than the estimates from earlier columns. The corresponding conditional relationship between the unstandardized counterparts of our variables of interest is depicted by the scatter plot in panel (b) of Figure 7. With respect to the geographical covariates, almost all variables enter the regression with their expected signs, although only temperature and precipitation

[51] Our finding that soil suitability for agriculture is associated with greater persistence in coercive labor institutions is in line with those reported by Bobonis and Morrow (2014) and Dippel, Greif and Trefler (2015). Interestingly, our alternative measure of soil suitability for agriculture, which reflects the share of sand in the top soil, does not appear to be significantly associated with the pace of *de facto* serf emancipation.

Table 1: Cross-sectional analysis—Controlling for geography

Dependent variable:	Serf emancipation 1821–48										
	Full sample									East-Elbe sample	
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS	(9) 2SLS	(10) OLS	(11) 2SLS
Water mills 1819	0.301***	0.304***	0.337***	0.292**	0.291***	0.299***	0.267***	0.243***	0.341***	0.286***	0.571***
	(0.102)	(0.092)	(0.100)	(0.102)	(0.096)	(0.102)	(0.086)	(0.057)	(0.100)	(0.089)	(0.170)
Average temperature		0.287**						0.155*	0.150	0.442***	0.352***
		(0.107)						(0.087)	(0.092)	(0.090)	(0.128)
Average precipitation			−0.251***					−0.381***	−0.383***	−0.189	−0.275
			(0.062)					(0.082)	(0.085)	(0.150)	(0.189)
Distance to navigable river				0.117				0.575	0.451	0.386	0.050
				(0.431)				(0.420)	(0.381)	(0.522)	(0.361)
Soil suitability (cereals)					−0.342**			−0.079	−0.073	−0.045	0.002
					(0.124)			(0.065)	(0.068)	(0.107)	(0.112)
Sandy soil (share)						−0.288		−0.368	−0.386	−0.281	−0.483
						(0.380)		(0.255)	(0.249)	(0.407)	(0.457)
East Elbe (dummy)							−0.434	−0.775**	−0.737**		
							(0.430)	(0.315)	(0.324)		
Observations	261	261	261	261	261	261	261	261	261	195	195
Adjusted R^2	0.09	0.14	0.16	0.08	0.15	0.09	0.12	0.31	0.30	0.24	0.17
Partial R^2 of mills		0.10	0.12	0.08	0.09	0.09	0.07	0.07		0.09	
Kleibergen-Paap F statistic									67.60		83.67

Notes. The dependent variable is the total number of serf emancipation cases settled in a county (under the 1821 ordinance) as of 1848, expressed as a fraction of the rural population of the county in 1816 (net of the population in small peasant landholdings). The main explanatory variable is the number of water mills (per 1,000 inhabitants) in a county in 1819. Both variables are standardized to have zero means and unit standard deviations in each regression sample. See Appendix E and the discussion in Section 4 for additional details on all variables. In columns 9 and 11, a quadratic formulation in terrain slope is employed as an excluded instrument for the prevalence of water mills in 1819. The corresponding first-stage regressions are reported in columns 1 and 2 of Table C.1 in Appendix C. Standard errors, clustered at the district level, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.



(a) Bivariate relationship

(b) Conditional on geography

Figure 7: Water mills in 1819 and serf emancipation 1821–48

Notes. These scatter plots illustrate the significant positive relationship across Prussian counties between the initial abundance of relevant physical capital, as proxied by the number of water mills (per 1,000 inhabitants) in a county in 1819, and the subsequent intensity of *de facto* serf emancipation, measured as the total number of serf emancipation cases settled in a county (under the 1821 ordinance) as of 1848, expressed as a fraction of the rural population of the county in 1816 (net of the population in small peasant landholdings). Panel (a) depicts the bivariate relationship between unstandardized variables, whereas panel (b) depicts the relationship after accounting for heterogeneity across counties in potentially confounding geographical factors. For visual clarity, both plots omit a non-influential outlier from the sample of counties. See the discussion in the main text and Appendix E for additional details.

are statistically significant, as is the negative fixed effect associated with counties located in East Elbia. Interestingly, conditional on the prevalence of water mills in 1819 and other geographical factors, the suitability of the soil for cereal crops is no longer statistically significant.

To mitigate potential omitted variable bias in our estimated coefficient of interest from column 8, we consider the same specification under the 2SLS approach in column 9, exploiting the non-monotonic influence of terrain slope on the prevalence of water mills in 1819 in the first-stage regression. The estimated 2SLS coefficient of interest suggests a more pronounced relationship between the prevalence of water mills in 1819 and the subsequent intensity of *de facto* serf emancipation. This result could partly be a reflection of attenuation bias in our coefficient of interest under OLS estimation, since the prevalence of water mills in 1819 is only a noisy proxy of the true but unobserved measure of the elites' incentives to emancipate their serfs and subsequently employ them in skill-intensive industrial production activities. Another possibility is that our set of covariates considered thus far is not quite sufficient to ensure the conditional excludability of terrain slope from a regression explaining the *de facto* decline in serfdom. Indeed, as will become evident shortly, once our specification is augmented to account for additional potential confounders, the estimated conditional relationship of interest is almost identical under OLS and 2SLS estimation frameworks.

Meanwhile, it may be noted that the remarkably high first-stage F statistic reported in column 9 precludes any potential weak-instrument issues. This assertion is further corroborated by the results from the corresponding first-stage regression (reported in column 1 of Table C.1 in Appendix C), which shows highly significant coefficients associated with the linear and quadratic terms of terrain slope, conditional on our set of geographical covariates. This regression is also characterized by a sizable partial R^2 relative to the overall R^2, reflecting the considerable explanatory power of the residual cross-county variation in terrain slope for the residual variation in the prevalence of water mills in 1819. Furthermore, as is evident from the remaining columns of Table C.1, the coefficients reflecting the non-monotonic influence of terrain slope on the prevalence of water mills (and, to a lesser extent, the partial explanatory power of terrain slope) remain quantitatively stable when our 2SLS framework incorporates additional control variables.

Finally, in columns 10 and 11 of Table 1, we estimate the specifications examined in the preceding two columns, focusing exclusively on the sub-sample of counties located in East Elbia. Although our full-sample analysis does account for differences in cross-county means between regions in the west versus east of the river Elbe, the presence of this fixed effect alone is insufficient to claim that the positive reduced-form association between the initial abundance of relevant fixed capital and the subsequent intensity of *de facto* serf emancipation actually held under the distinct institutional conditions that prevailed in regions east of the river Elbe. Reassuringly, based on variations exclusively across counties in East Elbia, the regression estimates reported in columns 10 and 11 document reduced-form empirical patterns that are qualitatively similar to and, if anything, quantitatively even stronger than those observed in our full sample of counties.[52]

5.2.2 Augmented analysis: Controlling for proximate confounders

Our analysis of the reduced-form relationship between the prevalence of water mills in 1819 and the subsequent pace of *de facto* serf emancipation has thus far only considered exogenous geographical covariates. We now augment our analysis to *additionally* account for less exogenous but more proximate potential confounders of this relationship, such as the initial levels of economic development, labor abundance, access to urban markets, and the intensity of human capital investments as well as various demographic, cultural, and institutional characteristics. Although the endogeneity of these proximate confounders (as well as those considered in the next section) precludes a causal interpretation of their associated coefficients in our regressions, our intention is to simply assess the extent to which these additional covariates can explain away the relationship of interest, conditional on our full set of geographical controls. The estimation results for our augmented specifications are collected in Table 2. As in the preceding analysis, we initially introduce additional controls one at a time, before including them all simultaneously. To highlight the key result from this exercise, we find that the strong positive association between the initial abundance of relevant fixed capital and the subsequent intensity of labor emancipation remains not only qualitatively unaffected but also largely stable and highly statistically significant across specifications, as is evident from the top row of Table 2.

In columns 1 and 2, we present the estimates from regressions that include, respectively, population density and the urbanization rate in 1816 as additional covariates. These factors partly account for the initial level of economic development (or even the initial extent of broad-based

[52]Furthermore, Table C.4 in Appendix C reassuringly shows that our main finding is additionally robust to the one-at-a-time exclusion of each of the seven Prussian provinces from the estimation sample, thus establishing that the key empirical pattern is not generated by unobserved heterogeneity between any one province and the remainder of the sample.

TABLE 2: Cross-sectional analysis—Controlling for proximate economic, demographic, cultural, and institutional confounders

Dependent variable:	Serf emancipation 1821–48											
	Full sample										East-Elbe sample	
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS	(9) OLS	(10) 2SLS	(11) OLS	(12) 2SLS
Water mills 1819	0.235***	0.271***	0.174***	0.245***	0.259***	0.243***	0.258***	0.206***	0.244***	0.232***	0.242***	0.318***
	(0.053)	(0.060)	(0.052)	(0.057)	(0.051)	(0.057)	(0.055)	(0.054)	(0.052)	(0.068)	(0.057)	(0.079)
Population density 1816	0.741								−1.585	−1.548	1.274	1.042
	(1.817)								(1.321)	(1.223)	(2.368)	(2.119)
Urbanization rate 1816		1.405*							1.481*	1.468**	1.241	1.358
		(0.749)							(0.726)	(0.707)	(0.986)	(0.922)
Family size 1849			−1.014***						−0.908***	−0.914***	−0.966**	−0.941**
			(0.230)						(0.277)	(0.261)	(0.400)	(0.374)
Knight estates (share)				−0.145**					−0.067	−0.066*	−0.077	−0.086*
				(0.059)					(0.040)	(0.036)	(0.056)	(0.050)
Protestants 1816 (share)					0.477**				0.219	0.211	0.168	0.279
					(0.182)				(0.222)	(0.220)	(0.432)	(0.400)
Other ethnic group 1861 (share)						−0.548***			0.125	0.125	−0.085	−0.060
						(0.130)			(0.206)	(0.193)	(0.267)	(0.259)
Partible inheritance law (dummy)							−0.201		−0.248	−0.239	−0.254	−0.277
							(0.357)		(0.313)	(0.294)	(0.227)	(0.195)
Enrollment rate 1816								0.858***	0.260	0.278	0.225	0.079
								(0.186)	(0.291)	(0.291)	(0.626)	(0.577)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	261	261	261	261	261	261	261	261	261	261	195	195
Adjusted R^2	0.31	0.33	0.39	0.33	0.34	0.33	0.31	0.33	0.42	0.42	0.40	0.40
Partial R^2 of mills	0.06	0.09	0.04	0.07	0.08	0.07	0.08	0.05	0.07		0.06	
Kleibergen-Paap F statistic										54.14		47.42

Notes. The dependent variable is the total number of serf emancipation cases settled in a county (under the 1821 ordinance) as of 1848, expressed as a fraction of the rural population of the county in 1816 (net of the population in small peasant landholdings). The main explanatory variable is the number of water mills (per 1,000 inhabitants) in a county in 1819. Both variables are standardized to possess zero means and unit standard deviations in each regression sample. See Appendix E and the discussion in Section 4 for additional details on all variables. In columns 10 and 12, a quadratic formulation in terrain slope is employed as an excluded instrument for the prevalence of water mills in 1819. The corresponding first-stage regressions are reported in columns 3 and 4 of Table C.1 in Appendix C. Standard errors, clustered at the district level, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

industrialization, as reflected by the urbanization rate) as well as theories of emancipation that emphasize the role of either labor abundance or the perceived threat of labor scarcity arising from better outside options for serfs (e.g., Postan, 1966; Domar, 1970; Brenner, 1976; Acemoglu and Wolitzky, 2011).[53] Although both covariates enter their respective regressions with positive coefficients, the one associated with initial population density is imprecisely estimated. Moreover, as shown in column 9, in the specification including the full set of covariates, urbanization rate continues to retain a significant positive relationship with the subsequent decline in coercive labor institutions, whereas the coefficient estimate on population density changes its sign and remains statistically insignificant. Thus, while our *prima facie* evidence regarding the influence of labor abundance (as captured by population density) on emancipation is mixed, the findings suggest that the threat of labor scarcity in agriculture due to better options for workers in urban markets (as captured by the urbanization rate) may well have played an important role in the decline of coercive labor institutions in nineteenth-century Prussia.

The specification in column 3 aims to account for the fact that because an emancipation settlement typically involved an entire peasant family rather than an individual serf, larger peasant family sizes could have been associated with higher redemption costs (and, thus, the reduced ability of peasant families to actually pay for their redemption), reflecting higher amounts of servile dues per family to the manorial lords. In addition, since our outcome variable normalizes the number of emancipation cases settled in a county as of 1848 by the initial rural population of the county, it is expected to be *mechanically* negatively associated with the average size of peasant families. Moreover, smaller family sizes could be reflective of higher levels of industrial demand for human capital and, thus, more intense shifts of households away from child quantity towards child quality, as suggested by human-capital-driven theories of the demographic transition (see, e.g., Galor, 2011).[54] The estimates in columns 3 and 9 indicate that average family size is indeed negatively and significantly associated with the pace of *de facto* serf emancipation.[55]

The regression presented in column 4 directly accounts for stronger vested interests of the landlords in maintaining coercive labor institutions in agriculture, by including the share of knight estates (*Rittergüter*) in a county as a proxy measure of landownership concentration amongst the elites.[56] These large manorial estates are known to have relied heavily on the intensive appropriation of serf labor for large-scale agriculture (Cinnirella and Hornung, 2016), especially in counties east

[53] Lagerlöf (2016) provides a nuanced interpretation of the influence of labor scarcity on the prevalence of coercive labor institutions, arguing that when free workers migrate from rural to urban areas to match with better outside options, rural elites can counteract the resulting labor scarcity in the long run by *temporarily* increasing the well-being of coerced workers to engender a Malthusian fertility response, which ultimately increases the supply of coerced labor (and their representation in the rural population) given the hereditary transmission of labor status.

[54] See also Becker, Cinnirella and Woessmann (2010, 2012) for evidence showing the existence of a negative effect of educational investments on fertility, both prior to and during the onset of the demographic transition in nineteenth-century Prussia.

[55] The earliest year for which county-level data on average family size are available is 1849. Because this date occurs towards the end of the time horizon over which our emancipation outcome is observed, the estimated coefficients associated with family size may well be marred by reverse causality. Indeed, Cinnirella and Hornung (2017) provide evidence of changes in patterns of education and fertility that may have occurred in response to the Prussian emancipation process over the course of the nineteenth century.

[56] Although our measure of the share of knight estates is based on data for 1856, as discussed by Cinnirella and Hornung (2016), the historical evidence suggests that this share remained largely unchanged throughout the period under consideration.

of the river Elbe. In line with priors, the covariate enters the regression in column 4 with a negative and statistically significant coefficient, although its magnitude is diminished when the full set of covariates is accounted for by the specification in column 9.

In columns 5 and 6, we control for differences across county populations in their religious and ethnic compositions – as captured by the share of Protestants in 1816 or the share of individuals of non-Germanic (mostly Slavic) ancestry in 1861 – that could have affected the pace of *de facto* labor emancipation, the onset of industrialization, or even the propensity to attract migrant groups from various ethnic backgrounds. In line with the connection between Protestantism and early human capital formation (Becker and Woessmann, 2009), the regression in column 5 indicates that the prevalence of Protestantism in 1816 may well have contributed to the subsequent pace of labor emancipation. Furthermore, the share of the non-Germanic population in a county enters the regression in column 6 with a significant negative coefficient, plausibly reflecting the fact that the prevalence of individuals with Slavic (Polish) ancestry was higher in counties belonging to the province of Posen, where coercive labor institutions were historically more persistent. The estimated coefficients associated with both religious and ethnic composition, however, become statistically insignificant in the fully specified regression model of column 9.

The regression in column 7 introduces an indicator for the predominant law of succession of peasant landholdings in a county (namely, partible inheritance versus primogeniture) as a covariate. On the one hand, the historical association between primogeniture and the prevalence of large-scale agriculture potentially implies a delayed emancipation process in regions that practiced this form of inheritance. On the other hand, because partible inheritance mechanically resulted in the increased prevalence of small peasant landholdings that were *de jure* excluded from the emancipation process until the passage of the Commutation Law of 1850, one expects lower rates of emancipation in regions that practiced divided succession. Consistently with the dominance of the latter effect, the indicator for partible land inheritance appears to be negatively associated with the share of serfs emancipated by 1848 in the specifications examined in columns 7 and 9, although this relationship is not precisely estimated.

In column 8, we directly account for heterogeneity across counties in the initial intensity of investments in human capital, as captured by the enrollment rate in public primary schools in 1816, which could have conditioned the propensity of the capital-owning elites to subsequently emancipate the peasantry while also affecting the pace of industrialization. Perhaps unsurprisingly, the regression in column 8 suggests that the primary school enrollment rate in 1816 is positively and significantly associated with the prevalence of *de facto* emancipated serfs as of 1848, although the estimated relationship becomes weaker and loses statistical significance when conditioned on the full set of covariates in column 9.

Columns 9 and 10 reveal the estimation results for specifications including the complete set of controls for proximate confounders, first under OLS and then employing our 2SLS strategy, in the full sample of counties. Notably, the OLS estimate of our coefficient of interest is virtually identical to that obtained in column 8 of Table 1, when only geographical covariates were taken into account. In addition, the OLS and 2SLS coefficient estimates are now very similar, suggesting that conditional on the credibility of our 2SLS framework, any residual omitted variable bias potentially afflicting the OLS estimate of our coefficient of interest is negligible.

Last but not least, in columns 11 and 12, we replicate the analysis from the preceding two columns but focusing exclusively on the sub-sample of counties in East Elbia. The analysis reassuringly yields an OLS estimate of the relevant relationship that is almost identical to that found in the full sample of counties in column 9. Furthermore, although the relevant 2SLS point estimate is somewhat larger than its OLS counterpart, this gap is substantially smaller than the one observed earlier in Table 1, when our analysis included only geographical covariates.

5.2.3 Augmented analysis: Additional robustness checks

The analysis presented in Table 3 accounts for further potential confounders of the positive reduced-form relationship between the prevalence of water mills in 1819 and the intensity of *de facto* serf emancipation during the 1821–1848 time horizon, conditional on all the covariates considered thus far. As highlighted by the top row of Table 3, our main finding is that the coefficient of interest remains both highly statistically significant and largely stable in magnitude across specifications for our full sample of counties, relative to its baseline estimate from column 9 of Table 2.

The specification in column 1 accounts for cross-county heterogeneity in the prevailing intensity of labor coercion, as proxied by the average amount of servile labor dues redeemed by former serfs (through compensation payments to their manorial lords) across the emancipation cases settled in a county as of 1848. Although the coefficient associated with this covariate is imprecisely estimated in column 1, the point estimate becomes statistically significant in the fully specified model of column 9 and always carries the expected negative sign, potentially reflecting both a diminished ability of the peasantry to make the necessary compensation payments and stronger economic incentives of the landlords to prolong the employment of serf labor when the intensity of coercion is already high.

In column 2, we simultaneously introduce dummy variables indicating, respectively, the presence of a main road and a railway line in 1848. In addition to the initial urbanization rate, these covariates plausibly capture the extent to which a county's rural locales were integrated with external goods and factor markets. Market integration could have affected not only the process of labor emancipation, by facilitating access to better outside options for the peasantry and, thereby, increasing their bargaining power against the elites, but also the pace of broad-based industrialization, through the standard Smithian mechanism of economic development.[57] The results in column 2 suggest that although the presence of a main road is not statistically significantly related to serf emancipation, access to railways may indeed have played an important role in accelerating the decline of serfdom in Prussia. These findings continue to hold qualitatively in the fully specified model of column 9.

The literature on Prussian industrialization during the latter half of the nineteenth century has emphasized access to coal deposits as an important determinant of not only the pace of industrialization but also the spatial distribution of industrial activities due to agglomeration effects (e.g., Pierenkemper, 1978; Kiesewetter, 2004; Gutberlet, 2014). Although coal mining in Prussia did not take off until circa 1850 and remained under state control until 1865, its emergence may nevertheless have created new labor-market opportunities for the peasantry, thus contributing to

[57]Indeed, Hornung (2015) provides evidence that causally links railway access to urban population growth in nineteenth-century Prussia.

Table 3: Cross-sectional analysis—Controlling for additional confounders

Dependent variable:	Serf emancipation 1821–48											
	Full sample										East-Elbe sample	
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS	(9) OLS	(10) 2SLS	(11) OLS	(12) 2SLS
Water mills 1819	0.239***	0.244***	0.232***	0.244***	0.245***	0.215***	0.244***	0.244***	0.206***	0.236***	0.151**	0.181*
	(0.054)	(0.052)	(0.054)	(0.052)	(0.052)	(0.057)	(0.052)	(0.053)	(0.057)	(0.077)	(0.068)	(0.104)
Servile duties (PCA)	−0.036								−0.053*	−0.050*	−0.099**	−0.096***
	(0.027)								(0.029)	(0.029)	(0.036)	(0.034)
Road 1848 (dummy)		−0.121							−0.122	−0.126	−0.123	−0.126
		(0.104)							(0.118)	(0.112)	(0.116)	(0.105)
Railway 1848 (dummy)		0.253***							0.213**	0.215***	0.395***	0.399***
		(0.078)							(0.078)	(0.074)	(0.126)	(0.113)
Coalfield (dummy)			0.413						0.259	0.252	1.009***	0.988***
			(0.256)						(0.253)	(0.235)	(0.176)	(0.154)
Number of uprisings 1816–47				0.027					0.035	0.035	−0.107	−0.108
				(0.073)					(0.068)	(0.063)	(0.093)	(0.084)
Commoner estates (share)					0.152				0.243	0.229	−0.130	−0.122
					(0.221)				(0.283)	(0.247)	(0.380)	(0.344)
Crown and state domains (share)						−2.036***			−2.341***	−2.302***	−2.360**	−2.315***
						(0.536)			(0.714)	(0.621)	(0.818)	(0.743)
Kulm estates (share)						−0.199			−0.061	0.028	−0.133	−0.086
						(0.350)			(0.368)	(0.292)	(0.346)	(0.362)
Commercial city (dummy)							−0.590**		−0.589**	−0.591***	−0.394	−0.386*
							(0.228)		(0.213)	(0.199)	(0.252)	(0.226)
Born outside county 1871 (share)								0.234	−0.414	−0.418	−0.925	−0.986
								(0.875)	(0.917)	(0.842)	(0.985)	(0.811)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other proximate controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	261	261	261	261	261	261	261	261	261	261	195	195
Adjusted R^2	0.42	0.43	0.43	0.42	0.42	0.44	0.44	0.42	0.47	0.47	0.48	0.48
Partial R^2 of mills	0.06	0.07	0.06	0.07	0.07	0.05	0.07	0.07	0.05		0.02	
Kleibergen-Paap F statistic										41.00		80.81

Notes. The dependent variable is the total number of serf emancipation cases settled in a county (under the 1821 ordinance) as of 1848, expressed as a fraction of the rural population of the county in 1816 (net of the population in small peasant landholdings). The main explanatory variable is the number of water mills (per 1,000 inhabitants) in a county in 1819. Both variables are standardized to possess zero means and unit standard deviations in each regression sample. See Appendix E and the discussion in Section 4 for additional details on all variables. In columns 10 and 12, a quadratic formulation in terrain slope is employed as an excluded instrument for the prevalence of water mills in 1819. The corresponding first-stage regressions are reported in columns 5 and 6 of Table C.1 in Appendix C. Standard errors, clustered at the district level, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

the likelihood of their *de facto* emancipation by increasing the perceived threat of labor scarcity in agriculture, at least towards the end of the time period over which our outcome variable is measured. In addition, the presence of coal deposits could be correlated with features of the local terrain (like elevation) that may have influenced the spatial distribution of water mills even in the early nineteenth century, posing a potential threat to the exclusion restriction in our 2SLS framework. The specification in column 3 thus examines the extent to which our coefficient of interest is affected by controlling for an indicator of the historical presence of a coalfield in a county, based on geospatial data from Fernihough and O'Rourke (2014). The indicator enters the regressions with an expected positive coefficient, in both column 3 and the fully specified model of column 9, although its point estimates are statistically insignificant.[58]

The specification in column 4 controls for the number of social uprisings that occurred in a county during the 1816–1847 time period, aiming to capture differences across counties in the strategic incentives of the elites to relinquish their coercive economic power when faced with a credible threat of social unrest and mass appropriation of elite assets (Acemoglu and Robinson, 2000; Aidt and Franck, 2015). Such strategic incentives could have been stronger when the elites had more to lose from mass appropriation (i.e., in those counties where their ownership of capital and land was higher) or perhaps weaker, given that wealthier elites could devote more resources to the suppression of popular revolts. The regression results presented in both columns 4 and 9 indicate that the number of social uprisings is in fact positively associated with the decline in serfdom, although the relationship is not precisely estimated. This association, however, hardly explains our key positive relationship between the prevalence of water mills in 1819 and the subsequent rate of serf emancipation.[59] Consistently with this robustness result, the scatter plots in panels (a) and (b) of Figure C.1 in Appendix C illustrate the absence of any systematic relationship across counties between either the prevalence of water mills or the share of knight estates, on the one hand, and the number of social uprisings, on the other. These findings suggest that the threat of mass revolts was not necessarily higher (or lower) in counties where the elites may have owned more assets, thus making it unlikely that wealthier elites harbored characteristically different strategic motives to emancipate the local peasantry.[60]

As discussed in Section 4.3, the termination of the nobility's monopoly rights over manorial landownership by the October Edict of 1807 may have resulted in the purchase of noble estates by bourgeois commoners with both emancipation oriented "enlightenment" ideals and stronger preferences for those demesnes where rural industrialization was already underway. Further, insofar as the noble lords of these estates happened to face a higher risk of delinquency in the aftermath of the Napoleonic Wars, they may have been compelled to accelerate the emancipation their serfs,

[58]Table C.3 in Appendix C shows the results from robustness checks in which, rather than controlling for the presence of a *mined* coalfield, which is potentially endogenous, we augment our baseline set of geographical covariates with an area-share measure of *subterranean* coal deposits from the Carboniferous geological period.

[59]This robustness result is insensitive to using alternative measures of social unrest at the county level, including either the total number of days of protests or a dummy variable indicating if there was ever a protest in a county during the 1816–1847 time period.

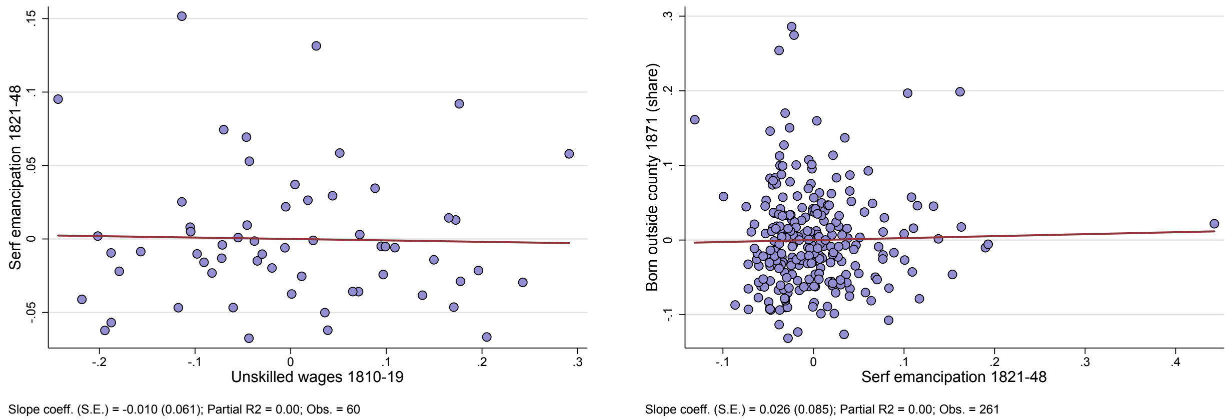
[60]In addition, panel (c) of Figure C.1 shows the absence of any systematic relationship across Prussian counties between the prevailing intensity of labor coercion, as proxied by the average amount of servile labor dues that needed to be redeemed by former serfs, and the number of social uprisings. This suggests that strategic incentives triggered by the threat of peasant revolts was not salient in the decision of the elites to emancipate their serfs in our setting, especially in counties where elite expropriation (and, thus, peasant immiseration) was high to begin with.

using the redemption payments to pay down their debts, prior to liquidating their demesnes by selling them off to commoners. To account for these alternative mechanisms, the specification in column 5 includes the share of noble estates in a county that came to be owned by commoners as of 1856 as a covariate. The results indicate that in both column 5 and the fully specified model of column 9, the covariate enters the regressions with an expected positive but statistically insignificant coefficient. Importantly, the association between the prevalence of water mills in 1819 and the subsequent rate of serf emancipation remains largely unaffected.

In column 6, we take into account the potentially confounding influence of the initial availability of free peasants, which could have diluted the economic incentive to emancipate the enserfed population (e.g., if the elites initially allocated the available free labor to industrial production activities). Further, because counties with a larger initial share of free peasants had smaller enserfed populations to begin with, they are *mechanically* expected to have converged less rapidly to a state to full emancipation. As explained in Section 4.3, we employ two historically relevant proxy measures of the initial availability of free peasants at the county level: the share of landholdings owned by the Prussian Crown and/or the state and the share of manorial estates that operated under the so-called Kulm law. The results shown in column 6 indicate that, as expected, both measures are negatively related to the share of serfs emancipated by 1848, although only the coefficient associated with the share of Crown and state domains is statistically significant. Moreover, the same empirical patterns continue to hold with respect to these covariates in the fully specified model of column 9.

The specification in column 7 examines the extent to which our coefficient of interest can be explained away by heterogeneity across counties in their historical exposure to the Commercial Revolution of the early modern period, by way of controlling for an indicator of the presence of a university in 1517 or a commercially vibrant city, as determined by its membership in either the Imperial or the Hanseatic Diet, in 1517. As is evident from the results in both column 7 and the fully specified model of column 9, the indicator enters the regressions with a statistically significant negative coefficient. These findings are consistent with the possibility that the landowning nobility in historically more commercial counties became increasingly entrenched over time in large-scale serf-intensive agricultural production, due to either the presence of merchant guilds that provided greater access to long-distance trade in staples, or the strategic influence of more powerful craft guilds with vested interests in blocking the widespread adoption of skill-intensive production methods.

As discussed in Section 3.2, the historical narrative of the Prussian labor emancipation process indicates that even upon redeeming their lifetime servile dues, many peasants continued to work for their former lords as free laborers, thus suggesting a relatively high degree of segmentation across labor markets. In addition, *ex ante* awareness amongst the elites of such segmentation may have been important; otherwise, even if they became aware that supporting labor emancipation would complement their increasing investments in industrial activities, the possibility that their workers, upon gaining freedom, could seek superior employment opportunities elsewhere would have discouraged (or prevented) the elites from acting upon their economic incentive to emancipate. Figure 8 provides *prima facie* empirical evidence suggesting not only that labor markets were highly segmented across Prussian counties in the early nineteenth century but also that the intensity of



(a) Unskilled wages and subsequent serf emancipation

(b) Serf emancipation and labor migration

FIGURE 8: Serf emancipation, unskilled wages, and labor migration

Notes. The scatter plot in panel (a) documents, consistently with segmented labor markets *across* Prussian counties, significant variation in unskilled wages, measured as the average daily wage rate of male "seasonal fill" workers (day laborers) in the forestry sector of a county during the 1810–19 time horizon. It also illustrates that this variation is seemingly unrelated to the variation in the subsequent intensity of *de facto* serf emancipation. The scatter plot in panel (b) illustrates the absence of any systematic relationship across Prussian counties between the prevalence of *de facto* serf emancipation as of 1848 and labor migration flows, measured as the share of a county's population in 1871 that was born outside the county. Both plots depict relationships that account for heterogeneity across counties in potentially confounding geographical factors. The sample of counties in panel (a) is constrained by the availability of county-level data on wages in the early nineteenth century. See the discussion in the main text and Appendix E for additional details.

de facto serf emancipation was plausibly unrelated to the potential threat of local labor scarcity, arising from the possibility that liberated serfs could have attempted to exploit better options as free laborers in another county.

In line with the non-convergence of prices across weakly integrated factor markets, the scatter plot in panel (a) of Figure 8 documents considerable heterogeneity across counties in the average wage rate of unskilled day laborers during the 1810–1819 time period, conditional on geographical covariates. It further shows that this residual variation in wages bears no systematic relationship with the residual variation in the share of serfs emancipated during the 1821–1848 time horizon. One interpretation of this finding could be that the potential for labor mobility *across* county boundaries did not influence the elites' decision to either delay or accelerate the emancipation process and, moreover, that serfs were not necessarily able to exploit higher day-laborer wages in order to expedite the redemption of their lifetime servile dues via larger compensation payments to the landlords. However, as explored in Section 5.2.5, this null relationship may also be masking heterogeneous effects associated with different mechanisms linking market wages to labor emancipation *within* counties.

Further, the scatter plot in panel (b) of Figure 8 shows that the intensity of county-level migration inflows over the relevant time period, proxied by the share of a county's population in 1871 that was born outside the county, was largely unrelated to the pace of the emancipation process, conditional on cross-county heterogeneity in geographical factors. This pattern is further confirmed by the regression results presented in column 8 of Table 3. Specifically, although the "born outside county" population share in 1871 enters the regression with a positive coefficient, the relationship is not statistically distinguishable from zero, and it hardly affects our primary coefficient of interest.

Finally, in columns 9–12, we present the results from estimating specifications that simultaneously include all the additional potential confounders, first under OLS and then applying our 2SLS framework, for either the full sample of counties or the sub-sample of counties located in East Elbia. In the regressions based on the full sample, the OLS and 2SLS point estimates of our coefficient of interest continue to remain reassuringly similar to one another and to their respective counterparts presented in columns 9 and 10 of Table 2. On the other hand, although the relevant OLS and 2SLS point estimates for the East Elbian sub-sample are somewhat more noticeably attenuated in comparison to their respective counterparts from columns 11 and 12 of Table 2, they continue to remain statistically and economically significant, and the gap between OLS and 2SLS estimates is appreciably smaller than before.

5.2.4 Explaining redemption costs

Thus far, our analysis has focused on establishing a robust and significant positive reduced-form link between the initial abundance of relevant (i.e., elite-owned and skill-complementing) physical capital, as proxied by the prevalence of water mills in 1819, and the subsequent intensity of serf emancipation at the county level. In this section, we provide some corroborating evidence regarding a possible mechanism underlying this reduced-form link. In particular, our conceptual framework suggests that, *ceteris paribus*, elites with increasing stakes in skill-complementing physical capital should have been more willing to hasten the process of labor emancipation by settling for lower compensation payments from their serfs for the redemption of lifetime servile dues.

Table 4 reveals the results of regressions aimed at exploring this mechanism, linking the prevalence of water mills in 1819 with the cost of redemption, based on the average compensation payments made to the landlords across emancipation cases settled between 1821 and 1848. The bivariate regression presented in column 1 indicates, in line with our framework, a statistically significant negative association between the two variables.

Because our data on the cost of redemption associated with a settled emancipation case reflects the overall compensation payment to the manorial lord, rather than the negotiated price *per unit* of servile dues redeemed, the outcome variable is expected to be mechanically positively correlated with the *amount* of servile dues in the redemption agreement. The specification in column 2 thus introduces the previously discussed measure of average coercion intensity across the settled emancipation cases in a county as a control variable, finding its expected positive association with the average cost of redemption. Although the introduction of this covariate noticeably attenuates our relationship of interest, the estimated coefficient retains its expected negative sign and remains statistically significant.

The regression in column 3 additionally controls for our full set of geographical covariates. Relative to its estimate from column 2, our coefficient of interest is hardly affected, and it implies that an increase in the prevalence of water mills in 1819 by one standard deviation is associated with a decrease in the average cost of redemption across emancipation cases settled between 1821 and

Table 4: Cross-sectional analysis—Explaining the cost of redemption

Dependent variable:	Redemption costs (PCA)			
	(1) OLS	(2) OLS	(3) OLS	(4) 2SLS
Water mills 1819	−0.230**	−0.087**	−0.094**	−0.162**
	(0.089)	(0.041)	(0.040)	(0.077)
Servile duties (PCA)		0.549*	0.578*	0.563*
		(0.293)	(0.303)	(0.300)
Geographical controls	No	No	Yes	Yes
Observations	261	261	261	261
Adjusted R^2	0.05	0.33	0.39	0.38
Partial R^2 of mills		0.01	0.01	
Kleibergen-Paap F statistic				66.06

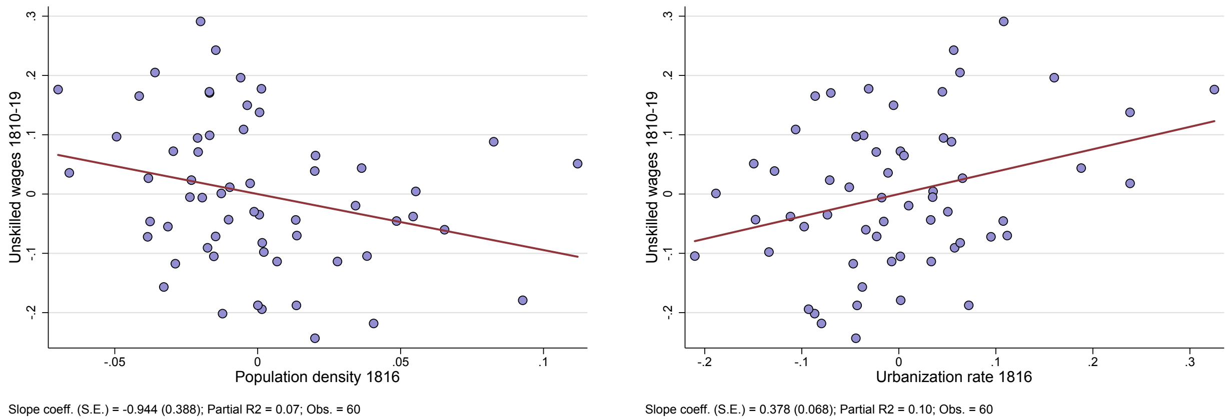
Notes. The dependent variable is the first principal component of four different types of total compensation payments (across all emancipation cases settled by 1848 under the 1821 ordinance) made by peasants in a county to their landlords for the redemption of lifetime servile duties, expressed as a fraction of the number of settled cases. The main explanatory variable is the number of water mills (per 1,000 inhabitants) in a county in 1819. Both variables are standardized to possess zero means and unit standard deviations. See Appendix E and the discussion in Section 4 for additional details on all variables. In column 4, a quadratic formulation in terrain slope is employed as an excluded instrument for the prevalence of water mills in 1819. The corresponding first-stage regression is reported in column 7 of Table C.1 in Appendix C. Standard errors, clustered at the district level, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

1848 by 9% of a standard deviation of the latter variable in our full sample of counties. Finally, in column 4, we estimate the specification from column 3 using our 2SLS framework, finding a somewhat stronger negative association between the prevalence of water mills and the average cost of redemption.

5.2.5 Examining the Domar and Brenner mechanisms

In this section, we exploit data on the average day-laborer wage rate during the 1810–1819 time period, although available for a limited sub-sample of only 60 Prussian counties, to perform a nuanced analysis of two canonical mechanisms of labor emancipation. Specifically, we empirically assess the extent to which these mechanisms were prevalent in our setting and examine whether they can explain away the main relationship of interest between the initial prevalence of water mills and subsequent serf emancipation.

The two canonical mechanisms of labor emancipation operate by generating opposing effects on market wages. On the one hand, according to Domar (1970), holding labor demand fixed, labor abundance could have contributed to the decline of serfdom by engendering downward pressure on market wages. In our setting, initial population density at the county level ought to capture the salience of this mechanism. On the other hand, according to Brenner (1976), holding labor supply fixed, higher market wages – particularly, due to increased labor demand from the urban sector – could have increased the bargaining power of serfs by improving their outside options, thereby promoting labor emancipation. It is worth noting that institutional restrictions on labor



(a) Population density and unskilled wages

(b) Urbanization rate and unskilled wages

FIGURE 9: Unskilled wages, population density, and urbanization rate

Notes. The scatter plot in panel (a) illustrates, consistently with the expected depression of market wages due to labor abundance *within* Prussian counties, a significant negative relationship across counties between population density, measured as the population of a county in 1816, divided by the county's land area (in Prussian Morgen), and unskilled wages, measured as the average daily wage rate of male "seasonal fill" workers (day laborers) in the forestry sector of a county during the 1810–19 time horizon. The scatter plot in panel (b) illustrates, in line with the elevation of market wages due to greater outside options for rural workers in the urban sector *within* Prussian counties, a significant positive relationship across counties between the urbanization rate, measured as the total number of inhabitants across cities that held city rights in a county in 1816, divided by the county's population in 1816, and the aforementioned measure of unskilled wages. Both plots depict relationships that account for heterogeneity across counties in potentially confounding geographical factors. The sample of counties is constrained by the availability of county-level data on wages in the early nineteenth century. See the discussion in the main text and Appendix E for additional details.

mobility *across* Prussian municipalities during the first half of the nineteenth century likely reduced the salience of this mechanism in our setting.[61] However, to the extent that this mechanism was still operative due to the existence of an urban sector *within* a county, we contend that the initial urbanization rate at the county level should effectively capture its role in our analysis.

The scatter plots in Figure 9 and the regressions in Table 5 reveal patterns that are consistent with the presence of *both* mechanisms in our setting, which could explain the overall null relationship between wages and serf emancipation seen previously in panel (a) of Figure 8. First, in line with the Domar mechanism, conditional on initial urbanization and geographical covariates, higher initial population density is indeed associated with lower contemporaneous wage rates and an accelerated pace of subsequent emancipation, with the implication for emancipation being especially prominent in the East-Elbian sub-sample of less industrialized or urbanized counties. Second, in line with the Brenner mechanism, controlling for initial population density and geographical confounders, initial urbanization is positively related to both contemporaneous wage rates and the

[61] Indeed, permanent relocation to another municipality was institutionally restricted in Prussia until 1842, involving both securing an official permit and paying a substantial admission fee to the host municipality (typical admission fees were levied at 5–10 times the annual value of an average household's use of public goods). Although municipalities were not allowed to reject most potential immigrants after 1842, the admission fees remained in place and represented a serious barrier to labor mobility. As a result of these constraints, poor peasants from rural areas were severely restricted from gaining employment in industrial centers (see, e.g., Ziekow, 1997, p. 155).

Table 5: Cross-sectional analysis—The "labor abundance" and "outside options" mechanisms

Dependent variable:	Unskilled wages 1810–19				Serf emancipation 1821–48			
Estimation sample:	Full		East Elbe		Full		East Elbe	
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS
Population density 1816	−0.277**	−0.233	−0.199***	−0.193*	0.157*	0.091	0.302***	0.164**
	(0.114)	(0.144)	(0.067)	(0.091)	(0.090)	(0.090)	(0.070)	(0.063)
Urbanization rate 1816	0.257***	0.255***	0.318***	0.318***	0.212**	0.215**	0.137	0.132
	(0.069)	(0.071)	(0.098)	(0.101)	(0.088)	(0.083)	(0.098)	(0.096)
Water mills 1819		−0.104		−0.014		0.156**		0.340***
		(0.141)		(0.113)		(0.065)		(0.109)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	60	60	44	44	60	60	44	44
Adjusted R^2	0.21	0.20	0.25	0.23	0.33	0.33	0.31	0.39
Partial R^2 of population	0.06	0.04	0.05	0.04	0.03	0.01	0.11	0.03
Partial R^2 of urbanization	0.08	0.08	0.12	0.12	0.06	0.07	0.03	0.03
Partial R^2 of mills		0.01		0.00		0.03		0.14

Notes. The dependent variable in columns 1–4 is the average daily wage rate of male "seasonal fill" workers (day laborers) in the forestry sector of a county during the 1810–19 time horizon. The dependent variable in columns 5–8 is the total number of serf emancipation cases settled in a county (under the 1821 ordinance) as of 1848, expressed as a fraction of the rural population of the county in 1816 (net of the population in small peasant landholdings). The main explanatory variables are (i) the population of a county in 1816, divided by the county's land area (in Prussian Morgen); (ii) the total number of inhabitants across cities that held city rights in a county in 1816, divided by the county's population in 1816; and (iii) the number of water mills in a county in 1819, divided by the county's population (in thousands) in 1821 (the population census year closest to 1819). All dependent and main explanatory variables are standardized to possess zero means and unit standard deviations in each regression sample. See Appendix E and the discussion in Section 4 for additional details on all variables. Standard errors, clustered at the district level, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

intensity of subsequent emancipation, although the connection with emancipation is noticeably weaker across counties in East Elbia.[62] Thus, our measures of initial population density and urbanization appear to capture, to a meaningful extent, the salience of these two mechanisms in our setting.

Nevertheless, as shown earlier in Table 2, and as verified in columns 6 and 8 of Table 5 for the limited sample of counties with wage data, the inclusion of initial population density and urbanization in our analysis does not explain away the relationship of interest between the initial prevalence of water mills and subsequent serf emancipation. Interestingly, conditional on initial population density and urbanization, the prevalence of water mills enters the contemporaneous wage regressions in columns 2 and 4 of Table 5 with a negative but imprecisely estimated coefficient, possibly reflecting the broader notion that despite being skill-complementing in the long run, the process of industrialization was largely unskilled-labor-saving in earlier stages (Mokyr, Vickers and Ziebarth, 2015).

[62]The prominence of the Domar mechanism in the East-Elbian sub-sample is in line with the findings of Klein and Ogilvie (2017) for Bohemia.

5.3 Flexible panel analysis

In this section, we complement the reduced-form cross-county analysis presented above by providing additional evidence based on both cross-sectional and temporal variations over the second half of the nineteenth century at the district level, which represents a higher level of administrative division than counties. Specifically, we exploit information on the annual number of *de facto* emancipation cases settled in each of 19 districts during the 1850–1898 time horizon to estimate the following flexible panel model (and less stringent variants thereof) using OLS:

$$\text{Emancipation}_{i,t} = \alpha_i + \gamma_t + \sum_{\tau=1850}^{1890} \beta_\tau \cdot \text{Mills}_{i,1819} \cdot \gamma_\tau + \sum_{\tau=1850}^{1895} \mathbf{X}'_{i,\tau} \cdot \mathbf{\Lambda}_\tau \cdot \gamma_\tau + \sum_{\tau=1850}^{1890} \mathbf{Z}'_i \cdot \mathbf{\Omega}_\tau \cdot \gamma_\tau + \eta_{i,t},$$

where $\text{Emancipation}_{i,t}$ is the natural log of the average annual number of emancipation cases settled in district i during a 5-year period (i.e., 1850–1854, 1855–1859, ... , 1895–1898) indexed by the period's initial year t; α_i and γ_t are, respectively, time-invariant district and sample-wide period fixed effects; $\text{Mills}_{i,1819}$ is the number of water mills (per 1,000 inhabitants) in district i in 1819 (i.e., our previous county-level measure aggregated up to the district level); $\mathbf{X}_{i,\tau}$ is a vector of time-varying covariates, including the population size of district i in the initial year of period τ and the number of social uprisings that occurred in district i during period $\tau - 5$; $\mathbf{Z}_i$ is a vector containing province and East Elbia fixed effects; and $\eta_{i,t}$ is a district-period-specific disturbance term.[63]

Although our proxy measure of the initial abundance of relevant physical capital is itself time-invariant at the district level, by interacting the measure with period dummies, our specification allows us to estimate – via the β_τ coefficients – how the cross-sectional relationship between the prevalence of water mills in 1819 and the subsequent *flow* of labor emancipation *evolved* over the course of the latter half of the nineteenth century, while accounting for both unobserved heterogeneity in time-invariant characteristics across districts and period-specific Prussia-wide shocks to the emancipation process. In addition, the interaction of the time-varying covariates with period dummies permits us to control for the possibility that the potentially confounding influences of these covariates could themselves be changing over time. Finally, by interacting the province and East Elbia fixed effects with period dummies, we are able to account, respectively, for differential trends in the emancipation process across provinces and between regions located to the east versus west of the river Elbe.

Table 6 reveals the results from estimating different variants of our flexible panel model. In column 1, we present the results from our simplest specification that controls for only period fixed effects, thus amounting to a repeated cross-district analysis of the association between the prevalence of water mills in 1819 and emancipation flows in the different 5-year time periods. Our baseline results are presented in column 2, which shows the estimated β_τ coefficients from a model that accounts for both district and period fixed effects but does not include any further controls. The coefficients of interest are to be interpreted with respect to the omitted (reference) category,

[63] A province is the administrative unit above a district (our sample of 19 districts spans 7 provinces). Further, because our sample horizon ends in 1898, the measurement of time-varying covariates for the last period is based on annual data for four rather than five years. The set of time-varying covariates included in our model is constrained by data availability at the relevant time frequency.

Table 6: Flexible panel analysis

Dependent variable:	Log emancipation cases					
Specification:	Time FE	Baseline	Population	Uprisings	East Elbe	Province
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS
Water mills 1819 × 1850	0.674**	0.833*	0.801**	0.774***	0.853***	0.491*
	(0.288)	(0.424)	(0.334)	(0.264)	(0.277)	(0.270)
Water mills 1819 × 1855	0.694***	0.852**	0.843**	0.797***	0.848***	0.399*
	(0.173)	(0.319)	(0.300)	(0.270)	(0.290)	(0.208)
Water mills 1819 × 1860	0.420***	0.579*	0.579**	0.563**	0.537**	0.196
	(0.124)	(0.284)	(0.275)	(0.247)	(0.253)	(0.209)
Water mills 1819 × 1865	0.822**	0.980*	0.987***	1.017***	1.152***	0.168
	(0.361)	(0.484)	(0.343)	(0.321)	(0.321)	(0.222)
Water mills 1819 × 1870	0.896***	1.054***	1.053***	1.020***	1.109***	0.736***
	(0.214)	(0.310)	(0.251)	(0.229)	(0.251)	(0.236)
Water mills 1819 × 1875	0.294*	0.453*	0.447*	0.558**	0.616**	0.646***
	(0.163)	(0.241)	(0.256)	(0.248)	(0.267)	(0.160)
Water mills 1819 × 1880	−0.199	−0.040	−0.039	−0.035	0.030	0.451**
	(0.198)	(0.254)	(0.250)	(0.233)	(0.230)	(0.174)
Water mills 1819 × 1885	−0.351**	−0.192	−0.194	−0.174	−0.119	0.067
	(0.163)	(0.202)	(0.201)	(0.210)	(0.227)	(0.266)
Water mills 1819 × 1890	−0.523**	−0.365***	−0.366***	−0.364***	−0.361***	−0.358**
	(0.204)	(0.110)	(0.108)	(0.095)	(0.084)	(0.154)
Period FE	Yes	Yes	Yes	Yes	Yes	Yes
District FE	No	Yes	Yes	Yes	Yes	Yes
Initial population × Period	No	No	Yes	Yes	Yes	Yes
Lagged uprisings × Period	No	No	No	Yes	Yes	Yes
East Elbe FE × Period	No	No	No	No	Yes	Yes
Province FE × Period	No	No	No	No	No	Yes
Observations	190	190	190	190	190	190
R^2	0.53	0.60	0.70	0.73	0.73	0.92
Joint sig. p-value for mills	0.000	0.000	0.000	0.000	0.000	0.000
Joint sig. p-value for population			0.000	0.005	0.080	0.000
Joint sig. p-value for uprisings				0.002	0.015	0.000
Joint sig. p-value for East Elbe					0.084	0.000
Joint sig. p-value for provinces						0.000

Notes. The dependent variable is the log of the average annual number of emancipation cases settled in a district (under the 1821 ordinance) over a given 5-year period. The main explanatory variable is the number of water mills (per 1,000 inhabitants) in a district in 1819, and its distribution is standardized to possess a zero mean and unit standard deviation. By interacting the latter variable with time, it is allowed to possess a time-varying cross-district relationship with the dependent variable across 5-year periods, with the exception of the last period, which is treated as the omitted category. Initial population and the lagged number of social uprisings are both time-varying measures themselves, and they are each allowed to possess a time-varying cross-district relationship with the dependent variable across all 5-year periods. See Appendix E for additional details on all variables. The reported p-value for a given explanatory variable is from the F-test for joint significance of the coefficients associated with its interaction terms that capture its time-varying cross-district relationship with the dependent variable. Standard errors, clustered at the district level, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

captured by the interaction between the prevalence of water mills in 1819 and the period dummy for 1895–1898. The results indicate that consistently with our earlier findings at the county level, districts exhibiting a higher prevalence of water mills in 1819 also experienced a larger flow of serf emancipation in the mid-nineteenth century. Specifically, the estimate for the 1850–1855 time period indicates that, relative to the reference period, a one standard deviation increase across districts in the prevalence of water mills in 1819 is associated with an 83.3% increase in the flow of new emancipation cases settled during this first 5-year period in our sample horizon. Thereafter, this significant relationship tends to become quantitatively even more pronounced, achieving its peak with respect to emancipation flows in the 1870–1874 time period, before weakening and turning negative (and even statistically significant) towards the end of our sample horizon in the 1890s. This late *reversal* is entirely consistent with our earlier findings as it reflects the fact that districts with a larger initial prevalence of water mills subsequently experienced a more rapid convergence to a state of full emancipation, and they were therefore already associated with substantially fewer new emancipation cases before the end of our sample horizon. More generally, in light of the inclusion of district fixed effects in the current analysis, the results uncovered here suggest that our previous cross-sectional findings, linking the initial prevalence of water mills with the subsequent pace of *de facto* labor emancipation at the county level, are likely not being driven by unobserved spatial heterogeneity in time-invariant geographical, cultural, or institutional characteristics.

In the remaining columns of Table 6, we examine the robustness of our baseline results to *incrementally* accounting for the time-varying influences of population size in the initial year (column 3) and the lagged number of social uprisings (column 4) on emancipation flow in a given 5-year period, before additionally accounting for differential time trends in the emancipation process, first between regions to the west versus east of the river Elbe (column 5) and then across provinces in our sample (column 6). Importantly, the results from estimating these other specifications suggest that our baseline time-varying relationship of interest uncovered in column 2 remains virtually insensitive to the inclusion of additional controls in our model. Remarkably, it is only in the most stringent specification from column 6 that our baseline pattern becomes muted, particularly with respect to emancipation flows in the earlier periods of our sample horizon, but even then it remains not only qualitatively robust but also largely statistically significant.

In sum, corroborating our cross-sectional findings at the county level, the results from our district-level flexible panel analysis suggest that a higher initial stock of relevant physical capital is systematically associated with a more rapid subsequent decline in serfdom and, thus, faster convergence to a state of full *de facto* labor emancipation.

5.4 Emancipation and subsequent investments in human capital

This section provides additional suggestive evidence corroborating our preferred interpretation of the positive reduced-form association between the initial abundance of relevant (i.e., elite-owned and skill-complementing) physical capital and the subsequent rate of *de facto* serf emancipation across Prussian counties. Specifically, we empirically examine the extent to which *ex post* outcomes with respect to the accumulation of human capital by the masses are consistent with the *ex ante* incentives of capital-owning elites to support labor emancipation.

Table 7: Cross-sectional analysis—Explaining educational investments

Dependent variable:	Enrollment rate 1864			Literacy rate 1871		
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS
Serf emancipation 1821–48	0.017**		0.013*	0.009***		0.007**
	(0.007)		(0.007)	(0.003)		(0.003)
Water mills 1819		0.020***	0.017***		0.009***	0.007***
		(0.005)	(0.006)		(0.002)	(0.002)
Enrollment rate 1816	0.233***	0.210***	0.207***	0.207***	0.197***	0.195***
	(0.063)	(0.059)	(0.058)	(0.029)	(0.029)	(0.029)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes
Other proximate controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	261	261	261	261	261	261
Adjusted R^2	0.64	0.65	0.66	0.89	0.89	0.90
Partial R^2 of emancipation	0.04		0.02	0.03		0.02
Partial R^2 of mills		0.07	0.05		0.04	0.02

Notes. In columns 1–3, the dependent variable is total attendance across primary schools in a county in 1864, expressed as a fraction of the county's population of children of recommended schooling age (6 to 14) in the same year. In columns 4–6, the dependent variable is the literacy rate amongst the population aged 10 and above in a county in 1871. The preceding intensity of serf emancipation is measured as the total number of emancipation cases settled in a county (under the 1821 ordinance) as of 1848, expressed as a fraction of the rural population of the county in 1816 (net of the population in small peasant landholdings). The initial stock of relevant physical capital is measured as the number of water mills (per 1,000 inhabitants) in a county in 1819. Both of these explanatory variables are standardized to possess zero means and unit standard deviations. See Appendix E and the discussion in Section 4 for additional details on all variables. Standard errors, clustered at the district level, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

According to our conceptual framework, labor emancipation was facilitated by the elites who, due to their increasing stakes in physical capital associated with skill-intensive production, rationally acted on their vested interests to incentivize the acquisition of skills by the masses. Hence, one expects that emancipation should indeed have triggered or intensified subsequent society-wide human capital accumulation.[64] In addition, if the incentives of the elites to emancipate labor were indeed associated with capital-skill complementarity, there should be a positive reduced-form link between the initial stock of relevant fixed capital and the intensity of skill acquisition by the masses after the emancipation process has been unraveling for several decades. Moreover, this link should be partially mediated by the intensity of emancipation itself, with the residual association between initial capital abundance and post-emancipation human capital accumulation partly reflecting the normal demand for human capital associated with capital-skill complementarity.

Table 7 presents the results from regressions that vindicate the aforementioned priors by linking our measures of relevant fixed capital abundance in 1819 and the intensity of serf

[64] Cinnirella and Hornung (2016) empirically document that the negative association between initial large landownership concentration and subsequent primary school enrollment rates across Prussian counties diminished over the course of the nineteenth century. The authors argue that this pattern can be explained by the stepwise *de facto* emancipation of labor and the nascent increase in the demand for human capital.

emancipation between 1821 and 1848 with two alternative indicators of the intensity of human capital accumulation following several decades of the onset of emancipation: the primary school enrollment rate in 1864 (columns 1–3) and the literacy rate amongst the population aged 10 and above in 1871 (columns 4–6). Throughout the analysis, our regressions account for our baseline set of geographical covariates from Table 1 as well as the full set of additional control variables considered in Table 2. Importantly, the latter set of covariates includes the primary school enrollment rate in 1816, which accounts for the potentially confounding influence of the initial intensity of investments in human capital in the context of the current analysis. Namely, early human capital accumulation could have not only driven both initial capital abundance and subsequent labor emancipation but may also be positively associated with the intensity of post-emancipation skill acquisition through other mechanisms of structural persistence (e.g., schooling infrastructure).

The results presented in columns 1 and 4 indicate that in line with priors, conditional on heterogeneity across counties in geographical factors and more proximate confounders, the share of serfs emancipated between 1821 and 1848 is positively and statistically significantly associated with either measure of the intensity of investments in human capital in the second half of the nineteenth century. Further, columns 2 and 5 suggest that consistently with the emergence of capital-skill complementarity and the associated rise in the demand for human capital over the course of industrialization, the initial stock of relevant fixed capital, as proxied by the prevalence of water mills in 1819, also bears a positive and statistically significant reduced-form relationship with either indicator of the intensity of skill acquisition.

Finally, as one might expect from a setting where emancipation is triggered by the capital-owning elites as a vehicle to incentivize investments in basic skills by the masses, the results in columns 3 and 6 show that in a "horse race" between the rate of serf emancipation and our proxy measure of initial capital abundance, both variables possess significant positive associations with either outcome measure of human capital accumulation, but the reduced-form influence of the prevalence of water mills becomes somewhat diminished in comparison to the relevant point estimates from columns 2 and 5. In addition, the finding that the prevalence of water mills continues to enter the regressions with a significant positive coefficient presumably reflects the demand for skilled workers arising from the capital-skill complementarity that remains salient even in the absence of coercive labor institutions that curb the incentives to acquire skills.

We conclude this section by emphasizing the mostly suggestive nature of the corroborating evidence uncovered here. Specifically, although our findings in this section are indeed broadly consistent with our conceptual framework of the historical decline in serfdom, we remain cautious with interpreting them as conclusive *per se*, primarily due to the possibility that our vector of covariates, despite being sizable, may not be sufficient to fully surmount the potential endogeneity of our measures of initial capital abundance and subsequent emancipation intensity with the long-run pace of human capital accumulation.

6 Concluding remarks

In this paper, we advance and empirically explore the novel hypothesis that the historical decline in institutions of labor coercion, particularly the *de facto* emancipation of labor from serfdom, occurred partly as a natural by-product of the process of industrialization, reflecting changes over time in the economic incentives of landowning capitalist elites. Specifically, due to capital-skill complementarity, the accumulation of physical capital by the elites in early stages of industrialization eventually raised their demand for skilled workers from society at large. Because skill acquisition by the masses requires private effort that is costly to monitor, the elites eventually found it incentive-compatible to end the extant regime of labor coercion, in order to encourage the masses to invest in human capital under the credible commitment that their skill premium would not face further risk of expropriation. Our hypothesis therefore suggests that, all else equal, the economic incentives of the elites to ultimately support labor emancipation would have been mobilized faster the larger were their stakes in forms of proto-industrial physical capital that came to be associated with skill-intensive industrialization.

Exploiting a unique data set on cases of *de facto* serf emancipation in nineteenth-century Prussia, we document empirical patterns that are consistent with our hypothesis. Our findings indicate a positive and significant relationship across Prussian counties between the initial stock of relevant (i.e., elite-owned and skill-complementing) physical capital, as proxied by the number of water mills (per 1,000 inhabitants) in the early nineteenth century, and the share of serfs that were *de facto* emancipated by the mid-nineteenth century. We document the robustness of this cross-sectional relationship to accounting for a wide range of potentially confounding factors, including observed heterogeneity across regions in geographical, cultural, and institutional characteristics and in various dimensions of historical development. We further show that the relationship remains both qualitatively and quantitatively insensitive to exploiting terrain slope as a plausibly exogenous source of spatial variation in the prevalence of water mills.

Complementing our cross-sectional analysis at the Prussian county level, we also exploit differential temporal variation in the *flow* of *de facto* serf emancipation cases across Prussian districts over the latter half of the nineteenth century, finding that a higher initial stock of relevant fixed capital is associated with a more rapid convergence to full emancipation during this time horizon. By controlling for district fixed effects, our flexible panel setting allows us to address concerns regarding endogeneity that might arise from unobserved heterogeneity in time-invariant characteristics at the district level. This setting also permits us to account for the dynamic effects of time-varying labor abundance and social uprisings at the district level, as well as region-specific time trends in emancipation flows at higher levels of spatial aggregation.

Finally, we provide two pieces of corroborating evidence that support our preferred interpretation of the positive reduced-form cross-sectional relationship at the county level between the initial stock of relevant fixed capital and the subsequent rate of *de facto* serf emancipation. Specifically, we show that a higher prevalence of water mills in the early nineteenth century is associated with a lower average cost of redemption per emancipation case as of the mid-nineteenth century, indicating that in counties where the elites had increasing stakes in skill-complementing physical capital, the elites were also willing to settle for lower compensation payments in exchange for the redemption of lifetime servile duties by their serfs. Furthermore, in line with the realization of indirect outcomes that are consistent with the *ex ante* incentives of the elites to grant freedom to their serfs, we find that conditional on initial capital abundance, counties in which *de facto* emancipation had occurred more intensely by the mid-nineteenth century also exhibit a higher rate of subsequent human capital accumulation by the masses, as reflected by higher enrollment rates in primary schools and higher literacy rates during the latter half of the nineteenth century.

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Appendix A Alternative measures of proto-industrial capital

The discussion in Section 4.2 introduces the various available county-level measures of proto-industrial physical capital (e.g., milling facilities, brick and glass factories, and looming devices) and also presents the fundamental restrictions that guide us in discriminating amongst these measures to adopt the one that is *conceptually* the most relevant for a falsification test of our hypothesis regarding serf emancipation. To reiterate the core argument, a relevant measure of proto-industrial capital ought to possess two crucial features in our specific setting. The first restriction – namely, exclusive ownership by the landed nobility – ensures that the returns to this form of capital accrue directly to those possessing *de facto* power over the emancipation process. The second restriction – namely, the ability to foreshadow the eventual adoption of skill-intensive technologies due to path dependence from technological complementarities and agglomeration effects – ensures that this form of capital is directly associated with the emergence of the *complex* production environments necessary for mobilizing the economic incentives of the capitalist elites to revise the coercive labor-market contracts with their peasants in favor of emancipation.

Drawing upon historical evidence, the discussion in Section 4.2 argues that the only available measures of proto-industrial capital that satisfy the first restriction pertain to grain-processing milling facilities. Specifically, because the ownership of grain mills was a noble prerogative, and because the nobility had been institutionally restricted from bourgeois occupations, measures capturing the presence of milling facilities, rather than either brick and glass factories or hand-powered looming devices, are the ones that are more relevant for examining our hypothesis. Moreover, among milling facilities, only water-powered ones satisfy the second restriction, in light of the fact that, of all the power sources exploited by proto-industrial milling facilities (i.e., water, wind, and animals), water is the only one that is also common to some of the canonical technologies of the Industrial Revolution, such as steam engines. In addition, because early steam engines were only water-pumping engines (e.g., the Newcomen and Savery variants) and were unable to convert steam power into a steady rotary motion by themselves, these engines were almost invariably used in conjunction with extant water wheels; i.e., the steam engine would pump water up into an elevated reservoir, from where hydraulic energy would be supplied to an overshot water wheel (Reynolds, 1983; Nuvolari, Verspagen and von Tunzelmann, 2011).

Thus, the complementarity between water-powered milling facilities and steam engines arises not just from their common reliance on water availability but also from the practical engineering considerations of the time. Importantly, this complementarity meant that over the course of industrialization, the adoption of more advanced technologies based on steam engines was considerably less costly for owners of water-powered mills than for owners of wind- or animal-powered ones. Indeed, the technological path dependence implied by this chain of reasoning is empirically confirmed not only in our setting by the scatter plots in Figure 3 of Section 4.2 but also in a setting external to ours by Nuvolari, Verspagen and von Tunzelmann (2011), who document that during the 1775–1800 time period, a larger number of Newcomen steam engines were installed in British counties that had a higher prevalence of water wheels. In contrast, the scatter plots in Figure 4 of Section 4.2 show that this technological path dependence is not significantly associated with any of the alternative measures of proto-industrial capital in our setting, especially those pertaining to wind- or animal-powered mills, brick and glass factories, and looming devices.

Therefore, based on the conceptual deficiencies of these alternative measures, we expect them to be either completely unrelated to subsequent serf emancipation, or if they are, we expect the relationships to be either attenuated (due to noisy measurement) or qualitatively different than what our framework predicts.

The results from the analysis in Table A.1 confirm these priors. Panel A examines the association, in our full sample of Prussian counties, between each of these alternative measures – capturing forms of proto-industrial capital that did not forecast skill-intensive industrialization and/or were not owned exclusively by the nobility – and subsequent serf emancipation, conditional on our full set of covariates. Panel B, on the other hand, presents the results from corresponding regressions for the sub-sample of counties located in East Elbia. In column 1 of both panels, we begin by replicating our baseline regressions, linking the prevalence of water mills with serf emancipation using ordinary least squares, conditional on the full set of controls. In contrast, the regressions in columns 2 and 3 show that the prevalence of neither wind- nor animal-powered mills is related to serf emancipation. This is in line with the evidence presented in panels (a)–(d) of Figure 4, reflecting the fact that these "dead end" milling technologies became disfavored due to their dependence on energy sources that were, relative to water power, naturally less predictable/reliable (e.g., wind) or more costly (e.g., animals that could have been more efficiently allocated to other activities).

In column 4, the regressions employ the prevalence of "other" (i.e., non-grain-processing) mills, which are classified by our data source according to their milling purpose (sawing of lumber, extraction of vegetable oils, pulping of wood for paper-making, etc.) rather than their source of power (i.e., water, wind, or animal). Although some of these mills were likely water-powered, others may have been based on the "dead end" wind- and animal-powered technologies. Thus, in line with the noise introduced by the irrelevance of the latter types of mills for subsequent skill-intensive industrialization, the association between this measure and serf emancipation, while positive in the full sample of counties, is non-robust to the exclusion of counties located west of the river Elbe. The regressions in column 5 employ an aggregate measure that captures the prevalence of all types of mills (regardless of milling purpose and power source). This measure is indeed significantly associated with serf emancipation in both regression samples, but the point estimates are slightly attenuated relative to those obtained using our preferred measure from column 1. This pattern in consistent with the fact that although a significant portion of the variation in this measure is driven by the variation in water-powered mills across counties, the measure is contaminated for our purposes with noise due to the less relevant milling technologies.

The results in column 6 show that the prevalence of brick and glass factories is unrelated to serf emancipation, even though the evidence presented in panels (g)–(h) of Figure 4 suggests that these proto-industrial establishments may possess weak predictive power for the localization of subsequent industrial activities. The observed "null" relationship with serf emancipation, however, is consistent with the fact that, as of 1819, these factories were still overwhelmingly owned by the bourgeoisie rather than the serf-owning landed nobility. In column 7, the regressions employ the prevalence of looming devices used in the production of different types of fabric, showing that this measure is significantly but *negatively* associated with the ensuing pace of serf emancipation. The fact that the landed nobility were largely excluded from possessing stakes in the bourgeois looming industry, along with the evidence presented in panels (i)–(j) of Figure 4 that the eventual adoption

Table A.1: Cross-sectional analysis—Explaining emancipation with alternative measures of proto-industrial physical capital

Dependent variable:	Serf emancipation 1821–48										
Proto-industry measure:	Water mills	Wind mills	Horse mills	Other types of mills	All types of mills	Brick and glass factories	All types of looms	Mills and factories	Mills, factories, and looms	1st PC of mills and factories	1st PC of mills, factories, and looms
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS	(9) OLS	(10) OLS	(11) OLS
	Panel A: Full sample										
Proto-industry 1819 (k)	0.206***	0.035	0.006	0.266**	0.195**	−0.001	−0.216***	0.191**	−0.206***	0.235***	0.178***
	(0.057)	(0.038)	(0.063)	(0.098)	(0.073)	(0.064)	(0.071)	(0.069)	(0.069)	(0.080)	(0.061)
Observations	261	261	261	261	261	261	261	261	261	261	261
Adjusted R^2	0.47	0.44	0.44	0.50	0.47	0.44	0.48	0.47	0.48	0.48	0.46
Partial R^2 of k	0.05	0.00	0.00	0.10	0.05	0.00	0.07	0.05	0.06	0.07	0.04
ρ of k with water mills	1.00	−0.26	−0.25	0.54	0.45	0.15	−0.12	0.47	−0.10	0.78	0.76
ρ of k with all mills	0.45	0.69	0.03	0.54	1.00	0.08	−0.24	0.98	−0.18	0.34	0.36
ρ of k with factories	0.15	−0.06	−0.03	0.18	0.08	1.00	0.23	0.26	0.25	0.28	0.21
ρ of k with looms	−0.12	−0.19	−0.04	−0.03	−0.24	0.23	1.00	−0.19	1.00	−0.02	−0.06
	Panel B: East-Elbia sample										
Proto-industry 1819 (k)	0.151**	0.097	−0.014	0.065	0.154*	0.040	−0.139**	0.156*	−0.128**	0.068	0.080
	(0.068)	(0.074)	(0.080)	(0.064)	(0.077)	(0.062)	(0.059)	(0.078)	(0.057)	(0.060)	(0.067)
Observations	195	195	195	195	195	195	195	195	195	195	195
Adjusted R^2	0.48	0.47	0.47	0.47	0.48	0.47	0.48	0.48	0.48	0.47	0.47
Partial R^2 of k	0.02	0.01	0.00	0.01	0.03	0.00	0.02	0.03	0.02	0.01	0.01
ρ of k with water mills	1.00	−0.20	−0.30	0.54	0.45	0.16	−0.10	0.46	−0.08	0.80	0.77
ρ of k with all mills	0.45	0.76	0.02	0.50	1.00	0.09	−0.22	0.98	−0.16	0.34	0.40
ρ of k with factories	0.16	−0.06	−0.04	0.24	0.09	1.00	0.26	0.27	0.28	0.31	0.21
ρ of k with looms	−0.10	−0.22	−0.04	0.07	−0.22	0.26	1.00	−0.17	1.00	0.01	−0.06

Notes. The dependent variable is the total number of serf emancipation cases settled in a county (under the 1821 ordinance) as of 1848, expressed as a fraction of the rural population of the county in 1816 (net of the population in small peasant landholdings). The main explanatory variables are the alternative measures of proto-industrial physical capital in a county in 1819, each divided by the county's population (in thousands) in 1821 (the population census year closest to 1819). These measures comprise the number of water mills (column 1); the total number of wind mills, including post and smock mills (column 2); the number of horse mills (column 3); the total number of other (i.e., non-grain-processing) types of mills, including oil, fulling, saw, and paper mills (column 4); the total number of all types of mills (column 5); the total number of construction factories, including brick works, lime kilns, and glass works (column 6); the total number of (hand-powered) looms, including looms for the weaving/knitting of silk, cotton, wool, linen, hosiery, band, shag, and other fabrics (column 7); the sum of the measures employed in columns 5 and 6 (column 8); the sum of the measures employed in columns 5–7 (column 9); the first principal component of the measures employed in columns 5 and 6 (column 10); the first principal component of the measures employed in columns 5–7 (column 11). In each regression, the dependent and main explanatory variables are standardized to possess zero means and unit standard deviations across counties in the relevant estimation sample. All regressions include the full set of control variables considered by the analysis in Table 3. See Appendix E and the discussion in Section 4 for additional details on all variables. Standard errors, clustered at the district level, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

of skill-intensive industries was not foreshadowed by proto-industrial looming activities, suggest that the statistical influence of looming activities on labor coercion is reflecting a mechanism that is unrelated to ours.

In particular, the pattern is consistent with the prevalence of the so-called putting-out or domestic system of cottage-industry-based fabric production, in which commoner merchant employers would "put out" raw materials and looming devices to rural households that worked primarily from their homes and returned the finished product to the merchants for wage payments. The households, in turn, would have to exploit flexibility in the allocation of their labor between farm and household chores, on the one hand, and domestic putting-out work, on the other, especially during the winter season, when there was little farming work to be done and the shadow value of household income was high. Thus, the observed association between looming devices and delayed emancipation could be partly explained to the extent that putting-out merchants rationally tapped more heavily into those seasonal markets for putting-out labor in which potential labor supply was particularly thick; namely, in the regions of Prussia that were characterized by large-scale serf-intensive farming during the growing and harvesting seasons, where serfdom is expected to have persisted longer.

The regressions in the next two columns employ aggregate measures of proto-industrial capital, based on the summation of the individual measures of either mills and factories (column 8) or mills, factories, and looming devices (column 9). The observed patterns associated with either of these aggregate measures essentially reflect the statistical influence of the individual measure that loads most prominently into the aggregate measure in question. Thus, because mills accounted for the majority of physical establishments (88% in the average county in the full sample), and because a significant portion of all mills were water-powered (between 45% and 67% in the average county in the full sample, depending on our assumption of the power source for non-grain-processing mills), the aggregate measure of mills and factories mostly captures the statistical influence of water-powered mills (as shown in column 1). However, the fact that this aggregate measure is contaminated with information on brick and glass factories and on non-water-powered mills implies that the relevant point estimates are expected to be attenuated relative to column 1, as is the case in the full sample. Further, in line with the prior that devices are expected to be far more numerous than physical establishments, looming devices accounted for the majority of physical establishments and devices taken together (73% in the average county in the sample). Hence, the aggregate measure for mills, factories, and looms mostly captures the statistical influence of looming devices (as shown in column 7), with the point estimates being attenuated relative to those in column 7 due to "noise" from the incorporation of information on mills and factories.

Finally, in the last two columns, the regressions employ alternative aggregate measures of proto-industrial capital, based on the first principal component of the individual measures of either mills and factories (column 10) or mills, factories, and looming devices (column 11). For either of these aggregate measures, and regardless of the sample, the common spatial variation across the individual component measures appears to be substantially correlated with the spatial variation in water mills (with the relevant correlation coefficients ranging between 0.76 and 0.80, depending on the aggregate measure and the sample). As such, the relationships between these measures of proto-industrial capital, on the one hand, and the pace of serf emancipation, on the other, are mostly reflective of the statistical influence of water-powered mills. Nevertheless, because the variation in either of these aggregate measures is tainted by information on less relevant individual components, like brick and glass factories or looming devices, the association of either of these aggregate measures with serf emancipation is non-robust to the choice of the regression sample.

Appendix B Alternative identification strategy

In this section we refine our identification strategy by considering *both* the topographic and the hydrological suitability for operating water mills. As will become apparent, despite the statistical importance of hydrological suitability, the substantially stronger explanatory power of topographic suitability renders the results from this analysis almost identical to those obtained under our baseline identification strategy.

To operationalize our alternative strategy, we proceed in two steps. In the first step, we construct an index of suitability for water mills at the county level, based purely on the extent to which topographic and hydrological factors can predict the locations of water mills in our data, after partialling out the potentially confounding influence of our baseline set of geographical covariates and after flexibly accounting for the smooth variation in unobserved geographical and climatic factors across space by way of cubic splines in latitude and longitude. In the interest of not contaminating our eventual suitability index with information on endogenous variables, we focus in this first step on the total number of water mills in a county in 1819 as the outcome variable, rather than its per-capita adjusted counterpart. Thus, in light of the fact that the dependent variable is based on count data, we employ the negative binomial rather than a least squares estimator for our regressions (the results, however, are robust to alternatively using the Poisson estimator). In addition, because our sample is based purely on the availability of data on water mills and geographical variables (i.e, it is not constrained by the availability of data on serf emancipation and non-geographical covariates), we are able to exploit variations across a significantly larger sample size of 330 counties for this step of our analysis.

As shown in Table B.1, the specifications examined in our first step incorporate the topographic suitability for operating water mills as in our baseline identification strategy; namely, by way of including linear and quadratic terms in the average terrain slope of a county. Importantly, however, they additionally incorporate hydrological suitability by way of including linear and quadratic terms in the average flow accumulation of a county. Flow accumulation is a measure of surface water *potential* at the grid-cell level from ArcGIS, and it reflects the cumulative number of "upstream" cells from which a given cell can receive water inflows. For our purposes, we aggregate this measure to the county level by averaging the information across the grid cells in a given county. Our prior is that intermediate values of flow accumulation should capture the hydrological potential for streams and ponds, which are more suitable for water mills; low values of flow accumulation reflect the potential absence of surface water, and high values reflect the potential presence of large river basins or still bodies of water, neither of which are complementary to operating a water mill. In line with this notion, we expect the linear term in flow accumulation to enter positively and the quadratic term to enter negatively in our estimated specifications.

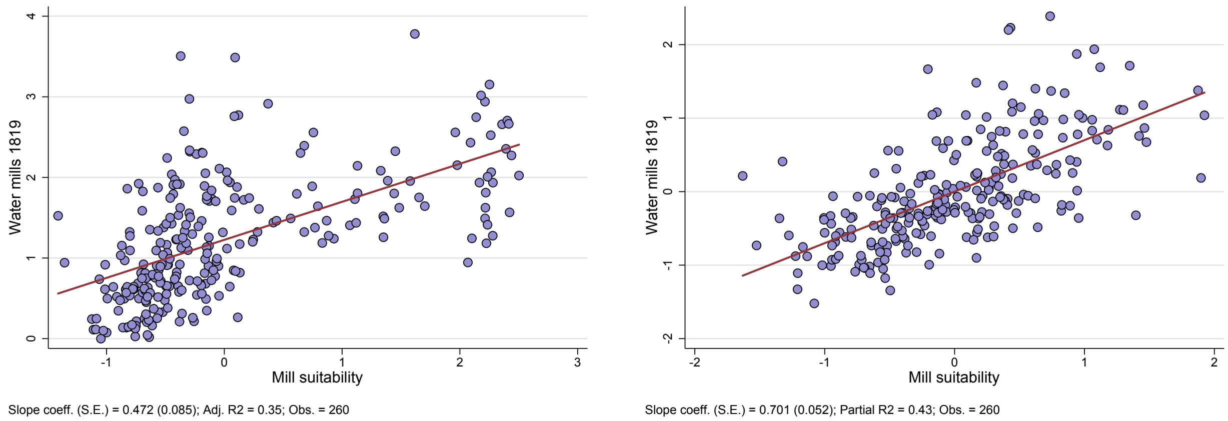
Table B.1: Cross-sectional analysis—The geographical determinants of water mills

Dependent variable:	Water mill count 1819				
	(1) NegBin	(2) NegBin	(3) NegBin	(4) NegBin	(5) NegBin
Terrain slope	2.068***		2.146***	1.281***	1.192***
	(0.214)		(0.207)	(0.185)	(0.238)
Terrain slope^2	−0.364***		−0.392***	−0.255***	−0.246***
	(0.057)		(0.058)	(0.043)	(0.053)
Flow accumulation		0.066**	0.067***	0.044**	0.038*
		(0.031)	(0.018)	(0.021)	(0.020)
Flow accumulation^2		−0.002*	−0.002***	−0.001**	−0.001**
		(0.001)	(0.001)	(0.001)	(0.001)
Geographical controls	Yes	Yes	Yes	Yes	Yes
Latitude and longitude splines	No	No	No	Yes	Yes
District FE	No	No	No	No	Yes
Observations	330	330	330	330	330
Pseudo R^2	0.06	0.01	0.07	0.09	0.10

Notes. The dependent variable is the total number (count) of water mills in a county in 1819. The main explanatory variables include linear and quadratic terms in the average terrain slope of a county and in the average flow accumulation of a county. The set of geographical covariates corresponds to the full set considered by the analysis in Table 1. The sets of cubic splines in latitude and longitude are each based on six evenly-spaced knots. See Appendix E and the discussion in Section 4 for additional details on all variables. The larger regression sample of the current analysis reflects the absence of restrictions associated with the availability of county-level data on serf emancipation and other socioeconomic variables. Standard errors, clustered at the district level, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

For our analysis in Table B.1, we start in columns 1 and 2 by examining the topographic and hydrological channels independently of one another but conditional on our baseline set of geographical covariates. We then proceed to examine the channels jointly in column 3. As is apparent from the stability of the estimated coefficients associated with each channel in the move to column 3, the topographic and hydrological mechanisms of mill suitability are largely orthogonal to one another. Nonetheless, based on the relative magnitudes of the coefficients associated with one channel versus another, it is also apparent that the topographic mechanism is quantitatively much more important than the hydrological one. In column 4, we substantially increase the stringency of our specification by introducing cubic splines in latitude and longitude to flexibly account for the smooth variation in unobserved geographical and climatic confounders across space. Although this reduces the magnitudes of the relevant coefficients (in absolute values), they maintain their expected signs and statistical significance. Indeed, the stringency of this specification is confirmed by the fact that even after adding district fixed effects in column 5, the estimated coefficients remain stable in magnitude.

Operationally, we employ the marginal effects associated with the linear and quadratic terms in both terrain slope and flow accumulation from the specification in column 5 to generate an overall index of mill suitability that captures both the topographic and the hydrological determinants of



(a) Bivariate relationship

(b) Conditional on geography

FIGURE B.1: Mill suitability and water mills in 1819

Notes. These scatter plots depict the significant positive relationship across Prussian counties between an index of mill suitability, capturing both the topographic and hydrological dimensions of a location's suitability for installing and operating a water-powered mill, and the number of water mills (per 1,000 inhabitants) in 1819. Panel (a) depicts the bivariate relationship, whereas panel (b) depicts the relationship after accounting for heterogeneity across counties in potentially confounding geographical factors. The index of mill suitability is standardized to possess a mean of zero and a standard deviation of one across counties. For visual clarity, both plots omit a non-influential outlier from the sample of counties. See the discussion in the text and Appendix E for additional details.

locations favorable for installing and operating water mills (the results from the subsequent step are qualitatively robust to using the marginal effects from the specification in column 6). Exploiting variations in the sample of counties for our main analysis of serf emancipation, the scatter plots in Figure B.1 show the significant positive influence of this overall suitability index on the number of water mills (per 1,000 inhabitants) in 1819.

The second step for implementing our alternative identification strategy is straightforward – we simply reproduce all of our 2SLS specifications from the paper, employing the index of mill suitability discussed above, rather than a quadratic formulation in terrain slope, as an excluded instrument for the number of water mills (per 1,000 inhabitants) in 1819. The relevant first- and second-stage results from these specifications are collected in Table B.2. There are two main takeaways from these results. First, in line with the fact that the excluded instrument under the current alternative strategy captures more information regarding the geographical suitability for operating water mills, the first-stage F-statistics are indeed larger than their counterparts in the corresponding specifications under our baseline identification strategy. Second, the current 2SLS coefficients associated with the influence of water mills in 1819 on serf emancipation are rather similar to those obtained under the baseline strategy, reflecting the fact that the topographic (as opposed to the hydrological) component of mill suitability is statistically more important in terms of predicting locations that are favorable for operating water mills.

Finally, as an internal consistency check on the validity of our identification strategy, we examine in Table B.3, the extent to which the reduced-form influence of mill suitability on serf emancipation can be explained away by the prevalence of water mills in 1819, once the latter

Table B.2: Cross-sectional analysis—Exploiting an alternative identification strategy

Dependent variable:	Serf emancipation 1821–48						Redemp.
Specification:	Geographical controls		Proximate controls		Additional controls		
Estimation sample:	Full	East Elbe	Full	East Elbe	Full	East Elbe	Full
	(1) 2SLS	(2) 2SLS	(3) 2SLS	(4) 2SLS	(5) 2SLS	(6) 2SLS	(7) 2SLS
	Panel A: 2nd-stage regressions of the dependent variable on water mills						
Water mills 1819	0.321***	0.610***	0.202***	0.445***	0.227***	0.285**	−0.145**
	(0.105)	(0.165)	(0.075)	(0.091)	(0.063)	(0.118)	(0.071)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Proximate controls	No	No	Yes	Yes	Yes	Yes	No
Additional controls	No	No	No	No	Yes	Yes	Yes
Observations	261	195	261	195	261	195	261
Adjusted R^2	0.30	0.15	0.42	0.38	0.47	0.47	0.39
Kleibergen-Paap F statistic	109.61	143.23	63.68	75.25	52.30	93.35	89.82
	Panel B: 1st-stage regressions of water mills on mill suitability						
Mill suitability	0.827***	0.640***	0.741***	0.535***	0.733***	0.549***	0.804***
	(0.079)	(0.054)	(0.093)	(0.062)	(0.101)	(0.057)	(0.085)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Proximate controls	No	No	Yes	Yes	Yes	Yes	No
Additional controls	No	No	No	No	Yes	Yes	Yes
Adjusted R^2	0.47	0.46	0.54	0.56	0.57	0.59	0.47
Shea partial R^2	0.40	0.38	0.34	0.28	0.30	0.26	0.38

Notes. The dependent variable in columns 1–6 of the top panel is the total number of serf emancipation cases settled in a county (under the 1821 ordinance) as of 1848, expressed as a fraction of the rural population of the county in 1816 (net of the population in small peasant landholdings). The dependent variable in column 7 of the top panel is the first principal component of four different types of total compensation payments made by serfs to the landlords (across all emancipation cases settled by 1848 under the 1821 ordinance) for the redemption of lifetime servile duties in a county, expressed as a fraction of the number of settled cases. The main explanatory variable in the top panel is the number of water mills (per 1,000 inhabitants) in a county in 1819. All three variables are standardized to possess zero means and unit standard deviations in each regression sample. See Appendix E and the discussion in Section 4 for additional details on all variables. In all columns, an index of geographical suitability for operating water mills, based on topographic and hydrological conditions, is employed as an excluded instrument for the prevalence of water mills in 1819. The bottom panel reports the corresponding first-stage regression coefficients associated with the excluded instrument, along with the Shea partial R^2, which reflects the explanatory power of the instrument for the variation in the prevalence of water mills across counties in 1819, after partialling out the influence of covariates. The set of specifications presented in columns 1–2, 3–4, and 5–6 corresponds, respectively, to the set examined under the baseline identification strategy in columns 9 and 11 of Table 1, columns 10 and 12 of Table 2, and columns 10 and 12 of Table 3. Similarly, the specification presented in column 7 corresponds to that examined in column 4 of Table 4. Standard errors, clustered at the district level, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

variable is introduced to the specification in semi-reduced-form OLS regressions. Regardless of the set of covariates included in the specifications, the results indicate that there is no *residual* influence of mill suitability on the serf emancipation outcome in the semi-reduced-form regressions, thus suggesting that the influence of mill suitability on serf emancipation likely runs entirely through its influence on the prevalence of water mills.

TABLE B.3: Cross-sectional analysis—Reduced-form and semi-reduced-form regressions of serf emancipation on mill suitability and water mills

Dependent variable:	Serf emancipation 1821–48					
Specification:	Geographical controls		Proximate controls		Additional controls	
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS
Mill suitability	0.265**	0.107	0.150**	−0.047	0.166**	0.022
	(0.095)	(0.105)	(0.068)	(0.086)	(0.067)	(0.072)
Water mills 1819		0.192***		0.265***		0.196**
		(0.060)		(0.075)		(0.073)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes
Proximate controls	No	No	Yes	Yes	Yes	Yes
Additional controls	No	No	No	No	Yes	Yes
Observations	261	261	261	261	261	261
Adjusted R^2	0.29	0.31	0.39	0.42	0.45	0.47
Partial R^2 of suitability	0.05	0.01	0.02	0.00	0.02	0.00
Partial R^2 of mills		0.03		0.05		0.03

Notes. The dependent variable is the total number of serf emancipation cases settled in a county (under the 1821 ordinance) as of 1848, expressed as a fraction of the rural population of the county in 1816 (net of the population in small peasant landholdings). The main explanatory variables include an index of geographical suitability for operating water mills, based on topographic and hydrological conditions, and the number of water mills (per 1,000 inhabitants) in a county in 1819. All three variables are standardized to possess zero means and unit standard deviations. In terms of control variables, the set of specifications presented in columns 1–2, 3–4, and 5–6 corresponds, respectively, to the set examined in columns 8–11 of Table 1, columns 9–12 of Table 2, and columns 9–12 of Table 3. See Appendix E and the discussion in Section 4 for additional details on all variables. Standard errors, clustered at the district level, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

Appendix C Supplementary results

Table C.1: Cross-sectional analysis—First-stage regressions

Dependent variable:	Water mills 1819						
Specification:	Geographical controls		Proximate controls		Additional controls		Redemp.
Estimation sample:	Full	East Elbe	Full	East Elbe	Full	East Elbe	Full
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS
Terrain slope	2.741***	2.825***	2.556***	2.639***	2.560***	2.598***	2.693***
	(0.337)	(0.306)	(0.340)	(0.366)	(0.365)	(0.307)	(0.329)
Terrain slope^2	−0.465***	−0.466***	−0.411***	−0.412***	−0.402***	−0.380***	−0.458***
	(0.123)	(0.126)	(0.117)	(0.117)	(0.115)	(0.103)	(0.121)
Average temperature	0.323***	0.538***	0.330***	0.517***	0.323**	0.562***	0.310***
	(0.121)	(0.144)	(0.114)	(0.120)	(0.134)	(0.137)	(0.118)
Average precipitation	−0.045	0.344*	−0.075	0.267**	−0.094	0.191**	−0.051
	(0.088)	(0.178)	(0.082)	(0.114)	(0.080)	(0.090)	(0.086)
Distance to navigable river	0.340*	0.232	0.151	0.056	0.194	0.114	0.351*
	(0.201)	(0.196)	(0.181)	(0.208)	(0.166)	(0.198)	(0.204)
Soil suitability (cereals)	−0.226*	−0.262	−0.203*	−0.199	−0.155	−0.212	−0.217*
	(0.124)	(0.169)	(0.117)	(0.144)	(0.131)	(0.134)	(0.128)
Sandy soil (share)	1.500***	1.615***	1.492***	1.653***	1.539***	1.679***	1.461***
	(0.275)	(0.280)	(0.278)	(0.294)	(0.307)	(0.304)	(0.293)
East Elbe (dummy)	0.540**		0.443**		0.407**		0.556**
	(0.263)		(0.188)		(0.177)		(0.266)
Proximate controls	No	No	Yes	Yes	Yes	Yes	No
Additional controls	No	No	No	No	Yes	Yes	Yes
Observations	261	195	261	195	261	195	261
Adjusted R^2	0.52	0.52	0.60	0.61	0.61	0.63	0.52
Shea partial R^2	0.46	0.45	0.42	0.37	0.37	0.34	0.43

Notes. The dependent variable is the number of water mills (per 1,000 inhabitants) in a county in 1819, standardized to possess a mean of zero and a standard deviation of one across counties in each regression sample. The explanatory variable of interest is the average slope of the terrain in a county as well as its quadratic term. These variables are excluded from the corresponding second-stage regressions presented in columns 9 and 11 of Table 1, columns 10 and 12 of Table 2, columns 10 and 12 of Table 3, and column 4 of Table 4. The Shea partial R^2 thus reflects the explanatory power of the quadratic formulation in terrain slope for the variation in the prevalence of water mills across counties in 1819, after partialling out the influence of covariates. Standard errors, clustered at the district level, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

TABLE C.2: Cross-sectional analysis—Accounting for spatial dependence across counties

Dependent variable:	Serf emancipation 1821–48											
Specification:	Geographical controls				Proximate controls				Additional controls			
Estimation sample:	Full		East Elbe		Full		East Elbe		Full		East Elbe	
	(1) OLS	(2) IV-GMM	(3) OLS	(4) IV-GMM	(5) OLS	(6) IV-GMM	(7) OLS	(8) IV-GMM	(9) OLS	(10) IV-GMM	(11) OLS	(12) IV-GMM
	Panel A: Spatial dependence cutoff = 200km											
Water mills 1819	0.243***	0.357***	0.286***	0.568***	0.244***	0.205**	0.242***	0.323***	0.206***	0.194**	0.151***	0.182*
	(0.054)	(0.108)	(0.084)	(0.131)	(0.062)	(0.087)	(0.057)	(0.088)	(0.061)	(0.090)	(0.054)	(0.107)
	Panel B: Spatial dependence cutoff = 250km											
Water mills 1819	0.243***	0.363***	0.286***	0.566***	0.244***	0.202**	0.242***	0.324***	0.206***	0.189**	0.151***	0.182*
	(0.050)	(0.107)	(0.078)	(0.126)	(0.061)	(0.086)	(0.057)	(0.083)	(0.063)	(0.088)	(0.053)	(0.100)
	Panel C: Spatial dependence cutoff = 300km											
Water mills 1819	0.243***	0.368***	0.286***	0.563***	0.244***	0.202**	0.242***	0.325***	0.206***	0.189**	0.151***	0.183**
	(0.050)	(0.103)	(0.073)	(0.118)	(0.060)	(0.084)	(0.055)	(0.075)	(0.064)	(0.086)	(0.053)	(0.089)
	Panel D: Spatial dependence cutoff = 350km											
Water mills 1819	0.243***	0.368***	0.286***	0.561***	0.244***	0.201**	0.242***	0.325***	0.206***	0.189**	0.151***	0.183**
	(0.050)	(0.101)	(0.070)	(0.112)	(0.059)	(0.081)	(0.055)	(0.072)	(0.065)	(0.086)	(0.053)	(0.084)
	Panel E: Spatial dependence cutoff = 400km											
Water mills 1819	0.243***	0.371***	0.286***	0.560***	0.244***	0.200***	0.242***	0.326***	0.206***	0.188**	0.151***	0.183**
	(0.049)	(0.094)	(0.068)	(0.107)	(0.055)	(0.077)	(0.054)	(0.070)	(0.064)	(0.083)	(0.052)	(0.082)
	Panel F: Spatial dependence cutoff = 450km											
Water mills 1819	0.243***	0.374***	0.286***	0.560***	0.244***	0.201***	0.242***	0.326***	0.206***	0.188**	0.151***	0.183**
	(0.047)	(0.089)	(0.067)	(0.103)	(0.052)	(0.072)	(0.052)	(0.067)	(0.062)	(0.080)	(0.050)	(0.079)
	Panel G: Spatial dependence cutoff = 500km											
Water mills 1819	0.243***	0.377***	0.286***	0.562***	0.244***	0.203***	0.242***	0.326***	0.206***	0.188**	0.151***	0.183**
	(0.044)	(0.086)	(0.065)	(0.100)	(0.049)	(0.069)	(0.051)	(0.064)	(0.060)	(0.078)	(0.048)	(0.075)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Proximate controls	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Additional controls	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes
Observations	261	261	195	195	261	261	195	195	261	261	195	195
Adjusted R^2	0.31		0.24		0.42		0.40		0.47		0.48	

Notes. The dependent variable is the total number of serf emancipation cases settled in a county (under the 1821 ordinance) as of 1848, expressed as a fraction of the rural population of the county in 1816 (net of the population in small peasant landholdings). The main explanatory variable is the number of water mills (per 1,000 inhabitants) in a county in 1819. Both variables are standardized to possess zero means and unit standard deviations in each regression sample. See Appendix E and the discussion in Section 4 for additional details on all variables. In all even-numbered columns, a quadratic formulation in terrain slope is employed as an excluded instrument for the prevalence of water mills in 1819. The set of specifications presented in columns 1–4, 5–8, and 9–12 corresponds, respectively, to the set examined in columns 8–11 of Table 1, columns 9–12 of Table 2, and columns 9–12 of Table 3. Standard errors, corrected for spatial dependence across counties, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

TABLE C.3: Cross-sectional analysis—Accounting for subterranean coal deposits

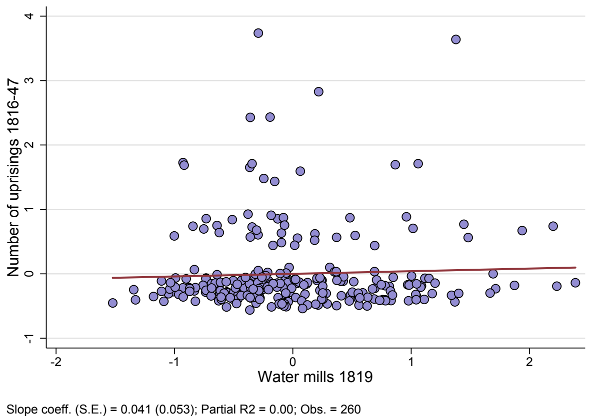
Dependent variable:	Serf emancipation 1821–48											
Specification:	Geographical controls				Proximate controls				Additional controls			
Estimation sample:	Full		East Elbe		Full		East Elbe		Full		East Elbe	
	(1) OLS	(2) 2SLS	(3) OLS	(4) 2SLS	(5) OLS	(6) 2SLS	(7) OLS	(8) 2SLS	(9) OLS	(10) 2SLS	(11) OLS	(12) 2SLS
Water mills 1819	0.195***	0.268**	0.280***	0.592***	0.195***	0.153**	0.243***	0.326***	0.176***	0.181***	0.184**	0.242**
	(0.062)	(0.116)	(0.081)	(0.168)	(0.049)	(0.065)	(0.058)	(0.082)	(0.046)	(0.063)	(0.074)	(0.097)
Carboniferous area (share)	2.799	2.577	0.430	−0.692	2.645*	2.753*	−0.108	−0.249	2.378	2.369*	−1.075	−1.112*
	(1.640)	(1.685)	(0.805)	(0.500)	(1.514)	(1.498)	(0.556)	(0.399)	(1.455)	(1.356)	(0.734)	(0.625)
Average temperature	0.173*	0.168*	0.442***	0.348***	0.254**	0.254***	0.420***	0.405***	0.165*	0.166*	0.200**	0.195***
	(0.097)	(0.099)	(0.092)	(0.129)	(0.100)	(0.093)	(0.090)	(0.085)	(0.095)	(0.090)	(0.080)	(0.070)
Average precipitation	−0.388***	−0.389***	−0.195	−0.269	−0.170**	−0.170**	−0.106	−0.120	−0.215***	−0.215***	−0.095	−0.113
	(0.085)	(0.086)	(0.147)	(0.182)	(0.070)	(0.067)	(0.111)	(0.095)	(0.072)	(0.064)	(0.125)	(0.115)
Distance to navigable river	0.543	0.458	0.385	0.039	0.576*	0.610**	0.591	0.519	0.529*	0.527**	0.409	0.376
	(0.389)	(0.356)	(0.517)	(0.366)	(0.307)	(0.298)	(0.454)	(0.409)	(0.286)	(0.262)	(0.351)	(0.319)
Soil suitability (cereals)	−0.112	−0.105	−0.048	0.009	−0.182**	−0.185***	−0.161*	−0.154*	−0.108*	−0.107**	−0.109	−0.101
	(0.083)	(0.084)	(0.101)	(0.121)	(0.071)	(0.069)	(0.090)	(0.081)	(0.053)	(0.052)	(0.074)	(0.071)
Sandy soil (share)	−0.140	−0.170	−0.246	−0.547	−0.087	−0.048	0.158	0.024	−0.158	−0.162	0.165	0.072
	(0.292)	(0.298)	(0.412)	(0.467)	(0.230)	(0.226)	(0.302)	(0.289)	(0.207)	(0.191)	(0.291)	(0.312)
East Elbe (dummy)	−0.726**	−0.702**			−0.604***	−0.608***			−0.704***	−0.704***		
	(0.324)	(0.327)			(0.188)	(0.170)			(0.158)	(0.148)		
Proximate controls	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Additional controls	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes
Observations	261	261	195	195	261	261	195	195	261	261	195	195
Adjusted R^2	0.34	0.34	0.24	0.16	0.45	0.45	0.40	0.40	0.49	0.49	0.46	0.46
Partial R^2 of mills	0.05		0.08		0.04		0.06		0.04		0.03	
Shea partial R^2 of slope		0.43		0.42		0.40		0.36		0.36		0.34
Kleibergen-Paap F statistic		64.77		91.83		53.82		46.82		41.02		82.15

Notes. The dependent variable is the total number of serf emancipation cases settled in a county (under the 1821 ordinance) as of 1848, expressed as a fraction of the rural population of the county in 1816 (net of the population in small peasant landholdings). The main explanatory variable is the number of water mills (per 1,000 inhabitants) in a county in 1819. Both variables are standardized to possess zero means and unit standard deviations in each regression sample. See Appendix E and the discussion in Section 4 for additional details on all variables. In all even-numbered columns, a quadratic formulation in terrain slope is employed as an excluded instrument for the prevalence of water mills in 1819. The Shea partial R^2 thus reflects the explanatory power of the quadratic formulation in terrain slope for the variation in the prevalence of water mills across counties in 1819, after partialling out the influence of covariates. The set of specifications presented in columns 1–4, 5–8, and 9–12 corresponds, respectively, to the set examined in columns 8–11 of Table 1, columns 9–12 of Table 2, and columns 9–12 of Table 3. Standard errors, clustered at the district level, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.

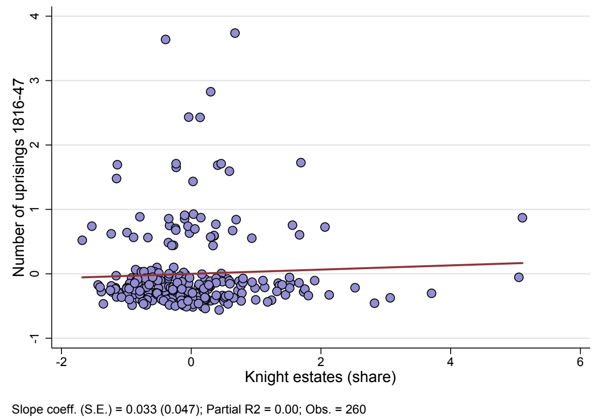
Table C.4: Cross-sectional analysis—Excluding provinces from the full estimation sample

Dependent variable:	Serf emancipation 1821–48						
Excluded province name:	Prussia	Posen	Silesia	Pomer.	Branden.	Saxony	Westph.
	(1) 2SLS	(2) 2SLS	(3) 2SLS	(4) 2SLS	(5) 2SLS	(6) 2SLS	(7) 2SLS
Water mills 1819	0.191*	0.214***	0.203**	0.175**	0.257***	0.180***	0.309***
	(0.101)	(0.074)	(0.094)	(0.073)	(0.076)	(0.066)	(0.091)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other proximate controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	207	235	204	239	231	223	227
Adjusted R^2	0.38	0.43	0.44	0.43	0.42	0.36	0.43
Shea partial R^2 of slope	0.29	0.44	0.42	0.40	0.45	0.42	0.42
Kleibergen-Paap F statistic	34.81	49.75	51.81	50.73	52.75	58.24	95.75

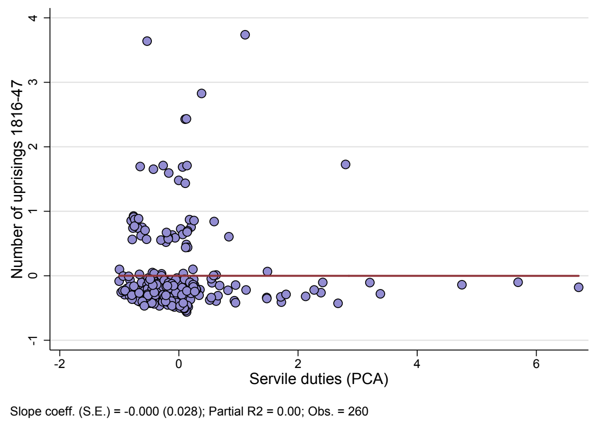
Notes. The dependent variable is the total number of serf emancipation cases settled in a county (under the 1821 ordinance) as of 1848, expressed as a fraction of the rural population of the county in 1816 (net of the population in small peasant landholdings). The main explanatory variable is the number of water mills (per 1,000 inhabitants) in a county in 1819. Both variables are standardized to possess zero means and unit standard deviations in each regression sample. See Appendix E and the discussion in Section 4 for additional details on all variables. In all columns, a quadratic formulation in terrain slope is employed as an excluded instrument for the prevalence of water mills in 1819. The Shea partial R^2 thus reflects the explanatory power of the quadratic formulation in terrain slope for the variation in the prevalence of water mills across counties in 1819, after partialling out the influence of covariates. The abbreviated province names are Pomerania, Brandenburg, and Westphalia. Standard errors, clustered at the district level, are reported in parentheses. *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level.



(a) Elite capital-ownership and social uprisings



(b) Elite landownership and social uprisings



(c) Peasant coercion intensity and social uprisings

FIGURE C.1: Threat of mass revolts, elite wealth, and peasant coercion intensity

Notes. These scatter plots illustrate the absence of any systematic relationship across Prussian counties between each of two proxy measures of the degree of elite wealth (panels (a) and (b)), as well as a proxy measure of the degree of peasant coercion intensity (panel (c)), on the one hand, and the threat of mass revolts, as proxied by the number of social uprisings in a county during the 1816–1847 time horizon, on the other. In panel (a), the degree of elite wealth (from capital-ownership) in a county is proxied by the number of water mills (per 1,000 inhabitants) in the county in 1819. In panel (b), the degree of elite wealth (from landownership) in a county is proxied by the share of all landholdings in the county that were classified as knight (noble) estates. In panel (c), the degree of peasant coercion intensity in a county is proxied by the first principal component of two different types of total labor services (across all emancipation cases settled by 1848 under the 1821 ordinance) redeemed by peasants in the county through compensation payments to their landlords, expressed as a fraction of the number of settled cases. The evidence presented in this figure thus supports the argument that counties in which the elites were more wealthy or in which peasants were coerced more intensely did not necessarily face a higher or lower threat of mass revolts, and as such, this mechanism was not salient in the decision of the elites to accelerate or delay the *de facto* emancipation of their serfs. All plots depict relationships that account for heterogeneity across counties in potentially confounding geographical factors. For visual clarity, all plots omit a non-influential outlier from the sample of counties. See the discussion in the main text and Appendix E for additional details.

Appendix D Legislative variation in *de jure* serf emancipation

According to the historical evidence, as of the late eighteenth century, serfdom across Prussia was being practiced at varying levels of intensity, depending on the customary obligations of the peasants and the strength of their land tenure rights, and such variation was indeed prevalent even at the village level (see, e.g., Bowman, 1980; Harnisch, 1984; Pierenkemper and Tilly, 2004; Cinnirella and Hornung, 2016). As such, the issue of *de facto* serf emancipation notwithstanding, the Prussian agrarian reforms of the early nineteenth century needed to enact different regulations for the *de jure* emancipation of different categories of the enserfed population. In addition, the political origin of these *de jure* reforms varied across regions of Prussia, depending on whether a region belonged to territories that were not ceded to France at the Second Treaty of Tilsit in 1807 (e.g., the provinces of Brandenburg, Pomerania, East and West Prussia, and Silesia) versus territories that were annexed or regained by Prussia following the Congress of Vienna in 1815 (e.g., the provinces of Posen, Rhineland, Saxony, Swedish Pomerania, and Westphalia). This appendix itemizes the idiosyncrasies associated with the *de jure* serf emancipation process throughout Prussia in the first half of the nineteenth century.

In regions belonging to territories that were not ceded to France at the Second Treaty of Tilsit in 1807, *de jure* serf emancipation was implemented in several stages between 1799 and 1850, with each stage pertaining to a different category of the peasantry as per their extant land tenure rights and the nature of their customary obligations to the nobility.

- Peasants residing on royal domains gained freedom from personal subjection in 1799. Their servile dues were commutated into leases either in money or in kind until 1806. Secure property rights to landownership were transferred to these peasants in 1808, and there was no *de jure* redemption process associated with their emancipation.

- Peasants residing on noble estates and holding weak (non-hereditary) rights to land tenure gained freedom from personal subjection in 1810, under the October Edict of 1807. Secure property rights to landownership as well as redemption of lifetime servile dues could be obtained *de jure* by these peasants under terms of the Regulation Edict of 1811 and the Declaration of 1816, at the cost of between one-third and two-thirds of their existing land parcels.

- Peasants residing on noble estates and holding strong (hereditary) rights to land tenure gained freedom from personal subjection in 1810, under the October Edict of 1807. Their lifetime servile dues could be *de jure* redeemed under the terms of the Dissolution Ordinance of 1821, at 25 times the equivalent annual cost of these duties. In the province of Silesia, however, regulation for the redemption of lifetime servile dues was implemented only in 1823.

- Peasants that were engaged in only manual servile duties (*nichtspannfähige Nahrungen*) to the nobility, due to the fact that they resided on small land parcels that did not permit any agriculture of sufficient scale, gained freedom from personal subjection in 1810, under the October Edict of 1807. Their lifetime servile duties, however, could only be *de jure* redeemed under the terms of the Commutation Law of 1850, at 25 times the equivalent annual cost of these duties.

In regions belonging to territories that were annexed or regained by Prussia following the Congress of Vienna in 1815, *de jure* serf emancipation was generally triggered by external political factors, but in many cases, the rehabilitated Prussian nobility exerted significant influence on the *de facto* emancipation process, much like they did in other regions of Prussia that never came under Napoleonic influence in the period between 1807 and 1815.

- The territory of South Prussia (i.e., the Grand Duchy of Posen, the regions of Kulm and Michelau, and the city of Thorn) was annexed by the French in 1807 (as part of the Duchy of Warsaw) and thus came under the influence of the Code Napoléon. Following its repossession by Prussia at the Congress of Vienna in 1815, the General State Laws for the Prussian States (*Allgemeines Landrecht für die Preußischen Staaten*) were reestablished in this territory in 1817. Despite temporarily coming under the influence of the Napoleonic code, the process of *de facto* peasant emancipation made little progress in this region until after its repossession by Prussia. An 1823 Edict specified that peasants in this region could *de jure* redeem their lifetime servile duties under terms similar to the Dissolution Edict of 1821; i.e., at 25 times the equivalent annual cost of these duties.

- Peasants in Rhineland gained freedom from personal subjection in 1794, under the Code Napoléon. According to legislation passed in 1798, their lifetime servile dues could be *de jure* redeemed at 15 times the equivalent annual cost of these duties, and redeemability was further clarified by legislation in 1804. Following Prussian annexation, the French legislation remained in place in Rhineland, which is therefore excluded from our empirical analysis.

- Peasants in the former Electorate of Saxony (i.e., the Prussian districts of Merseburg and Erfurt) did not come under the *de jure* influence of French legislation. They gained freedom from personal subjection under Prussian legislation in 1819, and their lifetime servile dues were declared to be *de jure* redeemable under the terms of the Dissolution Ordinance of 1821, at 25 times the equivalent annual cost of these duties.

- Peasants in the former Swedish Pomerania (i.e., Prussian district of Stralsund) were *de jure* emancipated under agrarian reforms enacted by the Swedish Crown in 1806. From a legislative perspective, this district continued to maintain an exceptional position after Prussian annexation, and we therefore exclude it from our empirical analysis.

- Peasants in the former Kingdom of Westphalia (i.e., the Prussian province of Westphalia and the district of Magdeburg) gained freedom from personal subjection in 1808, under the Code Napoléon. According to legislation passed in 1809, their lifetime servile dues could be *de jure* redeemed at 25 times the equivalent annual cost of these duties. The Westphalian nobility, however, successfully blocked the legislation, and redeemability was only clarified in 1825. Thus, although the French legislation remained in place in Westphalia following Prussian annexation, the significant influence of the elites on the *de facto* peasant emancipation process made the Westphalian experience akin to those of the Prussian regions that were not temporarily ceded to France.

Appendix E Variable definitions and data sources

E.1 Variables in the cross-sectional analysis

E.1.1 Variables reported in the main tables and figures

Serf emancipation 1821–48. The cumulative stock of emancipation cases settled in a county between 1821 and 1848, expressed as a fraction of the county's rural population (net of those ineligible for emancipation until after 1850) in 1816. The numerator of this variable reflects county-level data reported by Meitzen (1868, vol. 4), capturing only those settled emancipation cases in which former service and duty payers (*Dienst- und Agabenpflichtige, welche abgelöst haben*) redeemed their lifetime servile duties under the Dissolution Ordinance of 1821 (*Ablösungsordnung*).[E.1] For the denominator of this variable, the data on a county's rural population in 1816 is sourced from Mützell (1823-1825, vol. 6), but this information is then adjusted to exclude the subpopulation, reported at the county level by Meitzen (1868, vol. 4), of the peasant landowners residing on small parcels (with weak land tenure rights) that were ineligible for redeeming their lifetime servile dues under the 1821 ordinance (*nichtspannfähige bäuerliche Nahrungen*) and were only able to do so after the passage of the Commutation Law in 1850. This variable is standardized to possess a mean of zero and a standard deviation of one in each of the regression samples considered by our cross-sectional analysis.

Water mills 1819. The number of water mills (*Wassermühlen*) used for the grinding of grains into flour, grits, or pearl barley in a county in 1819, divided by the county's population (in thousands) in 1821 (the population census year closest to 1819), constructed using county-level data reported by Mützell (1823-1825, vol. 6). This variable is standardized to possess a mean of zero and a standard deviation of one in each of the regression samples considered by our cross-sectional analysis.

All types of factories 1849. The total number of factories across all manufacturing sectors (textiles, metals, paper, chemicals, food-processing, etc.) in a county in 1849, divided by the county's population (in thousands) in 1849, constructed using county-level data reported by Statistisches Bureau zu Berlin (1851–1855, vol. 6a).

Mills and factories 1849. The total number of factories across all manufacturing sectors (textiles, metals, paper, chemicals, food-processing, etc.), plus the total number of mills (including water mills, steam-powered mills, oil mills, fulling mills, tanning mills, saw mills, and other mills but excluding wind mills and animal-powered mills) in a county in 1849, divided by the county's population (in thousands) in 1849, constructed using county-level data reported by Statistisches Bureau zu Berlin (1851–1855, vol. 6a).

Steam engines 1875. The total number of steam engines (*Dampfmaschinen*) across manufacturing establishments in a county in 1875, divided by the county's population (in thousands) in 1875,

[E.1] The number of settled emancipation cases is missing for five counties in the districts of Königsberg and Gumbinnen. For four of these counties, we imputed the the number of settled cases based on information pertaining to redeemed labor services and redemption costs. No such information was available for one county (Lyk), which remains missing from our sample. Furthermore, in two instances, the 1848 emancipation census reports the number of settled cases and redemption costs for two counties combined. In these cases, we decided to assign the same value for the share of emancipated serfs to each of the two counties.

constructed using county-level data reported by the Königlich Preussisches Statistisches Bureau (1861–1934, vol. 40).

Motorized engines 1875. The total number of all types of motorized engines (*Umtriebsmaschinen und Arbeitsmaschinen*) across manufacturing establishments in a county in 1875, divided by the county's population (in thousands) in 1875, constructed using county-level data reported by the Königlich Preussisches Statistisches Bureau (1861–1934, vol. 40).

Wind mills 1819. The total number of wind mills, including post mills (*Bockmühlen*) and smock mills (*holländische Mühlen*), used for the grinding of grains into flour, grits, or pearl barley in a county in 1819, divided by the county's population (in thousands) in 1821 (the population census year closest to 1819), constructed using county-level data reported by Mützell (1823-1825, vol. 6). This variable is standardized to possess a mean of zero and a standard deviation of one in each of the regression samples considered by our analysis in Table A.1 in Appendix A.

Horse mills 1819. The number of horse mills (*Rossmühlen*) in a county in 1819, divided by the county's population (in thousands) in 1821 (the population census year closest to 1819), constructed using county-level data reported by Mützell (1823-1825, vol. 6). This variable is standardized to possess a mean of zero and a standard deviation of one in each of the regression samples considered by our analysis in Table A.1 in Appendix A.

Other types of mills 1819. The total number of non-grain-processing mills, including oil mills (*Oelmühlen*), fulling mills (*Walkmühlen*), saw mills powered by either water or wind (*Sägemühlen auf Wasser oder Wind*), and paper mills (*Papiermühlen*), in a county in 1819, divided by the county's population (in thousands) in 1821 (the population census year closest to 1819), constructed using county-level data reported by Mützell (1823-1825, vol. 6). This variable is standardized to possess a mean of zero and a standard deviation of one in each of the regression samples considered by our analysis in Table A.1 in Appendix A.

Brick and glass factories 1819. The total number of brick works (*Ziegeleien*), lime kilns (*Kalkbrennereien*), and glass works (*Glashütten*) in a county in 1819, divided by the county's population (in thousands) in 1821 (the population census year closest to 1819), constructed using county-level data reported by Mützell (1823-1825, vol. 6). This variable is standardized to possess a mean of zero and a standard deviation of one in each of the regression samples considered by our analysis in Table A.1 in Appendix A.

All types of looms 1819. The total number of (hand-powered) looms for weaving cloth (*Gehende Weberstühle zu Tüchern und Zeugen aller Art*) from silk and half-silk (*in Seide und Halbseide*), cotton (*in Baumwolle und Halbbaumwolle*), wool (*in Wolle und Halbwolle*), and linen (*Leinen*), hosiery knitting looms (*Strumpfweberstühle*), and band weaving looms (*Bandstühle, Zahl der Gänge*), plus the total number of looms in secondary employment (*Gehende Weberstühle als Nebenbeschäftigung*) for the processing of linen (*Leindwand*), shag (*grobes wollenes Zeug*), and other types of fabrics (*andere Stuhlwaaren*) in a county in 1819, divided by the county's population (in thousands) in 1821 (the population census year closest to 1819), constructed using county-level data reported by Mützell (1823-1825, vol. 6). This variable is standardized to possess a mean of zero and a standard deviation of one in each of the regression samples considered by our analysis in Table A.1 in Appendix A.

Terrain slope. The average slope of the terrain in a county, constructed using geospatial elevation information reported in Data Basin's "30 arc-second DEM of Europe" data set (https://databasin.org/datasets/7a286ca8a7fa492a9f95d58324ca918c), which is, in turn, derived from the U.S. Geological Survey's GTOPO30 data set (EROS, 1996). GTOPO30 is a global digital elevation model (DEM) that provides elevation information at a resolution of 30 arc seconds (i.e., grid cells of approximately 1 kilometer squared each). The measurement of this variable proceeds by first calculating for each grid cell the maximum of the elevation difference in angular degrees between itself and each of its eight neighboring cells and then averaging this information across all grid cells in a county.

Average temperature. The average temperature in degrees Celsius in a county during the 1960–1990 time horizon, constructed by temporally and spatially aggregating time series information on mean monthly temperature at a geospatial resolution of 30 arc seconds (i.e., grid cells of approximately 1 kilometer squared each), obtained from the WorldClim (version 1) data set (http://www.worldclim.org/version1) of Hijmans et al. (2005).

Average precipitation. The average precipitation in hundreds of millimeters in a county during the 1960–1990 time horizon, constructed by temporally and spatially aggregating time series information on total monthly precipitation at a geospatial resolution of 30 arc seconds (i.e., grid cells of approximately 1 kilometer squared each), obtained from the WorldClim (version 1) data set (http://www.worldclim.org/version1) of Hijmans et al. (2005).

Distance to navigable river. The distance in hundreds of kilometers from a county's centroid to the nearest navigable river, constructed using a map of all waterways (*Schiffahrtsstraßen*) in the *Zollverein* (German Customs Union) in 1850 (http://www.ieg-maps.uni-mainz.de/mapsp/mapw850d.htm), hosted by the "Server for Digital Historical Maps" at the Leibniz Institute of European History at the University of Mainz (IEG, 2010).

Soil suitability (cereals). The average suitability of the soil in a county for growing cereal crops, constructed by spatially aggregating information on an agro-ecological suitability index (class) for low-input-level rain-fed cereal crops at a geospatial resolution of 30 arc seconds (i.e., grid cells of approximately 1 kilometer squared each), obtained from the Food and Agriculture Organization's (FAO) Global Agro-Ecological Zones (GAEZ) Data Portal version 3.0 (http://gaez.fao.org).

Sandy soil (share). The share of a county's land area in which the soil texture is classified as sandy (i.e., where the soil is composed of 85-100% sand, 0-15% silt, and 0-15% clay), constructed using county-level data reported by Meitzen (1868, vol. 4).[E.2] The underlying data for this variable was collected by an 1866 census, which assessed the composition of the soil in a county by gathering information on three main soil categories: the area of "clay soils" (*Lehm- und Thonböden*), the area

[E.2] To elaborate on what this measure captures, it may be noted that the ideal soil texture for agricultural productivity has a composition of roughly 40% sand, 40% silt, and 20% clay. The suitability of a particular texture of the soil for agriculture is determined by the physical properties of soil particles; sand particles are relatively round, whereas silt and clay particles are relatively slim. Although the presence of round particles in the soil permits the absorption and retention of higher amounts of air and water, this is only true up to a certain point for water retention; soils excessively rich in sand are unable to retain water due to the presence of a large amount of empty spaces between particles, thus leading to a higher likelihood of drought and crop failure.

of "sandy loam and loamy sand soils" (*sandiger Lehm und lehmiger Sand*), and the area of "sandy soils" (*Sandboden*).

East Elbe (dummy). A binary variable that assumes a value of one for counties located on or east of the river Elbe, and zero otherwise.

Population density 1816. The population of a county in 1816, divided by the county's land area (measured in Prussian Morgen), constructed using county-level data reported by Mützell (1823-1825, vol. 6).

Urbanization rate 1816. The total number of inhabitants across cities that held city rights in a county in 1816, divided by the county's population in 1816, constructed using city- and county-level data reported by Mützell (1823-1825, vol. 5–6).

Family size 1849. The population of a county in 1849, divided by the number of families in the county in 1849, constructed using county-level data reported by the Statistisches Bureau zu Berlin (1851–1855, vol. 1).

Knight estates (share). The number of knight estates (*Rittergüter*) in a county in 1856 as reported by Rauer (1857), divided by the number of all landholdings in the county in 1849 as reported by the Statistisches Bureau zu Berlin (1851–1855, vol. 5).[E.3] This variable is expressed in percentage points.

Protestants 1816 (share). The number of a county's inhabitants that belonged to the Reformed or Lutheran Protestant religious denomination in 1816, divided by the county's population in 1816, constructed using county-level data reported by Mützell (1823-1825, vol. 6).

Other ethnic group 1861 (share). The number of a county's inhabitants that were not of ethnic German descent (*Stammesverschiedenheit*) in 1861, divided by the county's population in 1861, constructed using county-level data reported by the Königlich Preussisches Statistisches Bureau (1861–1934, vol. 10).

Partible inheritance law (dummy). A binary variable that assumes a value of one for counties that predominantly practiced partible inheritance (*Realteilung*), and zero for counties that predominantly practiced primogeniture (*Anerbenrecht*), coded using county-level maps from circa-1900 on historical inheritance laws (Sering, 1897-1905).

Enrollment rate 1816. The total number of enrolled students across a county's public elementary schools (*Öffentliche Elementarschulen*), private elementary schools (*Privat-Elementarschulen*), public middle schools for boys or girls (*Öffentliche Bürger- und Mittelschulen für Söhne oder Töchter*), and private middle schools for boys or girls (*Private Bürger- und Mittelschulen für Söhne oder Töchter*) in 1816, divided by the county's population of children of recommended schooling age (6 to 14) in 1816, constructed using town- and county-level data reported by Mützell (1823-1825, vol. 5–6).[E.4]

[E.3] Although 1856 is the earliest available census on the number of knight estates in a county, Rauer (1857) provides additional information asserting that the spatial distribution of knight estates across Prussia remained largely stable throughout the first half of the nineteenth century. For instance, only 324 out of 11,714 knight estates lost their noble prerogatives during the 1834–1856 time period.

[E.4] Of the four types of schools, public elementary schools were the only ones prevalent in both rural and urban areas in 1816. Our data source provides information on student enrollment in public elementary schools at the county level

Servile duties (PCA). The first principal component of the average amounts (per settlement) associated with two different types of labor services redeemed in the emancipation cases settled in a county as of 1848. This variable is constructed using county-level data reported by Meitzen (1868, vol. 4). The settled emancipation cases considered are those in which former service and duty payers (*Dienst- und Agabenpflichtige, welche abgelöst haben*) redeemed their lifetime servile duties under the Dissolution Ordinance of 1821 (*Ablösungsordnung*). The two types of labor services included in the principal component analysis are "draft animal services" (*Spanndienste*) and "hand labor services" (*Handdienste*), both measured in days. This variable, which captures 93% of the combined variation across counties in the two underlying measures of labor services, is standardized to possess a mean of zero and a standard deviation of one in each of the regression samples considered by our cross-sectional analysis.

Road 1848 (dummy). A binary variable that assumes a value of one for counties connected to at least one main road in 1848, and zero otherwise. The coding of this variable is based on a map of all paved and unpaved main roads (*Hauptstraßen*) in the *Zollverein* (German Customs Union) in 1848 (http://www.ieg-maps.de/mapsp/maproads1848.htm), hosted by the "Server for Digital Historical Maps" at the Leibniz Institute of European History at the University of Mainz (IEG, 2010).

Railway 1848 (dummy). A binary variable that assumes a value of one for counties connected to at least one railway line in 1848, and zero otherwise. The coding of this variable is based on a map of all railway lines (*Eisenbahnen*) in the *Zollverein* (German Customs Union) in 1848 (http://www.ieg-maps.de/mapsp/mape848d.htm), hosted by the "Server for Digital Historical Maps" at the Leibniz Institute of European History at the University of Mainz (IEG, 2010).

Coalfield (dummy). A binary variable that assumes a value of one for counties that had access to a coalfield (i.e., those in which a coalfield was located within 10 kilometers of the county's geodesic centroid), and zero otherwise, coded using geospatial data on the location of coalfields from Fernihough and O'Rourke (2014).

Number of uprisings 1816–47. The number of violent protests, each involving at least 20 participants, in a county during the 1816–1847 time period, constructed using data reported by Tilly (1990) on the location and timing of such protests.

Commoner estates (share). The number of a county's noble estates that were owned by commoners (*Bürgerliche*) in 1856, divided by the number of all noble estates in the county in 1856, constructed using county-level data reported by Rauer (1857).

Crown and state domains (share). The total land area across a county's real estates that either belonged to the Crown and members of the royal family or belonged to the state in 1861, including domains and forests (*Eigenthum des Staats: Domainen und Forsten*), divided by the total land area across all real estates (*Ertragfähige Liegenschaften*) in the county in 1861, constructed using county-level data reported by Meitzen (1868, vol. 4).

in 1816, and we supplement this with aggregated town-level information on enrollment in private and middle schools across all medium and large towns in a county.

Kulm estates (share). The number of a county's noble estates that were constituted under the Kulm law (*Kölmische Güter*) or whose legal constitution was consistent with the Kulm law (*den kölmischen gleichartige*) in 1856, divided by the number of all noble estates in the county in 1856, constructed using county-level data reported by Rauer (1857).

Commercial city (dummy). A binary variable that assumes a value of one for counties that harbored a university in 1517 or an urban center that maintained status as either an Imperial City (*Reichsstadt*) or a member of the Hanseatic League (*Hansestadt*) in 1517, and zero otherwise. The coding of this variable is based on county-level information obtained from the data set of Becker and Woessmann (2009). The primary sources of their information include Eulenburg (1904), for the locations of universities; Oestreich and Holzer (1973), for cities that participated in the Imperial Diet; and Hammel-Kiesow (2000), for cities that participated in the Hanseatic Diet.

Born outside county 1871 (share). The number of a county's inhabitants in 1871 that were born outside the county, divided by the county's population in 1871, constructed using county-level data reported by the Königlich Preussisches Statistisches Bureau (1861–1934, vol. 30).

Unskilled wages 1810-19. The average daily wage rate in Mark of unskilled male "seasonal fill" workers (day laborers) employed in a county's public forestry sector during the 1810–1819 time period, constructed by aggregating forestry-level wage data (for 88 public forestries) reported by the Königlich Preussisches Statistisches Bureau (1861–1904, vol. 23).

Redemption costs (PCA). The first principal component of the average amounts (per settlement) associated with four different types of compensation payments made by peasants to redeem their lifetime labor services in the emancipation cases settled in a county as of 1848. This variable is constructed using county-level data reported by Meitzen (1868, vol. 4). The settled emancipation cases considered are those in which former service and duty payers (*Dienst- und Agabenpflichtige, welche abgelöst haben*) redeemed their lifetime servile duties under the Dissolution Ordinance of 1821 (*Ablösungsordnung*). The four types of compensation payments included in the principal component analysis are "capital" (*Kapital*), measured in Prussian Thaler; "cash annuities" (*Geldrente*), measured in Prussian Thaler; "rye annuities" (*Roggenrente*), measured in Prussian Scheffel; and "land" (*Land*), measured in Prussian Morgen. This variable, which captures 52% of the combined variation across counties in the four underlying measures of compensation payments, is standardized to possess a mean of zero and a standard deviation of one in each of the regression samples considered by our cross-sectional analysis.

Enrollment rate 1864. The total number of enrolled students across a county's public elementary schools (*Öffentliche Elementarschulen*), private elementary schools (*Privat-Elementarschulen*), public middle schools for boys or girls (*Öffentliche Mittelschulen für Söhne oder Töchter*), and private middle schools for boys or girls (*Private Mittelschulen für Söhne oder Töchter*) in 1864, divided by the county's population of children of recommended schooling age (6 to 14) in 1864, constructed using county-level data reported by the Königlich Preussisches Statistisches Bureau (1861–1934, vol. 10).[E.5]

[E.5] For a small number of counties in our sample, our measure of the enrollment rate in 1864 exceeds unity, reflecting the enrollment of students that are either residents of neighboring counties or above 14 years of age or both.

Literacy rate 1871. The number of a county's inhabitants aged 10 and above that were able to read and write in 1871, divided by the county's population aged 10 and above in 1871, constructed using county-level data reported by the Königlich Preussisches Statistisches Bureau (1874).

E.1.2 Additional variables employed in appendix sections

Carboniferous area (share). The share of a county's land area that contains geological strata (including subterranean coal beds) created during the Carboniferous period, constructed using geospatial geological information from the "1:5 Million International Geological Map of Europe and Adjacent Areas (IGME 5000; https://www.bgr.bund.de/EN/Themen/Sammlungen-Grundlagen/GG_geol_Info/Karten/International/Europa/IGME5000/igme5000_node_en.html)" (Asch, 2005).

All types of mills 1819. The total number of water mills, wind mills, horse mills, and other types of mills (as defined above) in a county in 1819, divided by the county's population (in thousands) in 1821 (the population census year closest to 1819), constructed using county-level data reported by Mützell (1823-1825, vol. 6). This variable is standardized to possess a mean of zero and a standard deviation of one in each of the regression samples considered by our analysis in Table A.1 in Appendix A.

Flow accumulation. The average flow accumulation in a county, constructed using geospatial elevation information reported in Data Basin's "30 arc-second DEM of Europe" data set (https://databasin.org/datasets/7a286ca8a7fa492a9f95d58324ca918c), which is, in turn, derived from the U.S. Geological Survey's GTOPO30 data set (EROS, 1996). GTOPO30 is a global digital elevation model (DEM) that provides elevation information at a resolution of 30 arc seconds (i.e., grid cells of approximately 1 kilometer squared each). The measurement of this variable proceeds in three steps: first, a flow direction raster is generated from the projected elevation data; then, a flow accumulation raster is computed from the flow direction raster; finally, the information at the grid-cell level in the flow accumulation raster is averaged across all grid cells in a county.

E.2 Variables in the panel analysis

Log emancipation cases. The logged average annual number of emancipation cases settled in a district during a given 5-year period in the 1850–1898 time horizon, constructed using annual district-level data for this time horizon reported by Meitzen (1868, vol. 6).[E.6] The settled emancipation cases include those in which former service and duty payers (*Dienst- und Agabenpflichtige, welche abgelöst haben*) redeemed their lifetime servile duties under the Dissolution Ordinance of 1821 (*Ablösungsordnung*) as well as cases of redemption under the Commutation Law of 1850. The time intervals considered are 1850–1854, 1855–1859, 1860–1864, . . . , 1895–1898.

Water mills 1819. The number of water mills used for the grinding of grains into flour, grits, or pearl barley in a district in 1819, divided by the district's population (in thousands) in 1821 (the population census year closest to 1819), constructed by aggregating up county-level data reported

[E.6] Consistently with our cross-sectional analysis, we exclude the district of Stralsund (i.e., the former Swedish Pomerania) from our flexible panel analsyis, because the emancipation process in this district was influenced by radically different institutions.

by Mützell (1823-1825, vol. 6) to the district level. This variable is standardized to possess a mean of zero and a standard deviation of one across districts in the regression sample.

Initial population. The logged population of a district in the initial year of a given 5-year period in the 1850–1898 time horizon, constructed using district-level population census data reported by the Statistisches Bureau zu Berlin (1851–1855, various vols.) and the Königlich Preussisches Statistisches Bureau (1861–1934, various vols.) for various years of this time horizon (censuses were conducted, roughly, every 3 years until 1871 and every 5 years from 1875 onward). The variable employed is based on a log-linear interpolation of population observed at the district level across these various censuses. The time series extracted from the interpolation corresponds to the years 1850, 1855, 1860, ... , 1895.

Lagged uprisings. The number of violent protests, each involving at least 20 participants, in a district during a given 5-year period in the 1845–1894 time horizon, constructed using data reported by Tilly (1990) on the location and timing of such protests. The time intervals considered are 1845–1849, 1850–1854, 1855–1859, ... , 1890–1894.

Table E.1: Descriptive statistics of the main variables in the cross-sectional analysis

	Obs.	Mean	Std. dev.	Min.	Max.
Serf emancipation 1821–48	261	0.06	0.07	0.00	0.52
Water mills 1819	261	1.23	0.77	0.00	3.78
Terrain slope	261	0.66	0.64	0.07	3.91
Terrain slope^2	261	0.84	1.93	0.01	15.30
Average temperature	261	8.09	0.82	5.66	9.72
Average precipitation	261	6.34	1.13	4.89	10.70
Distance to navigable river	261	0.32	0.26	0.00	1.39
Soil suitability (cereals)	261	4.20	0.75	1.63	6.28
Sandy soil (share)	261	0.28	0.23	0.00	0.81
East Elbe (dummy)	261	0.75	0.44	0.00	1.00
Population density 1816	261	0.10	0.06	0.02	0.42
Urbanization rate 1816	261	0.24	0.13	0.00	0.86
Family size 1849	261	5.09	0.32	4.08	5.88
Knight estates (share)	261	1.25	1.11	0.00	7.46
Protestants 1816 (share)	261	0.68	0.37	0.00	1.04
Other ethnic group 1861 (share)	261	0.17	0.28	0.00	0.90
Partible inheritance law (dummy)	261	0.12	0.33	0.00	1.00
Enrollment rate 1816	261	0.60	0.21	0.03	0.95
Servile duties (PCA)	261	0.00	1.00	−0.61	7.00
Road 1848 (dummy)	261	0.75	0.43	0.00	1.00
Railway 1848 (dummy)	261	0.31	0.46	0.00	1.00
Coalfield (dummy)	261	0.08	0.27	0.00	1.00
Number of uprisings 1816–47	261	0.30	0.85	0.00	9.00
Commoner estates (share)	261	0.42	0.24	0.00	1.00
Crown and state domains (share)	261	0.08	0.09	0.00	0.50
Kulm estates (share)	261	0.04	0.13	0.00	0.90
Commercial city (dummy)	261	0.08	0.27	0.00	1.00
Born outside county 1871 (share)	261	0.21	0.07	0.05	0.52
Redemption costs (PCA)	261	0.00	1.00	−0.45	11.83
Enrollment rate 1864	261	0.75	0.11	0.44	1.20
Literacy rate 1871	261	0.61	0.12	0.26	0.75
Wind mills 1819	261	0.96	1.27	0.00	8.79
Horse mills 1819	261	0.08	0.14	0.00	1.37
Other types of mills 1819	261	0.63	0.54	0.00	3.29
Brick and glass factories 1819	261	0.36	0.27	0.00	2.53
All types of looms 1819	261	23.25	27.82	0.00	174.70
All types of factories 1849	261	2.38	1.71	0.37	16.98
Mills and factories 1849	261	3.92	2.19	0.47	18.93
Steam engines 1875	261	0.85	0.94	0.02	6.39
Motorized engines 1875	261	3.01	1.39	0.66	8.63