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Abstract

This research tests the long-standing hypothesis put forth by Lynn White, Jr. (1962) that the adoption of the heavy plough in Northern Europe was an important cause of economic development. White argued that it was impossible to take proper advantage of the fertile clay soils of Northern Europe prior to the invention and widespread adoption of the heavy plough. We implement the test in a difference-in-difference set-up by exploiting regional variation in the presence of fertile clay soils. Using a high quality dataset for Denmark, we find that historical counties with relatively more fertile clay soil experienced higher urbanization after the heavy plough had its breakthrough, which was around AD 1000. We obtain a similar result, when we extend the test to European regions.

JEL classification: J1, N1, N93, O1, O33

Keywords: Heavy plough, medieval technology, agricultural productivity

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1. Introduction

As of the 9th century until the end of the 13th century, the medieval European economy underwent unprecedented productivity growth (White 1962; Pounds 1974; Langdon et al. 1997). The period has been referred to as the most significant agricultural expansion since the Neolithic revolution (Raepsaet 1997). In his path-breaking book, "Medieval Technology and Social Change", Lynn White, Jr. argues that the most important element in the "agricultural revolution" was the invention and widespread adoption of the heavy plough (White 1962).

The earliest plough, commonly known as the ard or scratch-plough, was suitable for the soils and climate of the Mediterranean; it was, however, unsuitable for the clay soils found in most of Northern Europe, which "offer much more resistance to a plough than does light, dry earth" (White 1962, p. 42). The consequence was that Northern European settlement before the Middle Ages was limited to lighter soils, where the ard could be applied. The heavy plough and its attendant advantages may have been crucial in changing this. More specifically, heavy ploughs have three function parts that set them apart from primitive ards. The first part is an asymmetric plough share, which cuts the soil horizontally. The second part is a coulter, which cuts the soil vertically. The third part is a mouldboard, which turns the cut sods aside to create a deep furrow (Mokyr 1990; Richerson 2001). The mouldboard is the part of the heavy plough from which its principal advantages on clay soils derive. The first advantage is that it turns the soil, which allows for both better weed control on clay soil in damp climates and incorporation of crop residues, green manure, animal manure, or other substances into the soil (Richerson 2001; Guul-Simonsen et al. 2002). The second advantage is that mouldboard ploughing produces high-backed ridges, which contributes to more efficient drainage of clay soils. The ridges also allow for better harvests in both wet and dry seasons. The third advantage is that the heavy plough handles the soil with such violence that cross-ploughing is not needed, thus freeing up labor time. Hence, by allowing for better field drainage, access to the most fertile soils, and saving of peasant labor time, the heavy plough stimulated food production and, as a consequence, "population growth, specialization of function, urbanization, and the growth of leisure" (White 1962, p. 44).

While White's work is certainly not without its critics among historians,[1] others have followed his lead. Mokyr (1990, p. 32), for example, writes that it "has taken the combined

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[1] See Roland (2003) and Worthen (2009) for expositions of some of the criticism and for assessments of the enduring influence of Lynn White, Jr.

geniuses of Marc Bloch (1966) and Lynn White (1962) to make historians fully recognize the importance of the heavy plow, or *carruca*." Landes (1998, p. 41) notes that the heavy plough "opened up rich river valleys, turned land reclaimed from forest and sea into fertile fields, in short it did wonders wherever the heavy, clayey soil resisted the older Roman wooden scratch plow, which had worked well enough on the gravelly soils of the Mediterranean basin." In fact, the historiography of medieval technology and its impacts contains a large amount of circumstantial evidence pointing towards a crucial role of the heavy plough for medieval economic development (Jensen 2010; Pounds 1974). The *heavy plough hypothesis* has also been perpetuated in a leading textbook on "Civilization in the West", where students are told that the heavy plough "increased population in the heavy soil areas north of the Alps" (Kishlansky et al. 2010, p. 201). Yet to this date there exists no quantitative evidence on its impact. The present research aims to fill this gap.

We adopt a difference-in-difference type strategy to test the impact of the introduction of the heavy plough. We exploit two sources of variation: time variation arising from the adoption of the heavy plough and cross-sectional variation arising from differences in regional suitability for adopting the heavy plough. This allows us to compare changes in economic development, as measured by urbanization, in the post-adoption period relative to the pre-adoption period between regions that were able to benefit from the heavy plough and regions that were not. We implement the test using two different datasets: a high quality dataset for Denmark and a European dataset with less perfect measurements. We implement our test under two alternative assumptions. Our baseline test assumes that the breakthrough of the heavy plough was around AD 1000. We also use a flexible model, which allows us to assess when the plough began to have a detectable effect on our outcome variables for each century of the Middle Ages, and whether this is in line with the assumed breakthrough.

Testing the heavy plough hypothesis on Danish data has four major advantages. First, Denmark contains regional variation in the presence of clay soils. This allows us to exploit variation similar to the one within Europe in a setting that is arguably more homogenous across regions than the whole of Europe. Second, the presence of clay soil and the timing of town foundations can be precisely measured. Third, we can study the effects at very local levels by focusing on counties and the foundation of towns, whereas in the European case we use larger regions and foundation of cities. Finally, the Danish case allows us to shed some light on the plausibility of the assumptions underlying the test. For instance, we assume that soil maps from the late 20th century capture the location of medieval clay soils and historical suitability well. The Danish data allow us to show that the share of clay soil based on a *late* 20th century map correlates positively and significantly with the share of clay soil calculated on the basis of a late 19th century geological map for Denmark. We also demonstrate that our modern measure of suitability for growing the plough positive crop barley correlates positively and significantly with historical measures of agricultural productivity from the 1660s and the 1830s. This supports the assumption that soil suitability today captures that of the past.

We find evidence strongly consistent with White's hypothesis. With respect to the Danish sample, our estimations show that the heavy plough accounted for more than 40% of the increase in urbanization—as measured by establishment of new towns—in the High Middle Ages. The empirical evidence also largely confirms the historiographical evidence about the timing of the introduction and breakthrough of the heavy plough in medieval Denmark. In line with the results for Denmark, the European data provide evidence that regions with relatively more fertile clay soils experienced greater urbanization in the medieval epoch.

Overall, our research complements existing accounts from the historiography of medieval technology with quantitative evidence. To the best of our knowledge, we provide the first econometric test of the heavy plough hypothesis. Our empirical strategy, which—as already noted—exploits exogenous variation in fertile clay soil in a difference-in-difference setup, deals with the concern about reverse causality raised by Hilton (1963) in his critical review of White's book. Moreover, we present evidence that increased agricultural productivity can be a powerful driver of economic development in an agrarian economy. We also provide a clear historical example of what Acemoglu et al. (2005) call the "sophisticated geography hypothesis." This hypothesis holds that particular geographical characteristics that were not useful (or even outright harmful) for successful economic performance at some point in time may turn out to be beneficial later on. The reason is that certain technological inventions may benefit particular geographical characteristics. In the present case, the heavy plough (the technological invention) benefitted areas endowed with fertile clay soils (the geographical characteristic). Finally, our paper speaks to the literature on "the little divergence" which stresses regional differences in development within Europe (e.g. Broadberry et al. 2012; Baten and van Zanden 2008).

The rest of the paper is organized as follows. Section 2 contains a detailed discussion of the advantages of the heavy plough on clay soils, and it provides historical background for the introduction and diffusion of the heavy plough. Section 3 outlines the empirical model. Section 4 describes the Danish data. Section 5 presents the results for the Danish case, and Section 6 present the results for European sample. Finally, Section 7 concludes.

2. Background

This section first elaborates on the advantages of using heavy ploughs on clay soil. Understanding these advantages is important, as they form the foundation of the heavy plough hypothesis. Second, we review the existing evidence on the diffusion of the plough in Denmark in particular and Europe more generally. Doing so provides us with knowledge on the breakthrough of the heavy plough, which helps guide the empirical strategy

<Figure 1 about here>

2.1 Advantages of the heavy plough

The earlier ploughs—known as ards or scratch ploughs—are almost as old as agriculture itself, and they were probably already in use by BC 4000-6000 in ancient Mesopotamia (Anonymous 2007, p. 2). An ard, which exists in different varieties, is a symmetrical instrument that tends to tear up the soil more than it turns it over (Comet 1997). Heavy ploughs are asymmetrical instruments, which are fitted with a mouldboard that can be used to turn the soil either to the left or the right (Comet 1997; White 1962). Figure 1 compares the features of an ard and a heavy plough.

As noted above, the heavy plough has a number of advantages on clay soils, which we substantiate next. The first advantage of the heavy plough is that it turns the soil; ards, in contrast, only powder the surface of light soils. By turning the soil, the heavy plough allows for improved weed control (Guul-Simonsen et al. 2000, p. 58). Richerson (2001, p. 97) stresses that this is more advantageous in areas with heavy soils, and argues that heavy ploughs "are better at keeping heavy soils free of weeds in damp climates, where the mere stirring of the scratch plow does insufficient damage to root systems." Further, Pounds (1974, p. 193) notes that "the [heavy] plough not only buried the weeds, but also brought up to the surface a lower soil level in which percolating water tended to concentrate plant nutrients." Along with this, turning the soil also allows for incorporation of crop residues, green manure, animal manure or other substances. Poulsen (1997, p. 123), who also emphasizes this aspect, argues further that "the introduction of the heavy plough was important as it allowed a much more effective ploughing of manure into the soil."

The second advantage is that mouldboard ploughing allows for improved drainage by creating high-backed ridges,[2] which were long and narrow and placed on the height curves of the landscape (Comet 1997; Pounds 1974; Wailes 1972). Moreover, White (1962) explains that one implication of the ridges was the guarantee of a crop on the crest even in the wettest year or in the furrow in the driest seasons. In line with this, Jope (1956, p. 81) argues that the northern "clay-lands" had different problems compared to Mediterranean agriculture. In fact, agriculture in the northern "clay-lands" is more frequently concerned with efficient drainage of clay soils. In contrast, Mediterranean agriculture is mainly concerned with moisture conservation. However, Jope also observes that some areas with lighter soils in Northern Europe could use the Mediterranean style of agriculture suggesting regional variation in the use of ards and ploughs even within Northern Europe.

The third advantage emphasized by White (1962, p. 43) was that the heavy plough "handled the clods with such violence that there was no need for cross-ploughing." This meant less work effort for a given amount of land, thus increasing the productivity of farmers. Finally, the use of the heavy plough on light sandy soils may lead to a gradual destruction of the soils in the longer run (Henning 2009).

2.2 Origin and diffusion of the heavy plough[3]

In this section, we confront the task of establishing the breakthrough of the heavy plough. This is an important task, because our empirical strategy relies on comparing regions before and after the widespread adoption of the heavy plough. For this reason, we need to carefully examine the research that sheds light on this issue. We will consider both the archaeological research on high-backed ridges, plough remains, and figurative representations as well as the

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[2] (Pounds 1974, p. 195) explains that the method of ploughing "was first to cut a furrow down the middle of the strip, and then, ploughing alternately on each side, to turn the sward towards the middle. […] The effect was to heap up the earth along the middle of the strip, producing the corrugated pattern of 'ridge-and-furrow' or *Hochaker*" , "Ridge-and-Furrow" and "Hochaker" are synonymous with "high-backed ridges".

[3] The time periods for the introduction and breakthrough across modern states are discussed in Appendix F based on various sources. The time periods refer to the approximate time period of the *breakthrough* or, in some cases, the century of *introduction*. The slow diffusion across places has been explained by North (2005) by "the isolation of the manor."

linguistic evidence. As will be discussed in detail below, the existing evidence suggests that the heavy plough may have been *introduced* in some areas before AD 1000, but its *breakthrough* or *widespread adoption*—which is what should really interest us—seems only to have started in earnest around AD 1000. We begin our examination with the Danish evidence and then move on to the evidence for the rest of Europe.

2.2.1 Denmark

Poulsen (1997, p.116) summarizes the diffusion process of the heavy plough as follows: "Probably around 900 to 1100, then the mouldboard plough was introduced into Denmark, gradually diffusing from southern areas." The said time span is also supported by archaeological and other evidence from high-backed ridges, plough remains as well as other evidence discussed below.

High-backed ridges

As discussed above, mouldboard ploughing is known to create fields with high-backed ridges. Thus, the strongest indicator of the breakthrough of the heavy plough is the presence of high-backed ridges, which only a heavy plough could have created (Poulsen 1997). Grau-Møller (1990) notes that the earliest dating of high-backed ridges is from around AD 1000, but that the more certain dating is for the 1100s. Jensen (2010, p. 202) argues that the breakthrough happened in the middle of the 1100s. He bases this on the presence of high-backed ridges, as do other authors, but also stresses that heavy ploughs are mentioned in Danish medieval provincial laws from the second half of the 1100s and early 1200s.[4]

Plough remains

Heavy ploughs and ards consist of different parts (see Figure 1). The most prominent part is the mouldboard, which indicates most clearly the existence of heavy ploughs. Coulters and asymmetrical shares are also of interest, but as we note when we discuss the European case there are important reasons for doubting whether or not these parts give definite evidence of the presence of heavy ploughs. The Danish evidence is summarized in Larsen (2011), where

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[4] Larsen (2011) argues that the earliest evidence of *introduction* is from AD 200-400 based on two cases from Western Jutland. However, both cases remain controversial. For the first case, Larsen (2011) grants that the dating is problematic. Moreover, other experts have questioned whether the ridges are in fact proper high-backed ridges (Grau-Møller, personal communication). For the second case, Larsen (2011) notes that there is scholarly disagreement about this, as some scholars reject the assumption that a heavy plough could have produced the furrows.

two undated mouldboards are discussed. He also discusses coulters and asymmetrical shares, which all can be dated to after AD 1000.

Figurative and linguistic evidence

Larsen (2011) dates paintings depicting heavy ploughs to the 15th or 16th century for the case of Denmark. The linguistic evidence includes that the Old Norse word for heavy plough came into use after AD 1000. Porsmose (1988), for instance, mentions that the man who killed King Erik Emune in 1137 was named Black Plough (Sorte Plov in Danish).

AD 1000 as year of breakthrough

Given that the earliest high-backed ridges can be dated to around AD 1000, and that many of the plough remains can be dated to after AD 1000 along with the figurative and linguistic evidence, we use this dating as our baseline year for the breakthrough of the heavy plough for Denmark.

2.2.2 Europe

Manning (1964) notes that there is evidence for widespread use of bow ards in the Iron Age and Roman Period in Scandinavia, the Rhineland, Britain and Italy for the period before AD 500. He concludes that this distribution is wide enough for us to assume that it was the normal type of plough throughout Europe at the time. Fowler (2002) argues that the bow ard remained the plough available to most farmers in England throughout the first millennium AD, and that it remained important across Europe. Moreover, the evidence from the British Isles suggests that the heavy plough only came into use at the end of the first millennium. Other historians hold similar views. Fussell (1966), for example, concludes that the heavy plough only came into general use as of the 11th century and onwards for Europe as whole. Similarly, but focusing on Northern Europe, Heaton (1963, p. 100) argues that after AD 1000 the (wheeled) heavy plough drawn by eight oxen "was used more and more to turn the heavy clay lands which became available with the clearing of some forest areas." We now turn to a more detailed discussion of the various strands of evidence.

High-backed ridges

As mentioned the presence of high-backed ridges is probably the strongest indicator of the use of heavy ploughs. High-backed ridges have been observed and dated in several countries, including Britain, Denmark, Germany, Netherlands, and Sweden. As for the Danish case, the earliest of these are dated to around AD 1000 (Grau-Møller 1990). Thus, the evidence on high-backed ridges favors the view that the breakthrough of heavy ploughs took place after AD 1000. This conclusion is in line with the view of Fowler (2002), Fussell (1966), and others, as stated above.[5]

Plough remains

The European evidence on discoveries and dating of mouldboards, shares, and coulters is summarized below with discoveries of these three parts discussed in turn.

Mouldboards: Unfortunately, only few mouldboards have survived. We have already mentioned the undated Danish evidence, but note that for the British Isles there is no evidence of mouldboards for the first millennium AD according to Fowler (2002).

Coulters: Lerche (1994) provides an overview of findings of coulters, which for Hungary and the Danube area, can be dated to the first century AD. In Britain and Ireland, coulters that date back to the Roman era have been found; in Germany, coulters that date back to the period 3rd to 6th century AD have been found. However, as pointed out by, among others, Comet (1997) and Fowler (2002), the presence of coulters does not imply the heavy plough, as coulters were also attached to ards.

Shares: These plough remains are of particular interest as they indicate whether the instrument was symmetrical or asymmetrical. An asymmetrical share would be consistent with the existence of heavy ploughs, but it has been suggested by Wailes (1972) that asymmetrical ards have existed. The earliest evidence of asymmetrical shares comes from Roman Britain where three such parts have been found (Manning 1964; Wailes 1972). Yet Manning (1964) argues that the bow ard was the normal plough of the period, as noted above. More systematic evidence on the evolution of shares is given in Henning (1987) for South Eastern Europe, which encompasses parts of the Balkans as well as Hungary and Slovakia.

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[5] The earliest evidence that has been interpreted as indicating the use of a heavy plough comes from the Iron Age settlement Feddersen-Wierde in Northern Germany (Hardt 2003; Larsen 2011; Wailes 1972). The furrows discovered at Feddersen-Wierde can be dated back to the first century BC, but there are no high-backed ridges at Feddersen-Wierde (Grau-Møller 1990) and the furrows might have been made by an ard. Larsen (2011) notes that it may be difficult to distinguish the furrows from heavy ploughs and certain types of ards. In a similar vein, Wailes (1972, p. 161) argues that the furrows could have been produced by “skillful tilting of a heavy ard.” The presence of symmetrical shares found at Feddersen-Wierde corroborates the argument of Wailes (1972) that the furrows may indeed be ard marks.

Henning shows that from the 3rd to the 6th century there is no systematic asymmetry in the shares found, but concludes that for the period from the 7th to the 10th century there is a strong "overweight of left-sided asymmetry" (1987, p. 55). This is consistent with White's view that Slavic tribes had the heavy plough from around AD 600. Other asymmetrical shares are covered in Lerche (1994), where German and Czech findings of plough shares dating back to the 11th century or later are discussed. This is similar to the Danish evidence discussed by Larsen (2011) mentioned above.

Figurative representations

The earliest depictions are mentioned by Astill (1997), who points to seven English manuscript illustrations of ploughing dating back to the late 10th and 11th centuries. Another early and often cited figurative representation is found on the Bayeux Tapestry sewn in Normandy or England in the late 11th century (e.g. Fowler 2002). Later figurative representations are given in Duby (1968) who reproduces a drawing from the 12th century and a painting from the 15th century of a heavy plough from France, and who observes that the construction has not changed much over time in the two illustrations. Thus, to the extent that the dates of the figurative representations are informative of the breakthrough of heavy ploughs, the earliest date seems to be the late 10th century.

Linguistic evidence

White (1962) argues that Slavs may have introduced the heavy plough and that it therefore diffused from east to west starting in the late 6th century. This conclusion was reached by considering evidence indicating that a word for plough and many associated terms existed in all of the three Slavic linguistic groups. More specifically, White (1962, p. 50) reasons that "since the Slavic vocabulary surrounding *plug* probably would have developed rapidly, once the Slavs got the heavy plough, we have no reason to date its arrival among them very long before the Avar Invasion of 568." He also points out that the word 'plough' first appears in written form in 643 in Northern Italy as the Lombardian 'plovum' in the *Langobaridan Edictus Rothari*.[6] For South Western Germany, the *Lex Alemannorum* shows that the word 'carruca' had come to mean a plough with two wheels in front by the 8th century. There is

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[6] The word "plaumorati" also appears in a text by Pliny the elder from the 1st century. White (1962) says that this word is unintelligible, but if it is replaced by 'ploum rati', we have the first appearance of the non-classical word 'plough', but he later refers to this as "the questionable emendation of the Pliny text's plaumorati." Further, the exact nature of Pliny's plough has been questioned. Wailes (1972) says that it did not necessarily have a mouldboard as contented by other authors. Rapsaet (1997) notes that Pliny's plough is often believed to be a wheel ard.

also written evidence for a heavy plough in Wales in the 10th century in the laws of *Hywel Dda* (White 1962, pp. 50-51). Puhvel (1964) notes that the word for plough (plogr) does not appear in old Norse before AD 1000, whence it probably spread to 11th century England, where 'plog' or 'ploh' replaced the older word 'sulh'.[7]

AD 1000 as year of breakthrough

Our discussion of the evidence demonstrates that there is uncertainty about the timing of the breakthrough of heavy ploughs. As explained above, a view held by many historians, including Heaton (1963), Fowler (2002), Fussell (1966), Wailes (1972) and Poulsen (1997), is that the breakthrough happened from around AD 1000 onwards. We provide further evidence in Appendix F, which shows that for many countries the breakthrough is believed to have happened around this time. Moreover, AD 1000 is corroborated by the presence of high-backed ridges from around this year. The figurative evidence is also in line with the view of the breakthrough starting from AD 1000. Further, even if heavy ploughs existed earlier, ards seem to have been more common in the earlier periods, as emphasized by Manning (1964) and Fowler (2002).[8] In sum, we use the AD 1000 timing below. However, since there is uncertainty regarding this date, we also use estimation methods that allow for evaluating the breakthrough date.

3. Empirical strategy

As explained in Section 1, our identification strategy follows the logic of the standard difference-in-difference estimator. We exploit both the *time variation* arising from the breakthrough of the heavy plough and the *cross-sectional* variation arising from differences in local suitability for adopting the heavy plough. We test White's hypothesis on two independent datasets. However, we defer a detailed discussion of the data to later and next present our empirical models.

3.1 Non-flexible model

Our baseline model assumes that we know when the diffusion of the plough took off in earnest. As discussed above, the evidence indicates that this happened from around AD 1000.

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[7] White (1962) argues that the plough was introduced from Denmark to England in the late 9th and early 10th centuries. Myrdal (1997) accepts this possibility, but notes that the diffusion could have been in the opposite direction with the connection being Northern England and Norway.

[8] This is in line with Landes (1998), who stresses that the heavy plough went back earlier but was only taken widely into use from AD 1000.

We therefore estimate non-flexible models in which the post-treatment period is AD 1000 and onwards. The non-flexible model is:

$$\ln y_{it} = \beta \ln(1 + PloughFraction_i) I_t^{1000} + \sum_{j=t_0}^{T} X'_i I_t^j \phi_j + \sum_R \lambda_R I_i^R + \sum_{j=t_0}^{T} p_j I_t^j + \epsilon_{it} \qquad (1)$$

In the equation, t denotes time, i denotes county or region, y_{it} is economic development, and $\ln(1 + PloughFraction_i) I_t^{1000}$ measures the interaction between the share of heavy-plough-suitable area[9] in region i and the dummy variable I_t^{1000}, where I_t^{1000} takes the value 1 as of AD 1000. The coefficient of interest is β, which is the causal impact of having heavy-plough-suitable area (measured relative to the pre-adoption period).[10] A positive coefficient would be in line with the hypothesis that the heavy plough mattered for economic development. The remaining variables are control variables, X_i, interacted with time dummy variables; regional fixed effects, I_i^R; time fixed effects, I_t^j; and the error term, ϵ_{it}. With the Danish data, we begin in 675, use 25-year intervals, and end in 1300, whereas in the European case, we have data for each century from AD 500 to AD 1300 (see footnote 33 for further details). We postpone the discussion of control variables to Sections 4.2 and 6.2.

3.2 Flexible model

We assume alternatively that the exact date is unknown but that it happened after the initial period (t_0). In this case a flexible model is the natural complement to the non-flexible model. With a flexible approach we can assess when the plough began to have a detectable effect on agricultural productivity, and whether our baseline non-flexible model is plausible. The flexible model is described by:

$$\ln y_{it} = \sum_{j=t_0}^{T} \beta_j \ln(1 + PloughFraction_i)\, I_t^j + \sum_{j=t_0}^{T} X'_i I_t^j \phi_j + \sum_R \lambda_R I_i^R + \sum_{j=t_0}^{T} p_j I_t^j + \epsilon_{it} \qquad (2)$$

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[9] See description in Section 4.1 and 6.1

[10] Since we have no knowledge of the *take-up rate* of the heavy plough, β is an *intention-to-treat* (ITT) type estimate.

The crucial difference between equations (1) and (2) is that with (2) we obtain an estimate for all j periods and hence let the data 'speak' as to when the effect of the heavy plough becomes (statistically) observable. All the other variables are the same as in the previous section. This model estimates the excess effect of having fertile clay soil in period j compared to the first time-period in the dataset.

4. Data for Denmark

In order to estimate the above equations, we need several data series. First, we need a measure of regional economic development and a measure of fertile clay soil. We discuss these in Section 4.1. Second, we need control variables to address potential threats to identification as discussed in Section 4.2.

4.1 Main variables

We focus on urbanization as our measure of regional economic development. This is justified by the fact that historians have linked the heavy plough and urbanization (e.g., White 1962; Jensen 2010). The effect on urbanization could come from a variety of mechanisms. First, Nunn and Qian (2011) and Pounds (1974) argue that urbanization is closely related to per capita income; and Acemoglu et al. (2005) assert that only societies with a certain level of agricultural productivity and a relatively developed system of transport and commerce can sustain large urban centers (see also Diamond 1998).[11] The heavy plough arguably increased agricultural productivity, and it therefore allowed for urbanization. Second, productivity increases in the agricultural sector may have spawned migration to the urban sector (Nunn and Qian 2011).[12] Pounds (1974) notes that evidence indeed suggests that migration to towns and cities was taking placing in the Middle Ages. Third, since the period studied is likely to have been Malthusian (Ashraf and Galor 2011), increases in agricultural productivity are associated with larger populations. Larger populations would arguably affect the degree of specialization, which could increase urban populations (Galor 2011). In this (Malthusian) case, there would be no increase in income per capita, but more people in urban occupations. Moreover, larger agricultural populations also drive the foundation of new urban centers in the models considered by Fujita, Krugman and Venables (2001).

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[11] In line with this, Glaeser (2014, p.1154) has recently argued that "historically, urban growth required enough development to grow and transport significant agricultural surpluses."

[12] Pounds (1974) argues that all towns had an agricultural sector, and therefore may have benefitted directly from the heavy plough.

Urbanization measured by establishment of towns

We build on Beresford (1967), Pounds (1974), Andrén (1985) and Jensen (2010) who all suggest using the number of cities and towns as an indicator of urbanization and economic development for the medieval period. Specifically, we construct our urbanization measure as the number of towns per square kilometer for each county based on Jensen's (2010) dating of the approximate establishment of Danish medieval towns.[13] He uses, among other things, information on when the town had main streets, a town center with a market square, and a town church in order to give an approximate earliest date of when the town was established (Jensen 2010). His dating builds on, and is in line with, earlier work by Andrén (1985). Jensen provides data for the timing of the establishment of towns for every 25 years, and from this we obtain towns per square kilometer from AD 675 to 1300.[14]

Heavy plough measure

We construct the variable *PloughFraction* to measure the soils that will benefit from heavy ploughs. For this purpose, we have digitized the soil map from Frandsen (1988), which gives the locations of clay soils in Denmark.[15] Jensen (2010) used this map to pinpoint the location and types of soil that would benefit from the heavy plough. We also note that most of the remaining Danish soils are classified as sandy soils. For the European sample, we construct a measure based on the soil type known as luvisol. We discuss this measure in greater detail below, but for the purposes of comparison we also use this alternative in the Danish sample. Some of the moraine clay soils on Zealand in Eastern Denmark are not captured by the luvisol measure, but still the luvisol-based measure is highly correlated with the clay measure.[16] The location of the clay soil can be seen in Figure 2, which also reveals that the spread of new towns happens almost exclusively in the clay soil areas after AD 1000.[17]

On this background we identify the areas with high prevalence of clay soil as our baseline measure for soil that benefits from the heavy plough. Yet in order to identify the areas that would benefit from adopting the heavy plough we need a second condition to be fulfilled: the

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[13] See table E2 in appendix E for a complete list of the Danish towns.

[14] An urbanization criterion based on royal privileges is not feasible as these were received by the towns after 1300, and the towns had been established long before these dates, see appendix I in Andrén (1985).

[15] We include five categories (”predominantly clay soil", "sandy clay soil", "clayey sandy soil", "clay soil from the late glacial period" and "heavy clay soil") to measure clay soil.

[16] The correlation coefficient is 0.70 and strongly significant.

[17] The clear outlier in this regard is Aalborg, located in the northern part of Jutland. There is no clay soil near Aalborg, but being positioned at the narrowest point on the Limfjord (a shallow fjord) made the city a natural harbor.

soils need to be suitable for growing plough-positive crops such as wheat, barley, and rye.[18] We may therefore need to adjust for the suitability of the soil for growing plough-positive crops since areas with infertile, clay soil are unlikely to benefit from the heavy plough. Also, using only data for plough-positive crops would not distinguish between areas that benefitted from using heavy ploughs or scratch ploughs. We consequently adjust for barley suitability since this crop was grown in Denmark throughout the period (see also footnote 27). The adjustment is made by using a suitability map from the Global Agro-ecological Assessment 2002 by FAO, which classifies the soil using thresholds on a soil-suitability index denoted by SI. The corresponding classification divides soil suitability into categories ranging from "very marginal" to "very high" (see Figure C1 in Appendix C for details). For the Danish case, 74 percent of the clay soil has at least good suitability for growing barley, so this may not matter much for results. Still, we construct a quality-adjusted measure of $PloughFraction$ using clay soil with $SI \geq 55$ for barley.[19]

Next we probe into 1) the use of modern soil maps for identifying the location of clay soils and 2) the use of present-day suitability for growing plough-positive crops. Doing so is important since our tests, especially in the European sample discussed below, rely on using present day geology.

<Figures 2 and 3 about here>

Use of present day soil maps for identifying the location of clay soils

To investigate whether the use of present day soil maps captures historical soils, we have digitized an older soil map that dates back to 1899.[20] To the best of our knowledge, this is the oldest soil map for Denmark. Correlating the share of clay soil in the late 19th century with our present-day soil measure reveals a strong positive correlation (see Figure 3).[21] This suggests strong persistence in the location of clay soils, and it adds further credibility to our assumption that the present-day location of clay soils accurately reflects the past. Furthermore, Milthers (1925) notes that the clay soils formed during the ice age in Denmark.

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[18] See Pryor (1985) for a discussion of which staple crops are plough-positive. Pryor also discusses the need for the right climatic/geographical conditions for the usefulness of the plough.

[19] For a precise definition of SI, see footnote 43.

[20] The map is digitized from Harder and Ussing (1913). The same map is given in Ussing (1899), but for the purpose of digitizing the map, we have used the version from 1913 since this proved to be easier to handle by ArcGIS.

[21] Three counties are left out due to missing data. Data are partially available for two counties, and if we keep them we obtain similar results.

Use of present-day soil suitability

We have data on historical soil suitability in the form of barley, rye and wheat yields[22] from 1837 and a measure of peasant payments in terms of barley to landlords (known as "*Landgilde*") from the 1660s, available at sub-national level for the Danish case. The advantage of these two datasets is that they are collected at the level of the parish—a very small unit—and cover both manors as well as smaller farms. In this way we can build county level data that cover the whole area. Figure 4 shows the correlation between 1837 barley yields and the FAO suitability measure at the county level. We see that the FAO suitability measure is positively correlated with the historical measure of barley yields.[23] Moreover, Frandsen (1988) proposes that the geographical distribution of tenant barley payments in the 1660s reflects soil fertility (see Figure 5).[24] We regress the barley payment per square kilometer at the county level on the FAO barley suitability measure, leaving out regions completely or partly without data on payments,[25] and find a positive and strongly significant relationship (see Figure 6). These results support that present-day soil suitability resembles past suitability.

<Figures 4, 5 and 6 about here>

4.2 Control variables and threats to identification[26]

A first step in controlling for potentially omitted factors is to add county and time fixed effects. County fixed effects capture time-invariant characteristics such as soil quality and other geographical factors, while time fixed effects control for underlying aggregate changes that affect economic development.

While county and time fixed effects go some way in ruling out spurious results, we cannot reject this possibility a priori. Specifically, the identification of a causal impact hinges on the assumption that we are able to control for all other changes *unrelated* to the heavy plough which (i) occurred around the time of plough adoption in Denmark, and which at same time

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[22] These data come from the first Danish agricultural census and were kindly provided by Jørgen Rydén Rømer. Yields are measured as the ratio of harvest to seed.

[23] Similar pictures emerge for rye and wheat.

[24] We use the map in Figure 5 to construct the measure.

[25] Keeping counties only partly represented in the payment data only increases the significance.

[26] See Appendix A for full definitions of control variables and Appendix B for descriptive statistics.

both (ii) correlate with plough suitability and (iii) affect urbanization. We next discuss some changes that potentially fulfill conditions (i) to (iii) as well as ways of dealing with them.

Medieval warm period: The available temperature data at the aggregate level suggest little variation within Denmark, and we therefore trust that time fixed effects capture temperature changes well. Hybel (2002) argues that the medieval warm period was predominantly felt during the 11th century in Scandinavia. Consequently, if there is an effect of clay soils after the 11th century in the flexible estimates, we can plausibly rule out that the warm period is driving our results. In fact, the effect of clay soils is present in the 13th century, as will be shown below.

Institutions: Time fixed effects will also capture aggregate institutional changes. However, there could be regional effects of institutional change. From the late 900s, one king ruled Denmark, and this may have influenced regional development. Jutland (the peninsular that shares a border with Germany) had proven difficult to defend, and it has been argued that rich-in-clay Zealand, an island in the east of Denmark (see Figure 2), was more easily defended. This may have led to a shift in gravitational center towards Zealand. In fact, the second Danish king founded some eastern towns around AD 1000 (Sawyer 2002). We address this by testing whether our results continue to hold within Jutland. The test within Jutland also helps to address that the counties were subject to different provincial laws. The so-called Jyske lov—Jutland's provincial law, which among other things regulated the distribution of farmland within a village and incentivized agricultural expansion—is from AD 1241 (Porsmose 1988). Since this law was the same across Jutland, we capture its effects by time fixed effects.

Rye as a winter crop and the three-field system: In Denmark, rye has been cultivated since the early Iron Age (Mikkelsen and Nørbach, 2003),[27] but it was introduced as a winter crop in the Middle Ages (Grau-Møller, 1990). Rye itself is a plough-positive crop, and the introduction of rye as a winter crop was made possible only by the heavy plough. Grau-Møller (1990) explains that the heavy plough is a precondition for high-backed ridges, and that these may have influenced the choice of crops and, in particular, the introduction of rye as a winter crop. During wintertime, rye would be exposed to snow and frost, especially on

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[27] The same is true for barley and oats. Wheat lost prominence among Danish farmers during the Viking age (700-1050) and was not cultivated during the Middle Ages (1050-1500); see Mikkelsen and Nørbach (2003).

poorly drained fields. The water could be quite high and would sometimes freeze, possibly causing damage to the crops. With the high-backed ridges, the furrows would contain the water and the rye could be grown on the ridges. Further, according to Porsmose (1988), introducing rye as a winter crop was necessary for the adoption of the three-field system in the Danish case. This discussion suggests that the introduction of rye as a winter crop and the three-field system are indirect effects of the heavy plough. Yet we add the interaction of suitability for growing rye and time fixed effects to gauge the importance of this. Since the location of soil with good suitability for growing barley, wheat and rye are strongly correlated, we use very good soil suitability for rye.[28]

Trade: North and Thomas (1970) point out that increased population density may have led to higher levels of trade. To the extent that the introduction of the heavy plough led to higher population density, it is therefore conceivable that one mediating channel was trade. To partial out this effect, we control for a time-varying effect of access to trading routes by sea. Transportation over longer distances was in this period far easier by sea; hence, distance to the sea may have been important for trade. Increasing trade would presumably have led to higher prosperity, which in turn would have had a positive effect on development.

The discussion of rye adoption and trade logically directs attention to so-called heavy-plough-induced changes (i.e., changes that occurred as a result of adoption of the heavy plough). These changes fulfill conditions (i)-(iii) discussed above, but they are *not* unrelated to the heavy plough. While heavy-plough-induced changes are inconsequential for our ability to establish the presence of a causal impact, they do have important bearings on which type of causal impact we actually end up establishing. If we neglect heavy-plough-induced changes, we identify the total effect (i.e., direct plus indirect effects) of the heavy plough. When we control for certain heavy-plough-induced changes, we partial out any associated indirect effects. To be sure, it is not possible to control for all such indirect effects. Therefore, while we are convinced that we can capture a causal impact of the heavy plough on regional economic development, it is rather a total than a direct effect that we identify. That is, we capture both direct effects (e.g., access to new and more fertile land) and some indirect

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[28] We do so in order to identify counties that would benefit *strongly* from the adoption of rye, since counties that merely have land suitable for rye cultivation typically also have land suitable for wheat and barley cultivation as revealed by a strong correlation between measures of suitability.

effects (e.g., the adoption of rye) of the invention and widespread adoption of the heavy plough.

5. Results for Danish sample

We first discuss the main results and then turn to a number of robustness checks, which include changing the PloughFraction indicator and adding extra control variables.

Main results

Non-flexible estimations are reported in Table 1. We calculate both standard errors corrected for clustering at the county level and Conley standard errors corrected for spatial autocorrelation. We have allowed counties further apart than 200 km to be independent. Spatial autocorrelation does not affect our results, as we obtain similar results regardless of which of the two types of standard errors we use. Column 1 reports the baseline measure when we only control for county and time fixed effects. Column 2 reports results for clay soil with good suitability for growing barley. Both regressions show a positive and significant effect of clay soils from AD 1000. The fertile soils (in terms of plough-positive crops) largely coincide with the clay soils of Denmark as mentioned above, and we therefore find little effect of making the quality adjustment. In column 3, where we add extra covariates, the regression coefficient hardly changes.

We mentioned above that as of the late 900s Denmark had rule by one king. This possibly led to a gravitational shift towards the island of Zealand. Given that the shift was away from Jutland, we can test whether it explains our result by restricting the estimation sample to counties in Jutland. When we do this, a statistically significant (although economically smaller) effect still emerges. This suggests that the effect of clay soil is not merely picking up the gravitational shift towards Zealand, cf. column 4. Column 5 investigates whether using the 19th century clay-soil measure changes conclusions. Inspection of the table reveals that this choice has little effect.

In order to measure the size of the impact of the heavy plough, we calculate county level urbanization in a counterfactual setting where the plough was never introduced. That is, we first use the urbanization from our last period of observation and subtract the estimated effect of adopting the heavy plough: $\ln\left(1+urbanization_{i,1300}\right)-\hat{\beta}\cdot\ln(1+PloughFraction_i)$ using the model in column 3 in Table 1. We then aggregate over all counties and calculate the average urbanization in a world without the heavy plough. This is found to be 35.8 towns. This should be compared to the actual number of 63 towns in AD 1300. In AD 975, before the heavy plough became widespread, only two towns existed in Denmark. Hence, in the counterfactual setting the increase in number of towns would have been only 33.8 compared to the actual increase of 61; or, to put it differently, the increase would have been only 55.4% of the actual increase. This means that the heavy plough explains 44.6% of the increase in urbanization from AD 975 to 1300 holding everything else constant. [29] That the heavy plough explains more than 40% of the increase in productivity observed in the High Middle Ages in Denmark is not unreasonable given the large amount of clay soil in this country.

<Tables 1, 2 and Figure 7 about here>

Turning to flexible regressions, we obtain similar results. We show one representative example in Figure 7, which controls for covariates. The effect of clay soils increases over time and becomes significant as of AD 1175, with point estimates increasing from this time onwards. Results are similar for the other models.[30] We also note that the timing of the effect is later than both the medieval warm period in Denmark and the shift to rule by one king.

Robustness

In Table 2, we show robustness checks. Columns 1 and 2 use the luvisol measure, both unadjusted and adjusted for quality. While we find similar results, the coefficients are smaller and less precisely estimated. There is little effect on the point estimate from the quality adjustment, but precision does increase. We already mentioned that some clay soils are not classified as luvisol. This is in particular true for the county of Sorø on Zealand; and if we drop this observation, results become stronger. Given that the Danish case has relevance for Northern Europe in general, the Sorø case suggests that we may inadvertently exclude some

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[29] Urbanization may lead to pressure for adoption of the heavy plough. If so, our results indicate that it is only the counties with fertile, clay soil that are successful in using the heavy plough to support new towns. Ideally, we would want to investigate the importance of pressure for urbanization by checking if agricultural prices are increasing. Price data are unfortunately not available for this period. Note, however, that since we estimate an ITT effect, reverse causality is not a concern.

[30] One could posit that the result in Figure 7 is driven by the fact that these soils are the most fertile in Denmark, and not the effect of the heavy plough. However, this is not plausible as grains had been grown in Denmark at least since the Iron Age, as also mentioned above, and we would expect that settlements took place on the best soils first.

clay-soil areas when we employ the luvisol-based measure.[31] Still, the fact that we obtain similar (albeit weaker) results suggests that this choice is reasonable.

Jensen (2010) includes clayey sandy soils among the soils that would benefit from the heavy plough. This choice may be questioned since this soil is not defined as clay soil. On the other hand, the sandy clay soils often coincide with areas that the older map mentioned above classifies as moraine clay. Nevertheless, we investigate the importance of this soil type by excluding it from our measure in column 3, and we reach a similar conclusion as with the baseline measure.

Column 4 demonstrates that adding latitude does not matter. This is hardly surprising given that we are already investigating variation within a geographically small high-latitude country.

In column 5 of Table 2, we exploit that the Danish data allow us to control for the historical level of suitability for growing barley. We use the barley payments density measure, which most closely resembles historical conditions in the middle ages. Moreover, it can plausibly be interpreted as increasing in suitability. The advantage of adding this measure is that it will capture the effects of other innovations such as the three-field system and the harness, which led to increased use of horsepower in ploughing (Mokyr, 1990). Areas with higher suitability for growing plough-positive crops arguably benefit more from these innovations. Yet, if there is still an effect of clay soils, it cannot be attributed to differences in suitability. In fact, column 5 shows that we get a significant coefficient, which is a bit larger than in the baseline model. This is consistent with the heavy plough playing a pivotal role in opening up the clay soils.

Column 6 investigates whether it matters that we applied the log transformation to the variables, and we find that it does not.

Overall, the results presented in this section provide strong quantitative evidence that the breakthrough of the heavy plough mattered for economic development in Denmark.

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[31] The Sorø area is classified as mainly cambisol according to the European soil database. This suggests that some cambisol is clay soil and may be better classified as clay soils. We have investigated the effect of including fertile cambisol in our *PloughFraction* measure in the European dataset. Effects become stronger and more significant. Consequently, these results are in line with what we find for Denmark.

6. The European sample

As indicated above, the measurements we have collected for Europe are less precise. Yet testing the heavy plough hypothesis for the whole of Europe is important as White (1962) intended his plough hypothesis to be applicable to Europe in general. The next subsections describe the dataset as well as the results of using it to estimate equations (1) and (2).

6.1 Data

Compared to the Danish case, the European data are more aggregate, spatially as well as temporally. They are constructed at the regional level, and they are only observed every 100 years. The European regions we use are the Nomenclature of Territorial Units for Statistics (NUTS) regions. We have chosen NUTS level 2, because it gives a detailed and relatively uniform subdivision of Europe. At this level, Europe is divided into 317 regions.[32] Given our historical period of interest, we focus on the period 500-1300 with observations every 100 years.[33] Next we discuss the data in more detail.

With respect to urbanization, we construct a measure that is analogous to the town density measure in the Danish sample,[34] but now we use historical maps from EurAtlas for the period 500-1300.[35] In the construction of EurAtlas, the researchers relied on historical atlases as well as the historical records to construct maps.[36] The approximate foundation year of cities is the inclusion criterion for a specific century.[37] In the empirical analysis below, we use the number of cities per square kilometer. Bairoch (1991, pp.135-136) stresses that the period from 900-1300 was a period of rapid urban growth in Europe and points out that the way this

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[32] Figure C2 in Appendix C shows the NUTS 2 division. In our analysis we use 269 regions. 38 regions cannot be included due to lack of soil data (Cyprus, Iceland, Malta, Turkey as well as overseas territories of France, Spain and Portugal). We also exclude 10 regions due to uncertainty about their soil types; see footnote 42.

[33] We begin our investigation before the (presumed) widespread adoption of the heavy plough, and we end before the medieval economy was hit by the devastating plague. Given the evidence in Henning (1987) and the linguistic evidence, AD 600 appears the most plausible century in which we should expect to find an earlier effect. Thus, we begin 100 years before in AD 500. For Denmark, starting in AD 675 is equivalent to starting in AD 500, since no towns had been founded before AD 700.

[34] Note that the measure for Denmark includes towns that were left out of the EurAtlas. In fact, the EurAtlas researchers indicated in personal communication that cities are missing in the case of Denmark and Scandinavia more generally. We have 63 towns in the Danish dataset and 18 cities in EurAtlas. Yet, the timing of urbanization is largely the same in the two datasets in the sense that new urban settlements become more frequent after AD 1000.

[35] Table E3 in appendix E shows a list of the number of cities for each century.

[36] For an example of their sources, see http://shop.euratlas.com/bibliography/gis_500.html

[37] The EurAtlas researchers indicated in personal communication that the foundation is determined using information on when the city is included on a historical map or from the time when the remains of a city can be attested.

happened was partly by "the creation of a great many new urban centers" and partly by the expansion of existing cities. He produces estimates of the number of cities from 800 to 1300 for Europe as a whole, and shows that both the number of cities and urban populations more than tripled during this period. This suggests that in the historical period we cover the number of cities follow growth in urban population, and we therefore regard our measure as the best proxy available. We also note that an advantage of this measure is that it tracks the transition from insignificant villages to cities, which took place in the period under study. Another advantage is that we do not have to make an arbitrary population-based cut-off of what constitutes a city. A disadvantage of this measure is obviously that we do not capture the growth of existing cities.[38] In order to give an impression of the data, we plot our city density measures for AD 500, 1000 and 1300 in Figure 8 and note that many new cities are founded in the North of Europe; for all centuries see Figure C3 in Appendix C.

<Figure 8 about here>

We also need a measure of clay soils for the European dataset. We employ the European Soil database, which builds on the classification system of the Food and Agriculture Organization (FAO). In this system the soil type known as *luvisol* fits most closely the description given in the historiographical literature and correlates with clay soils presence from other sources. Luvisol is rich in clay, has higher clay content in the subsoil than in the topsoil, and its soil profile implies that clay content increases with soil depth (FAO 2006; Louwagie et al. 2009).[39] In fact, evidence on the relative advantage of the heavy plough on clay soils exists in the form of modern mouldboard ploughing tests, which reveal that mouldboard ploughing increases crop yields on clay soils with considerably higher clay content in the subsoil than the topsoil (Guul-Simonsen et al. 2002).

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[38] Available data on the size of cities by Bairoch et al. (1988) are unfortunately very sparse for the period before AD 1300, and even in AD 1300 there are many missing observations (see Table E4 in Appendix E). For all countries, the majority of cities have missing observations, and for some they are missing entirely for AD 800, 900, and 1000. For AD 1100 there are no data. For AD 1200 some countries has one or two observations, but they are missing for most cases. This is true for Austria, Belgium, Denmark, Hungary, Netherlands, Norway, Romania, and Sweden. For the United Kingdom and Ireland, a similar picture emerges, but there a few cities with non-missing data for AD 1000. Both the EurAtlas and the Danish data suggest that we cannot simply replace missing observations by zero values for these years. Thus, we cannot use the Bairoch et al. data.

[39] This is a result of pedogenetic processes, which leads to a so-called argic subsoil horizon. The presence of an argic subsoil horizon requires that the clay content increases sufficiently with depth (http://eusoils.jrc.ec.europa.eu/library/Maps/Circumpolar/Download/39.pdf).

Fertile luvisol is much more common in Northern Europe than in Southern Europe. As mentioned, its geographical locations fit closely with the areas where historians have pointed to the presence of "clay soils", "heavy soils" or "heavy clay soils", and where they believe heavy ploughs would have been beneficial. At this general level, Hodgett (1972, p. 16) argues that the temperate zone of Europe contained much more "heavy clay soil" than did the Mediterranean zone, though some heavy soils exist "even in Southern Europe".[40] Pounds (1974, p. 112) argues that "the heavy plough, with its coulter and mouldboard" was "essential if the heavy clays of the Polish plain were to be cultivated." And luvisol is in fact the dominant soil in Poland; see Figure C4, Appendix C. Hodgett (1972, p. 16) argues that the heavy plough would be useful on the "heavy soils" in the valley of the river Po. White (1962) also notes that the heavy plough was in use in the Po Valley in later times for reasons of soil and climate. In fact, in the region of Lombardy, which covers a large part of the Po Valley, luvisol is highly prevalent. In line with this, Parain (1966) notes that heavy ploughs were used on the clay soils of Lombardy.

As noted, a concern regarding the use of data based on 20th century soil maps is that they may not represent the composition of soils in the Middle Ages. Many authors in the historiographical tradition write on the presumption that present-day soil maps are informative of past conditions. Comet (1997, p. 27), for example, argues that the "fundamental composition of soils in Northern France has probably not changed much since the eleventh century." This is not an unreasonable presumption as the available evidence indicates that heavy clay soils appear to have been formed long before the Middle Ages.[41] According to Alexandrovskiy (2000, p. 238), for instance, the steppe stage with chemozem soils was replaced by a forest stage with luvisol in regions of Russia 3000 years ago and in Central Europe some 11,000 years ago. The evidence presented for the case of Denmark suggests that modern geology correlates with that of the past. Moreover, country level data for 1925 from Mitchell (2007) show a positive and significant relationship between historical barley production and suitability (see Figure D1 in Appendix D). County level data from 19th century Prussia confirm a positive and statistically significant correlation between historical barley yields and our barley suitability measure based on present-day FAO data (see Figure D2 in Appendix D). Finally, data for 19th century Prussian counties, as well as for Danish

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[40] Table E5 in appendix E shows the distribution of heavy-plough-suitable soils across present day countries.

[41] Nevertheless, Comet (1997) warns that it would be wrong to take continuity for granted. For example, he notes problems of soil erosion, which was facilitated by the clearing of land.

counties, show that the location of luvisol and historical clay soil correlates positively (see Figures D3 and D4 in Appendix D).

For the European case, we construct *PloughFraction* as the fraction of the area of each region that contains luvisol with SI greater or equal to a certain threshold for a plough-positive crop.[42] We construct the baseline measure of *PloughFraction* using luvisol with $SI \geq 55$ for barley. In terms of soil suitability classification, this corresponds to using luvisol with at least good suitability for growing barley, but we also investigate other crops and different thresholds for SI.[43] We focus on the quality-adjusted measure, as only about half the luvisol in Europe has good soil suitability. Since our measures are a function of SI, a clearer notation is *PloughFraction(SI)*, and we therefore denote our baseline measure by *PloughFraction(55)*; see footnote 43. *PloughFraction(55)* is visualized in Figure 9. This map confirms that relatively more heavy-plough-suitable land is found in Northern Europe and the northern parts of Italy.

<Figure 9 about here>

6.2 Control variables and threats to identification

The conditions for identification of a causal impact are similar to the Danish case. We repeat them here for convenience: Identification of a causal effect requires that we are able to control for all changes unrelated to the heavy plough, which (i) occurred around the time of plough adoption in Europe, and which at same time both (ii) correlate with plough suitability and (iii) affect urbanization. Given that temperature and other variables vary little within Denmark, given that universities were not founded in this period in Denmark, and given that the Romans never occupied Denmark, these conditions are arguably more demanding in the European sample. We next discuss potential factors that fulfill the three conditions and how

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[42] Due to uncertainty we drop regions where more than 20% of the soil is not defined. 10 regions are omitted in this regard but including these regions only strengthens our results. See Figure C2 in Appendix C.

[43] *PloughFraction* can be written in precise terms in the following way: Let *F* be the distribution function for luvisol, and let *G* be the distribution for suitability. Then our measure of usefulness of the heavy plough is

$$PloughFraction(SI) = \frac{\iint 1_{[luvisol>0]} 1_{[suitability \geq SI]} \, dFdG}{Area}$$

where $1_{[\ ]}$ is the indicator function and *SI* is the suitability index threshold level. In most estimations, *SI* = 55, which is the definition of "good suitability"; however, we also run estimations with "medium suitability", corresponding to *SI* = 40 and "high suitability", corresponding to *SI* = 70. See Figure C1 in Appendix C for further details.

we deal with them in the empirical analysis. Note also that we always include regional and time fixed effects in our regressions, as in the Danish sample.

Medieval Warm period: As mentioned for the Danish case, the climatic changes that occurred throughout the so-called Medieval Warm Period may have played a role. The period from AD 950 to 1250 is considered to have been warm (Guiot et al. 2010), and this may have been beneficial for agricultural productivity (Koepke and Baten 2008). If higher temperatures correlate with the prevalence of heavy clay soil across Europe, we risk confounding the heavy plough effect with a climatic effect. To take this possibility into account, we include a variable measuring the mean temperature in a given region for each century.

Universities: A recent study finds that the establishment of medieval universities played a causal role in expanding regional economic activity (Cantoni and Yuchtman 2014).[44] This would constitute a problem to the extent that a correlation between the location of universities and heavy-plough-suitable areas exists. To rule out this concern, we include a variable measuring the number of universities in a given region for each century.

Rye and three-field system: Mitterauer (2010) emphasizes the importance of rye and oats as newly introduced crops in the Middle Ages. A new crop such as rye may have increased cereal production in some areas, which may have led to higher urbanization. In an effort to separate out the effect of rye, we include the share of the land of the region that is strongly suitable for rye cultivation as in the analysis of the Danish data. Nevertheless, the introduction of rye is unlikely to be completely independent of the adoption of the heavy plough, as also discussed in Section 4.2.

Institutions: The introduction of the heavy plough may have been a function of local institutions. In some places its introduction may have been delayed; in other places, institutions may have pushed it forward. Regional fixed effects will partly account for these scenarios. However, the heavy plough itself may have induced institutional change, as suggested by White (1962).[45] To deal with this possibility, we control for a time-varying effect of institutional heritage. Specifically, we interact a dummy variable for being a part of

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[44] The majority of medieval universities were only established after AD 1300, the time at which our observation window closes. Yet some universities were open before 1300, for which reason we control for their presence.

[45] White (1962) emphasized a link from the heavy plough to the development of the medieval manorial system, which is an indirect effect of the heavy plough on development.

the Roman Empire at some point in the past with time dummies. Landes (1998) has argued that Roman presence in an area left important cultural and institutional imprints that may have had persistent effects.

Trade: We also include a time-varying effect of access to trading routes by sea for the same reasons as discussed in Section 4.2.

6.3 Results

The discussion in this section is organized as follows: Section 6.3.1 presents main results from the estimation of, respectively, the non-flexible and the flexible model, Section 6.3.2 presents rolling estimates, while Section 6.3.3 reports the robustness of our findings.

6.3.1 Main results

In the non-flexible setup we assume that the exact date when the heavy plough was widely adopted in Europe is known; and, as discussed in detail in Section 2.2, it is reasonable to set this date to AD 1000.

<Table 3 about here>

Table 3 presents the results for the non-flexible model in columns 1 and 2. Column 1 shows the results when the only controls are time and regional fixed effects, whereas column 2 includes all controls. Inspection of the table reveals that the effect of having heavy-plough-suitable area is positive and significant, both with and without control variables.

We also carry out a counterfactual calculation similar to the one for Denmark. For Europe, we find that the heavy plough explains 15.7% of the increase in urbanization from AD 900 to AD 1300 holding everything else constant. That the heavy plough explains more than one tenth of the increase in productivity observed in the High Middle Ages is not unreasonable, keeping in mind that we are considering the *total effect* of the plough in a mainly agricultural economy. Yet, given the information from the Danish data, we also note that the use of cities rather than towns and less precise clay soil data could lower the effect.

Turning to the flexible model, where the timing of the widespread diffusion of the plough is assumed unknown, we report results in columns 3 and 4 with and without controls. As is evident upon inspection of the table, the plough's effect on urbanization increases as of AD 900, and the precision of the estimated effect also rises. In earlier centuries, before the breakthrough of the heavy plough, there was no effect of having fertile, heavy clay soil.[46] Hence, the results based on the more demanding flexible model are consistent with those of the non-flexible model.

The flexible approach has the obvious advantage that we can visualize the time varying effect of the heavy plough in a graph. Figure 10 shows the estimates for each century (based on column 4 of Table 3). As in the Danish case, we include two types of 95% confidence bands: one set of bands based on clustered standard errors at the NUTS 2 level and another set based on Conley standard errors. Clustering takes into account the fact that we observe the same regions over time, for which reason we do not have independence in the time dimension. Conley standard errors take spatial autocorrelation into account. We expect realistically that geographically closer regions exhibit increasing dependence; distant regions are assumed independent. In effect, we assume that regions separated by more than 500 km are independent.

<Figure 10 about here>

6.3.2. Rolling regressions

In order to further test whether our chosen cut-off date is reasonable, we follow Nunn and Qian (2011) in performing rolling regressions for a number of four hundred-year epochs. The idea is to assume different dates of introduction, and then test whether the heavy plough contributed to growth under that assumption.

The results can be seen in Table 4. In column 1 we assume a breakthrough of the heavy plough in AD 700, using only data from 500-800. In particular, we test whether there is an effect of having heavy-plough-suitable area in AD 700 and 800. We repeat this in columns 2 to 6 for the periods 600-900, 700-1000, 800-1100, 900-1200, and 1000-1300. A result consistent with the cut-off date being AD 1000 would be insignificance for the cases that do

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[46] We note that the coefficient on the dummy for AD 700 is positive and marginally significant at the 10% level when we include our full set of controls in the urbanization model. This result is not very robust. First, significance is absent in the model without controls. Second, the finding is not robust to making reasonable changes to PloughFraction; see Figure E2 in Appendix E, where we add eight models to our baseline model. Four produce results where significance is below the 10 percent level. Finally, the rolling estimates reported below suggest no early effects.

not include AD 1000 in the post-adoption period. For the later rolling periods, during which the heavy plough was presumably already in widespread use, both post- and pre-adoption periods will in effect have been treated.

<Table 4 about here>

By and large, the rolling regressions reveal an increasing effect over time. In panel A1 and A2, the point estimate of the causal effect of the heavy plough increases significantly when both post centuries contain AD 1000 and AD 1100. This is not surprising given that this is the first specification where both pre-centuries are in the expected *untreated* range and both post-centuries are in the expected *treatment* range. The main difference between panel A1 and A2 is that in column 6 the effect of the heavy plough is not precisely estimated when we include the full set of controls (panel A2), though it is similar to the one with only region and year fixed effects (panel A1). Note that in column 6 we estimate on data, which *only* include treatment years.

6.3.3 Robustness

So far, we have found strong evidence that the heavy plough had a sizeable and increasing impact on regional economic development as of the closing of the first millennium AD. In this section we report on the sensitivity of our results with respect to permutations of the main independent variable.[47] First, we check whether the results are robust to alternative measures of heavy-plough-suitable land and we also run a placebo experiment. Second, we discuss additional robustness checks.

Alternative measures of heavy-plough-suitable land

So far we have worked with a measure of heavy-plough-suitable land that relies on luvisol and good conditions for growing barley. This particular choice of soil, suitability level, and crop may be questioned. Table 5 explores this issue.

We first quality adjust using wheat rather than barley and obtain similar a result (see column 1). We next use medium and high suitability levels for growing barley and obtain qualitatively similar results (see columns 2 and 3). Then we investigate the effect of not

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[47] We have also estimated models using available data on population density. Discussion of these data and some representative results may be found in Appendix E.

adjusting for quality (column 4). While the effect remains positive, the coefficient is smaller. Given that almost 50 percent of luvisol has less than good suitability, it is hardly surprising that the effect is reduced. Yet the coefficient remains significant at the 10 percent level. As discussed above, luvisol fits well with the soils that historians identify as being suitable for the heavy plough. But there may be other soils that would gain from the heavy plough. We therefore turn to the sensitivity of our choice of soil type.

Gleysol is a wetland soil (FAO 2006), which Edwards (1990) describes as poorly drained soil for the case of the Ireland. Since one of the advantages of the heavy plough was its ability to assist drainage, we add this soil to our plough measure. We do so in order to test the sensitivity of our choice of luvisol, but also to test for a potential impact in these areas. Inspection of Table 5 (column 5) reveals that results are similar. A soil type, which is very similar to luvisol, is albeluvisol. Both have argillic horizons, and modern day deep ploughing may have converted luvisol into albeluvisol (Arnold et al. 2009, p. 48), which may in turn be a cause of measurement error. Yet including this soil type does not change the results (see column 6), which is not surprising since Arnold et al. (2009, p. 48) note that the difference between the two soil types is subtle. We then investigate whether we are in fact capturing another differential effect, which we would have captured with any kind of crop. We know that the potato strongly influenced urbanization in potato suitable areas after 1700 (Nunn and Qian 2011). However, as the potato was unknown to Europeans before the discovery of the Americas, we should not—as a matter of logic—see any positive effect of potato-suitable soil on urbanization during our observation window, 500-1300. Consequently, we perform our regressions using the share of a region with good suitability for growing potatoes as our main independent variable. This is a placebo-type experiment. The result from a non-flexible model using potato suitability is shown in column 7. We note that the effect is completely absent. Overall, this result substantiates that the effect which we attribute to the heavy plough is not just a general, positive effect that any crop would give rise to and, in particular, not a crop that would turn out to be very important later in history.

<Table 5 about here>

Further robustness checks

Table 6 provides further robustness checks. In column 1, we show that the result is unaffected by allowing for a quadratic effect of temperature. Next in column 2, we demonstrate that using the log transformation is not critical for the result. In the Danish case, we demonstrated that latitude did not affect results, and we note that this is also true in the European case though precision is decreased. Regarding controls for institutions, we follow Blaydes and Chaney (2013) and use the fact that the institution of feudalism originated in the Carolingian empire, and add a control for the share of a region that was part of the Carolingian empire in AD 800. Again, there is little effect on the results. We also show that results are robust to including a redefined measure of Roman heritage which includes a larger set of countries, see column 5. In column 6, we consider clustering at the country level as an alternative to the Conley method, and while precision is decreased the t-value is still about 2.

<Table 6 about here>

7. Conclusion

This paper provides the first empirical examination of the "heavy plough hypothesis", proposed by White (1962). The hypothesis holds that the heavy plough played an important role for population growth and urbanization in the Middle Ages. The results emerging from our analysis of two independent datasets strongly corroborate the hypothesis. We find that the heavy plough accounts for more than 40 percent of the increase in urbanization experienced in the High Middle Ages in Denmark in particular and 15.7% in Europe more generally. Our paper therefore complements the qualitative accounts found in the historiographical literature on medieval technology.

This paper also speaks to the modern literature on the deep determinants of economic development. Specifically, we analyze an important example of the sophisticated geography hypothesis: Clay soils conferred no advantages prior to the introduction of the heavy plough; however, once the heavy plough arrived, access to the fertile clay soils provided advantages in terms of productivity, access to new and fertile land, et cetera.

Our empirical analysis naturally contains some weaknesses. First, since we estimate the total effect of the heavy plough, the paper is unable to add to the debate on the *relative* importance of institutions versus geography in economic development (Acemoglu et al. 2005). Second, identification of a causal impact rests on our ability to control for all other changes unrelated to the heavy plough that occurred around the time of plough adoption in Denmark, and at the same time both correlate with plough suitability and affect urbanization. Third, we cannot disentangle interaction effects of the heavy plough with the introduction of horses for ploughing caused by the invention of the harness (Mokyr, 1990). Yet, a detailed study of England by Langdon (1983, p.268) concludes that "there is little evidence to indicate that the introduction of the work-horse increased crop yields" which is arguably related to the fact that oxen could perform the same function as horses (Mokyr, 1990). Finally, we have to assume that the geology of the medieval period is similar to that of later periods. We have shown that present day soil suitability matches that of the 17th and 19th centuries for the Danish and Prussian cases. For the whole of Europe, we only have early 20th century data, and while these data are consistent with the Danish and Prussian data, we are unable to go back any further. We leave attempts to improve the analysis along the said dimensions for future research.

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Figures and Tables

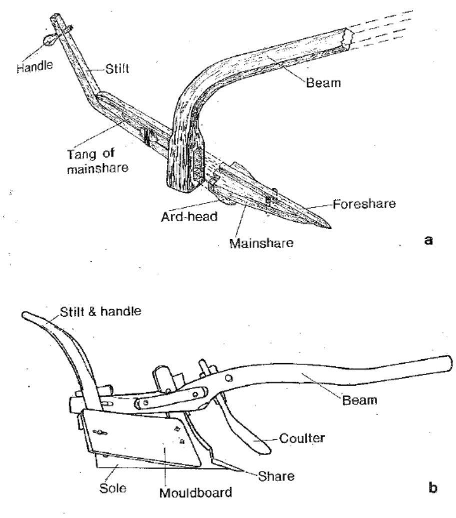
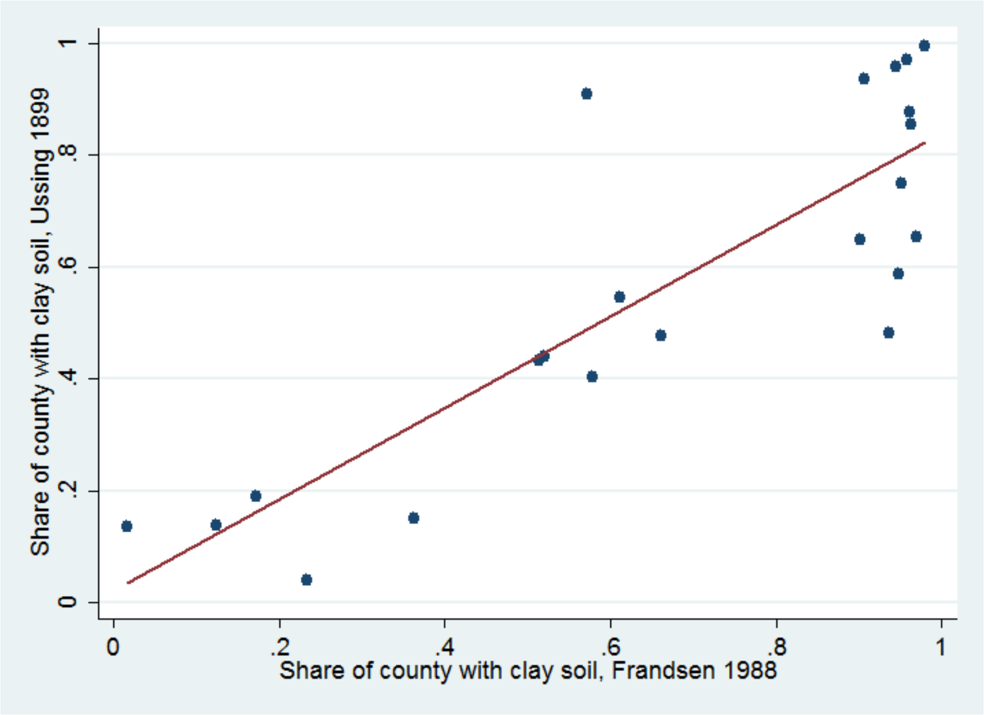


Figure 1: The ard (a) and the heavy plough (b). Source: Fowler (2002).

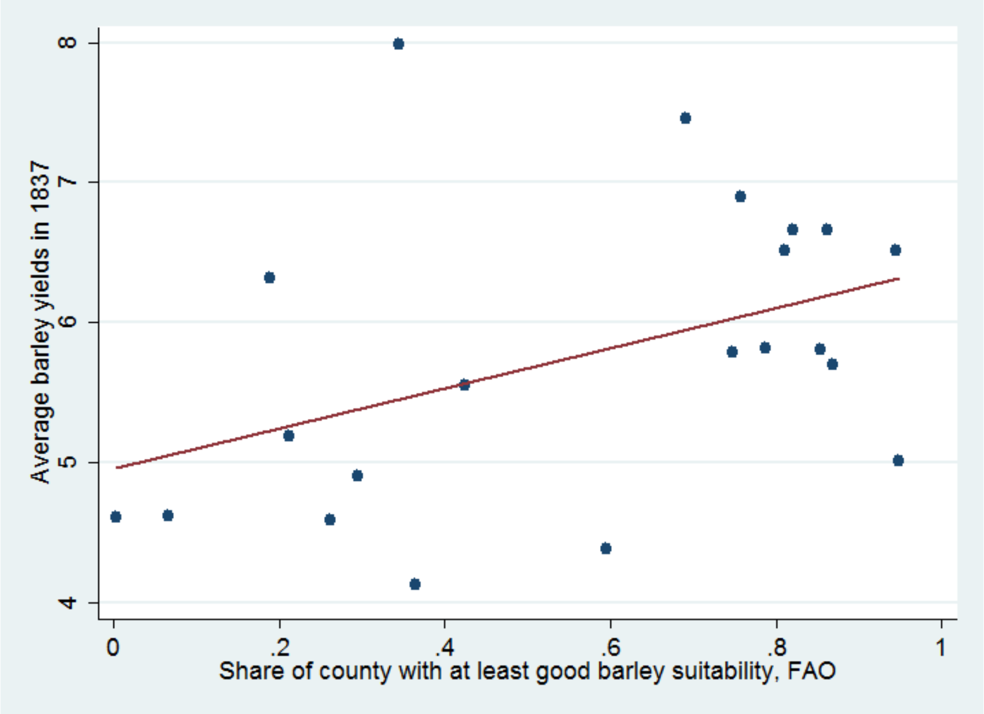
Figure 2: Establishment of towns and clay soils in Denmark

Figure 3: Historic and present day clay soil, Danish counties



Coefficient $= 0.8177, t\text{-stat} = 8.78, N = 22, R^2 = 0.72$

Figure 4: Historic barley yields and FAO barley suitability, Danish counties

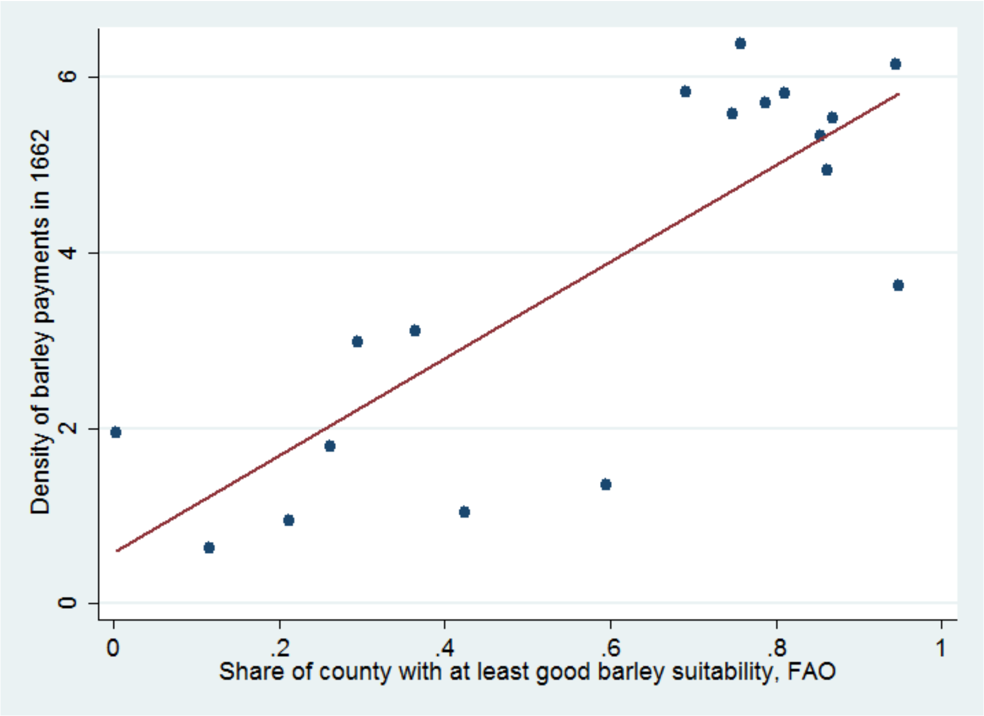


Note: Coefficient $= 1.427, t\text{-stat} = 2.47, N = 21, R^2 = 0.17$

Figure 5: Tenant barley payments in 1662

Notes: Each point on the map represents 20 toender barley in payment to the landlord. Toender is an old Danish measure (1 toende = 0.55 hectares).

Figure 6: Barley payments in 1662 and FAO barley suitability



Note: Coefficient $= 5.5173$, t-stat $= 5.55$, $N = 18$, $R^2 = 0.64$. Densities of barley payments calculated as the sum of barley payments divided by the county area.

Table 1: Results for the Danish dataset

	(1)	(2)	(3)	(4)	(5)
	Dependent variable: ln(1+Urbanization)				
	Clay	Clay with good barley suitability	Clay with all covariates	Clay for subsample Jutland	Clay (Ussing,1899) with all covariates
ln(1+PloughFraction) *I^{Post}	0.00169***	0.00153***	0.00168***	0.00063*	0.00185***
	(0.00031)	(0.00031)	(0.00049)	(0.00031)	(0.00041)
	[0.00028]	[0.00024]	[0.00038]	[0.00021]	[0.00045]
Distance Coast	No	No	Yes	Yes	Yes
ln(1+rye)	No	No	Yes	Yes	Yes
FE (Time and county)	Yes	Yes	Yes	Yes	Yes
Observations	650	650	650	364	624
R-squared	0.71	0.71	0.75	0.82	0.75

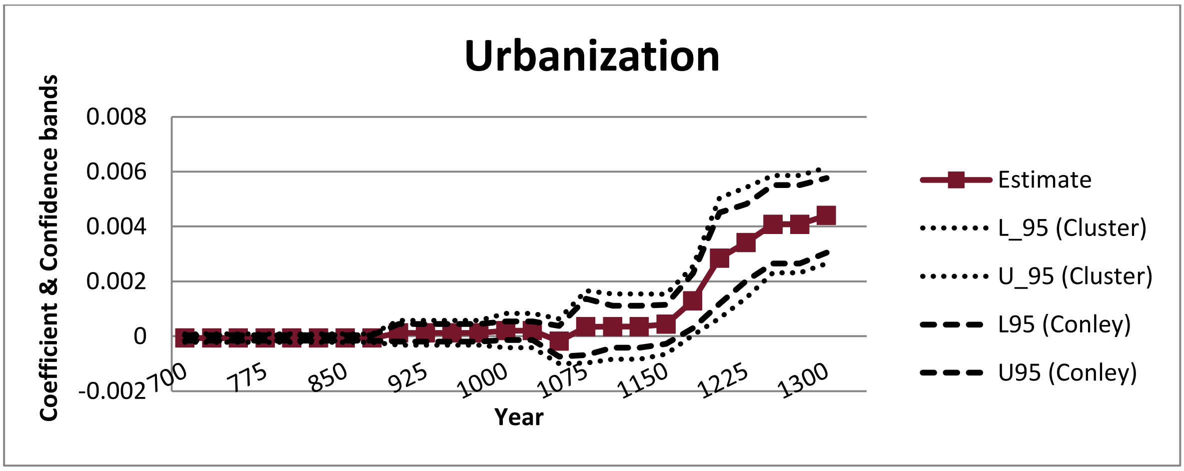
Notes: PloughFraction = fraction of county with clay (columns 1, 3, and 4), = fraction of county with clay and good barley suitability (column 2), = fraction of county with clay, based on Ussing, 1899 (column 5). Column 4 only includes counties in Jutland. Column 5 excludes one county due to the extent of the Ussing 1899 map. $I^{Post} = 1\, if\, year \geq 1000.$ Controls interacted with time fixed effects. Clustering at county level. Cluster-robust standard errors in parentheses with corresponding significance levels: *** p<0.01, ** p<0.05, * p<0.1 Conley standard errors calculated for spatial autocorrelation within 200 km in square brackets.

Table 2: Robustness for the Danish dataset

	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent variable: ln(1+Urbanization)					
	Luvisol	Luvisol with good barley suitability	Clay without clayey sand soil	Clay with all covariates add latitude	Clay with all covariates add suitability	Clay with all covariates – linear model
ln(1+PloughFraction) *I^{Post}	0.00097*	0.00107**	0.00163***	0.00151**	0.00173***	
	(0.00050)	(0.00050)	(0.00024)	(0.00055)	(0.00056)	
	[0.00035]	[0.00034]	[0.00020]	[0.00043]	[0.00040]	
PloughFraction* I^{Post}						0.00116***
						(0.00031)
						[0.00023]
Distance Coast	No	No	No	Yes	Yes	Yes
ln(1+rye)	No	No	No	Yes	Yes	Yes
FE (Time and county)	Yes	Yes	Yes	Yes	Yes	Yes
Observations	650	650	650	650	546	650
R-squared	0.68	0.68	0.72	0.79	0.80	0.75

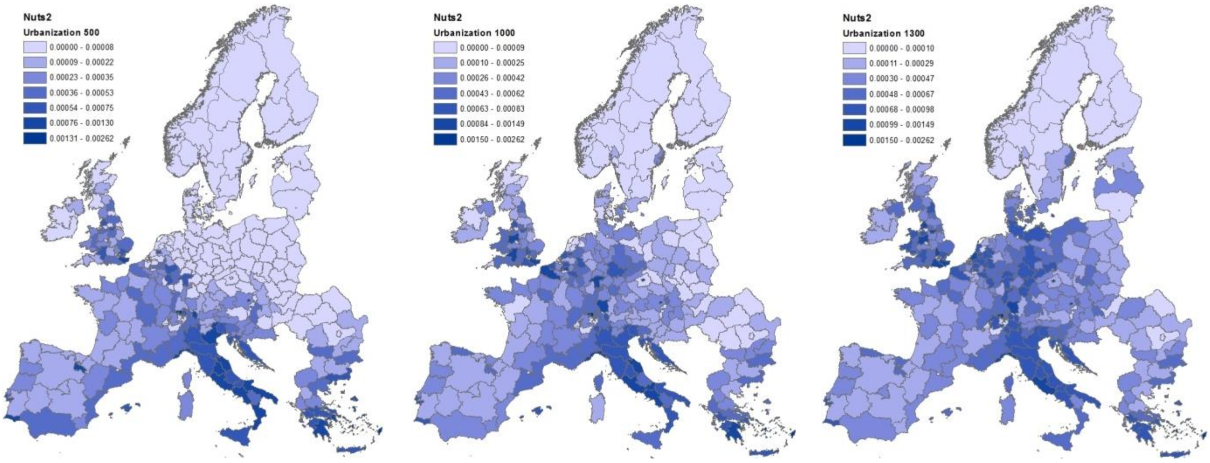
Notes: PloughFraction = fraction of county with luvisol (column 1), fraction of county with luvisol and good barley suitability (column 2), = fraction of region with clay but not clayey sand (column 3), = fraction of county with clay (columns 4, 5, and 6). $I^{Post} = 1\, if\, year \geq 1000.$ Controls interacted with time fixed effects. Clustering at county level. Cluster-robust standard errors in parentheses with corresponding significance levels: *** p<0.01, ** p<0.05, * p<0.1 Conley standard errors calculated for spatial autocorrelation within 200 km in square brackets.

Figure 7: The effect of the heavy plough on urbanization in Denmark



Notes: Estimates correspond to the flexible model of column 3 in Table 1. Clustering on county level (25 clusters), Conley standard errors calculated for spatial autocorrelation within 200 km.

Figure 8: Urbanization in Europe AD 500, 1000 & 1300 at NUTS 2 level



Source: EurAtlas and own calculations

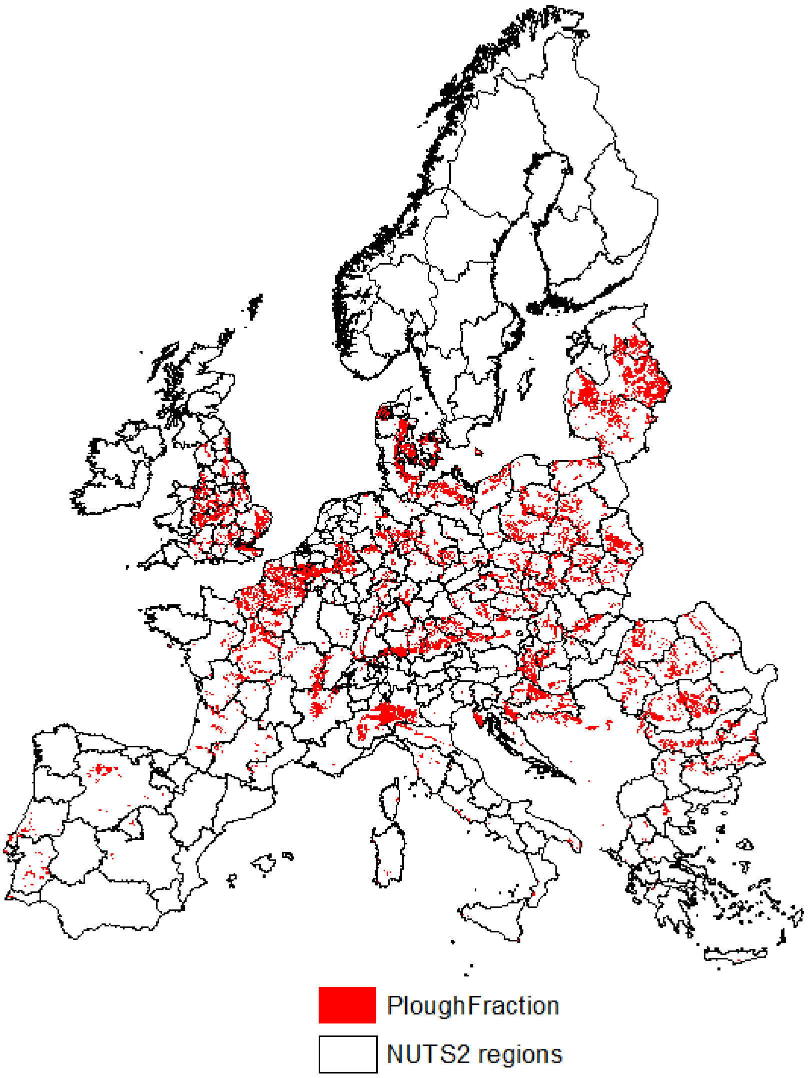


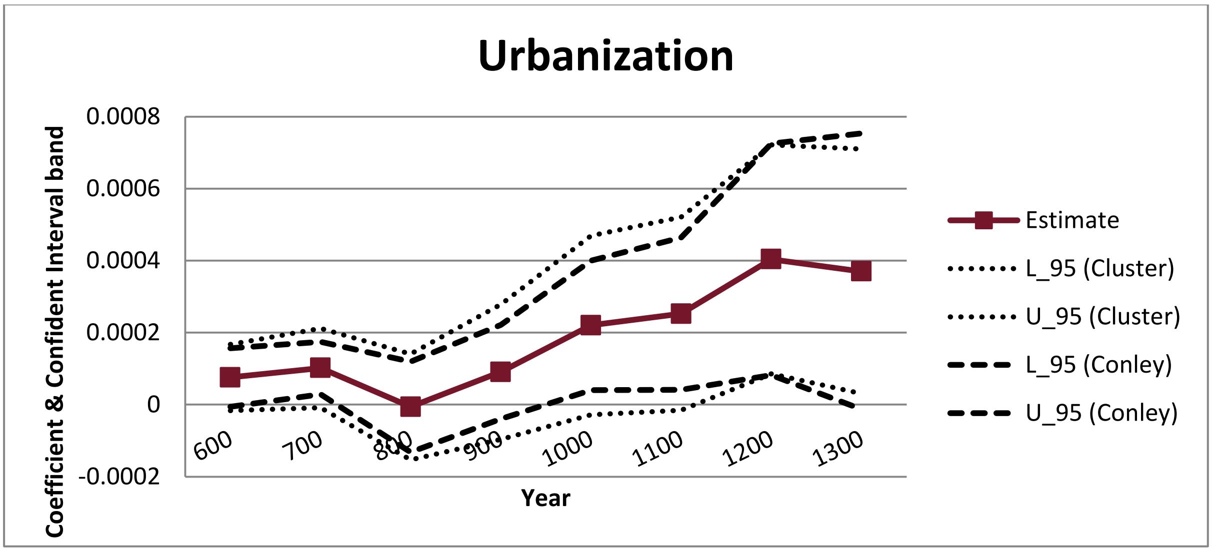
Figure 9: Distribution of "*PloughFraction(55)*" in Europe

Table 3: Results for the European dataset

	(1)	(2)	(3)	(4)
	Dependent variable: ln(1+Urbanization)			
	Non-Flexible		Flexible	
ln(1+PloughFraction(55))*I^{Post}	0.00031*** (0.00011)	0.00026** (0.00011)		
ln(1+PloughFraction(55)) *I^{600}			0.00005 (0.00005)	0.00008 (0.00005)
ln(1+PloughFraction(55)) *I^{700}			0.00007 (0.00006)	0.00010* (0.00006)
ln(1+PloughFraction(55)) *I^{800}			0.00001 (0.00006)	-0.00001 (0.00007)
ln(1+PloughFraction(55)) *I^{900}			0.00012 (0.00009)	0.00009 (0.00010)
ln(1+PloughFraction(55)) *I^{1000}			0.00024** (0.00012)	0.00022* (0.00013)
ln(1+PloughFraction(55)) *I^{1100}			0.00030** (0.00013)	0.00025* (0.00014)
ln(1+PloughFraction(55))*I^{1200}			0.00043*** (0.00015)	0.00040** (0.00016)
ln(1+PloughFraction(55))*I^{1300}			0.00047*** (0.00017)	0.00037** (0.00017)
Controls (x Year fixed effects):				
Roman Heritage	No	Yes	No	Yes
Rye	No	Yes	No	Yes
Universities	No	Yes	No	Yes
Distance Coast	No	Yes	No	Yes
Mean Temperature	No	Yes	No	Yes
FE (Time and Region)	Yes	Yes	Yes	Yes
Observations	2,421	2,421	2,421	2,421
R-squared	0.89	0.89	0.96	0.97

Notes: PloughFraction(55) = fraction of region with luvisol and good barley suitability ($SI \geq 55$). $I^{Post} = 1$ if year ≥ 1000. Clustering on NUTS 2 level. Cluster-robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Figure 10: The effect of the plough on urbanization



Notes: Main specification (table 3, column 4). Clustering on NUTS 2 level (269 clusters), Conley standard errors calculated for spatial autocorrelation within 500 km.

Table 4: Alternative dates of introduction

	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent variable: ln(1+Urbanization)					
Post:	700-800	800-900	900-1000	1000-1100	1100-1200	1200-1300
Years:	500-800	600-900	700-1000	800-1100	900-1200	1000-1300
Panel A1: Region and time FE						
ln(1+PloughFraction(55))*I^{Post}	0.00002 (0.00005)	0.00000 (0.00006)	0.00014* (0.00008)	0.00021** (0.00008)	0.00019** (0.00008)	0.00018** (0.00009)
Observations	1,076	1,076	1,076	1,076	1,076	1,076
R-squared	0.92	0.93	0.95	0.95	0.95	0.95
Panel A2: Main specification						
ln(1+PloughFraction(55))*I^{Post}	0.00001 (0.00005)	-0.00005 (0.00007)	0.00010 (0.00008)	0.00019** (0.00009)	0.00017** (0.00008)	0.00015 (0.00010)
Observations	1,076	1,076	1,076	1,076	1,076	1,076
R-squared	0.92	0.93	0.95	0.95	0.95	0.95

Notes: The dependent variable is urbanization. For each dependent variable panel 1 shows estimates with no covariates and panel 2 our main specification controlling for Roman heritage, rye, universities, distance to the coast and mean temperature. Dummies capturing time and regional fixed effects (FE) are included in all estimations. PloughFraction(55) = fraction of region with luvisol and good barley suitability ($SI \geq 55$). $I^{Post} = 1$ if year ≥ 1000. Clustering at NUTS 2 level. Cluster-robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 5: Alternative Plough fraction measures

	(1) Wheat(55)	(2) Barley(40)	(3) Barley(70)	(4) Unadjusted	(5) With Gleysol	(6) With Albeluvisol	(7) Potato placebo
ln(1+PloughFraction) *I^{Post}	0.00024** (0.00011)	0.00023** (0.00011)	0.00033** (0.00016)	0.00015* (0.00009)	0.00036*** (0.00010)	0.00021** (0.00010)	
ln(1+PotatoFraction) *I^{Post}							0.00008 (0.00010)
Observations	2,421	2,421	2,421	2,421	2,421	2,421	2,421

Notes: Dependent variable is ln(1+urbanization). Main specification controlling for Roman heritage, rye, universities, distance to the coast and mean temperature. Dummies capturing time and regional fixed effects (FE) are included.

Table 6: Other robustness checks

	(1) Quadratic temperature	(2) Linear model	(3) Latitude	(4) Carolingian Empire control	(5) Alternative Roman Heritage	(6) Clustering At Country level
ln(1+PloughFraction) *I^{Post}	0.00025** (0.00011)		0.00022* (0.00012)	0.00027** (0.00012)	0.00026** (0.00011)	0.00026* (0.00013)
PloughFraction		0.00020** (0.00010)				
Observations	2,421	2,421	2,421	2,421	2,421	2,421

Notes: Dependent variable is ln(1+urbanization). Main specification controlling for Roman heritage, rye, universities, distance to the coast and mean temperature. Dummies capturing time and regional fixed effects (FE) are included

Appendices A-G for
"The Heavy Plough and the Agricultural Revolution in Medieval Europe."
(Intended as supplementary material – not intended for publication).

Appendix A: Control variables

Rye

A measure controlling for the adoption of rye is calculated as the share of each county/NUTS region with very high suitability for growing rye. The suitability measure comes from a raster map from the Global Agro-ecological Assessment 2002.

Distance to the coast

The variable is constructed as the distance from the centroid of each county/NUTS region to the nearest coast calculated in ArcGIS.

Roman heritage

Roman heritage is coded as 1 if the region was once occupied by the Roman Empire and zero otherwise. Data on Roman occupation are based on Langer (1972). The countries with Roman heritage are Belgium, Britain, France, Italy, Netherlands, Portugal, Spain, and Switzerland.

Universities

We calculate the number of universities in each NUTS region for each century. The variable is coded as the sum of universities founded before a given century. Data on university foundations are from Verger (1992).

Temperature

Guiot et al. (2010) have estimated gridded summer-spring temperature for each year back in time until AD 600. The estimations are based on tree-rings, historical written documents, pollen assemblages, and ice cores. To obtain a measure for each century and region we interpolate the data for each century using inverse distance weights[1] and afterwards calculate the mean temperature for each turn of century from AD 700 to 1300 for each region. The mean is based on the temperatures for the preceding and following fifty years. (Data only go

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[1] See Appendix G for a description of the method.

back to AD 600 so the mean temperature in AD 600 is based on the mean from 600 to 649. We make the crude assumption that the mean temperature in 500 is the same as in 600, but our results are robust to excluding AD 500.) An alternative method, to which our results are robust, is allocating a temperature to each NUTS region from the measurement of the gridded data that is closest to the centroid of the region.

The power parameter used in the interpolation is two. The number of observations used as neighbors is seven. Figure A1 shows the estimates of the average temperatures for AD 1000 on NUTS 2 level and the 5 x 5 degree geographical distribution of the measurements they are based on:

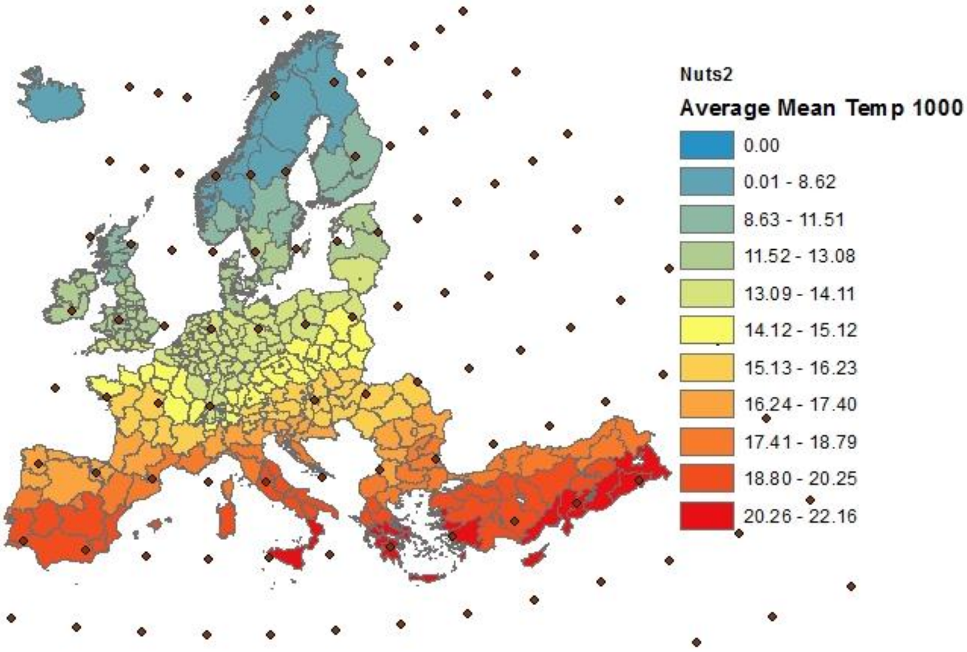


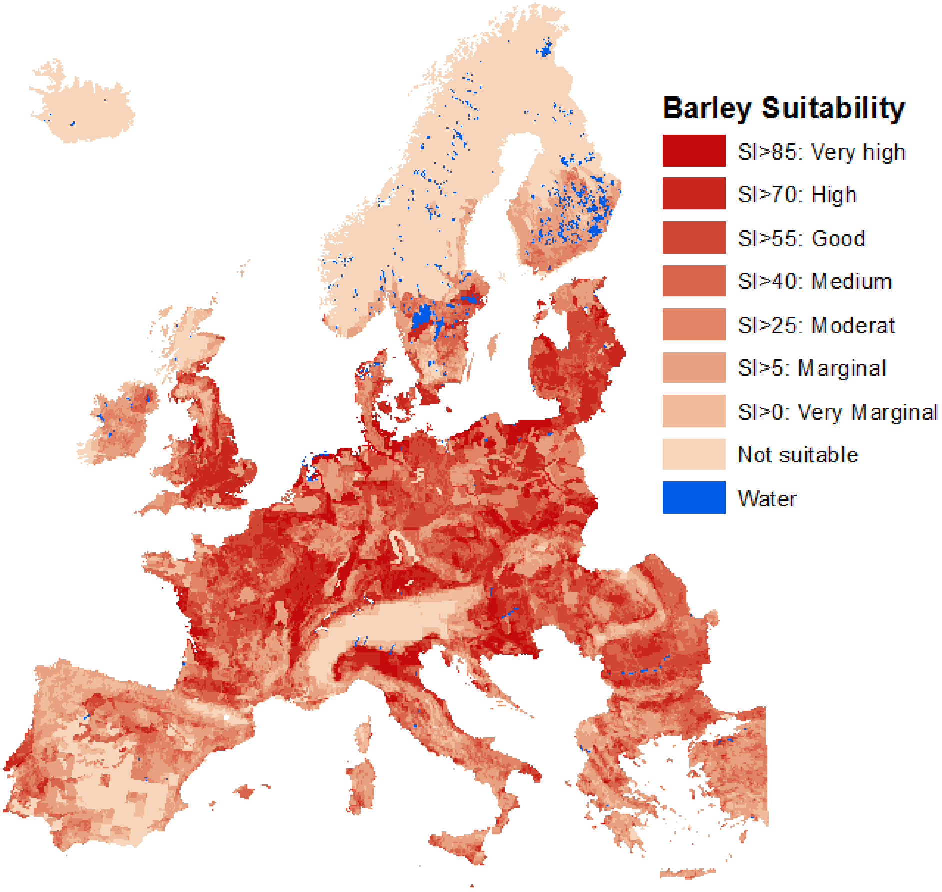
Figure A1: IDW average temperature in AD 1000 on NUTS 2 level

Appendix B: Descriptive Statistics

Variable	Number of observations	Mean	Standard deviation	Min	Max	Definition
Danish sample						
Urbanization	650	0.0005	0.0008	0.0000	0.0036	Number of towns per square kilometer
Distance to coast	650	10209.6	7541.8	0.0000	29454	Distance from the centroid to the coast in meters
Rye	650	0.0390	0.0835	0.0000	0.3745	Share with very high suitability for growing rye
Luvisol share	650	0.4781	0.2996	0.0000	0.9425	Fraction with luvisol
Clay share	650	0.6465	0.3264	0.0159	0.9792	Fraction with clay soil
European sample						
Urbanization	2421	0.000342	0.000373	0	0.002622	Number of cities per square kilometer
Population density	2421	10.52863	14.00224	0.009202	312.5913	Average population per square kilometer
PloughFraction (55)	2421	0.100194	0.124867	0	0.933831	Fraction with luvisol and good suitability for growing barley
PloughFraction (55, barley + gleysol)	2421	0.130462	0.159400	0	0.933831	Fraction with luvisol or gleysol and good suitability for growing barley
Roman heritage	2421	0.460967	0.498577	0	1	Indicator being 1 if once occupied by the Romans
Rye	2421	0.057716	0.105481	0	0.662891	Share with very high suitability for growing rye
Universities	2421	0.005783	0.081106	0	2	Number of universities founded before the given century
Distance to coast	2421	133494	126962	0	551854	Distance from the centroid to the nearest coast in meters
Mean temperature	2421	14.77275	2.764674	4.530412	21.96702	Average temperature calculated as the mean of each region for the inter-polations of every century

Appendix C: Soil and suitability maps

Figure C1: Barley suitability in Europe



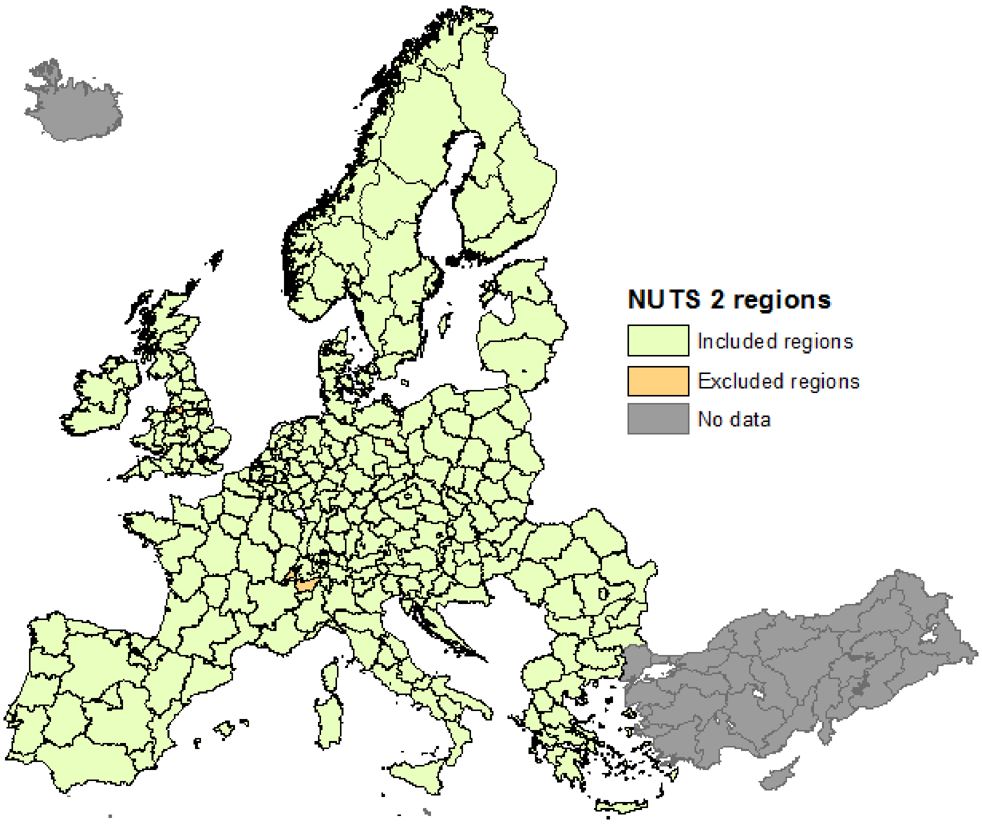
Source: GAEZ, FAO 2002.

For each cell (0.5 x 0.5 degrees) a suitability index (SI) is calculated as a weighted average of the parts of the cell that are "Very Suitable" (VS), "Suitable" (S), "Moderately Suitable" (MS) or "marginally Suitable" (mS). The weights used in the calculation are

$$SI = VS * 0.9 + S * 0.7 + MS * 0.5 + mS * 0.3.$$

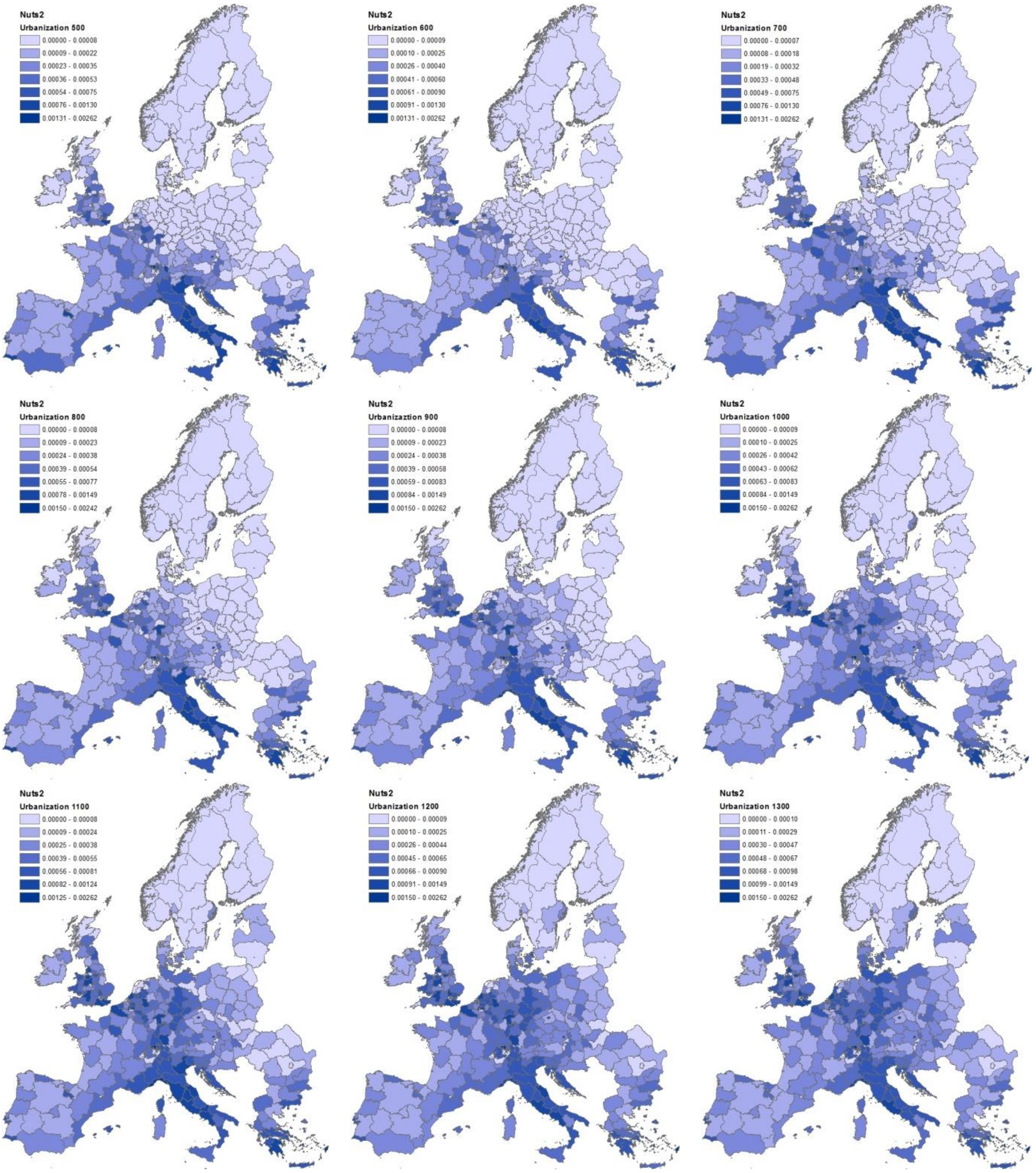
The classification is determined in the following way. First each cell is characterized as either suitable or unsuitable for cultivation from a number of climatic and geographic constrains. Then the maximum obtainable yield is estimated as the constrain-free yield. For the suitable cells the suitability of land is then determined as the percentage of maximum obtainable yield. That is, the parts of the cell with attainable yields of 80% or above the maximum potential yield are classified as "VS". Parts that attain only 60-80% of maximum yields are classified as "S" and so on: as "MS": 40-60%, as "mS": 20-40%.

Figure C2: NUTS 2 regions and geographical coverage



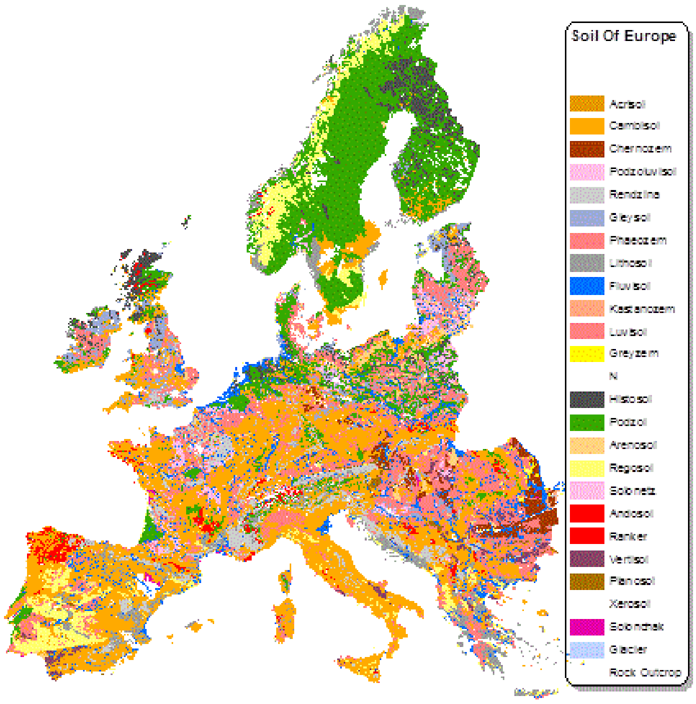
Note: Excluded regions are regions with more than 20 % undefined soil.

Figure C3: Average urbanization in Europe AD 500-1300 at NUTS 2 level



Source: EurAtlas and own calculations

Figure C4: Distribution of soil in Europe, dominant soil



Source: The European Soil Database

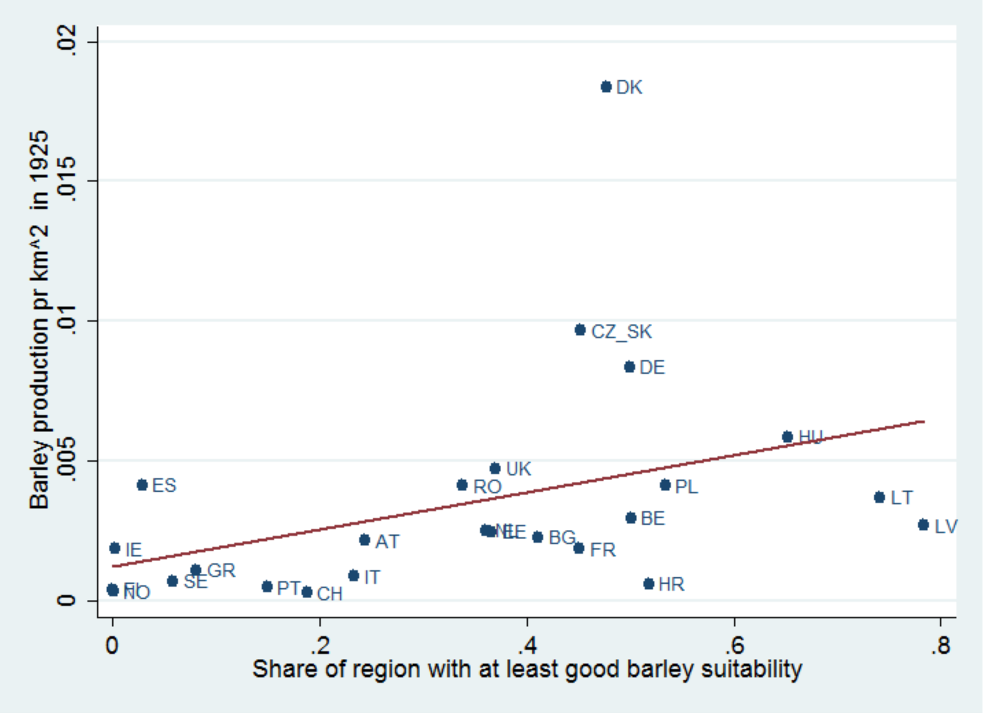
Appendix D: Modern and historical soil maps and the use of luvisol.

In this appendix, we probe into 1) the use of present-day suitability for growing plough-positive crops and 2) the use of luvisol for identifying the location of clay soils.

Use of present-day soil suitability

We begin by correlating the FAO suitability measure at a national level with the actual barley production in metric tons in 1925 per square kilometer from Mitchell (2007).[2] The scatter plot shows a positive and significant correlation between the two; see figure D1. While the relation is not very strong at the national level in terms of fit, we expect it to be much stronger in sub-national data given the regional variation present in the map shown in figure C4. We can dig further into this by using county level data from the agricultural census of 1886 for Prussia. This census covers historical counties for Prussia, which covers a large part of present day Germany as well parts of Poland and southern Denmark. Figure D2 demonstrates a positive and significant relationship between the FAO suitability measure and historic yields. The Danish data reported in the main text also speaks to this, and we see that all results go in the same direction, see Figures 4 and 6.

Figure D1: Barley production in 1925 and FAO suitability



Note: Coefficient $= 0.0066$, t-stat $= 2.04$, $N = 25$, $R^2 = 0.116$.

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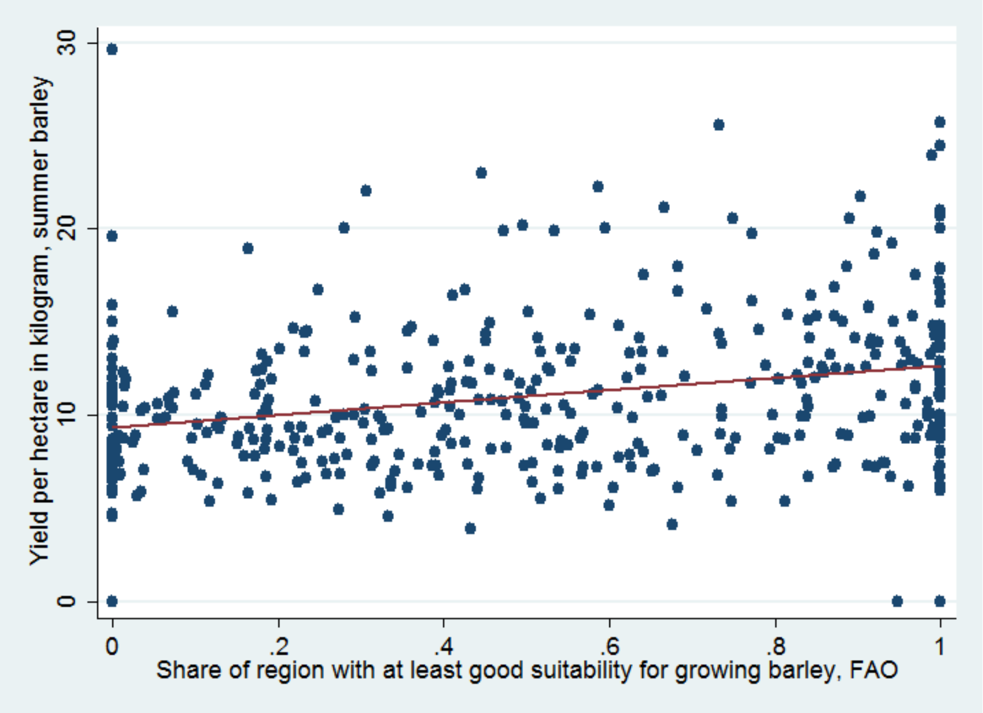
[2] Entries nominated in hectoliter have been converted into 'metric tons' by multiplying with 0.077.

Figure D2: Historical summer barley yields and FAO barley suitability

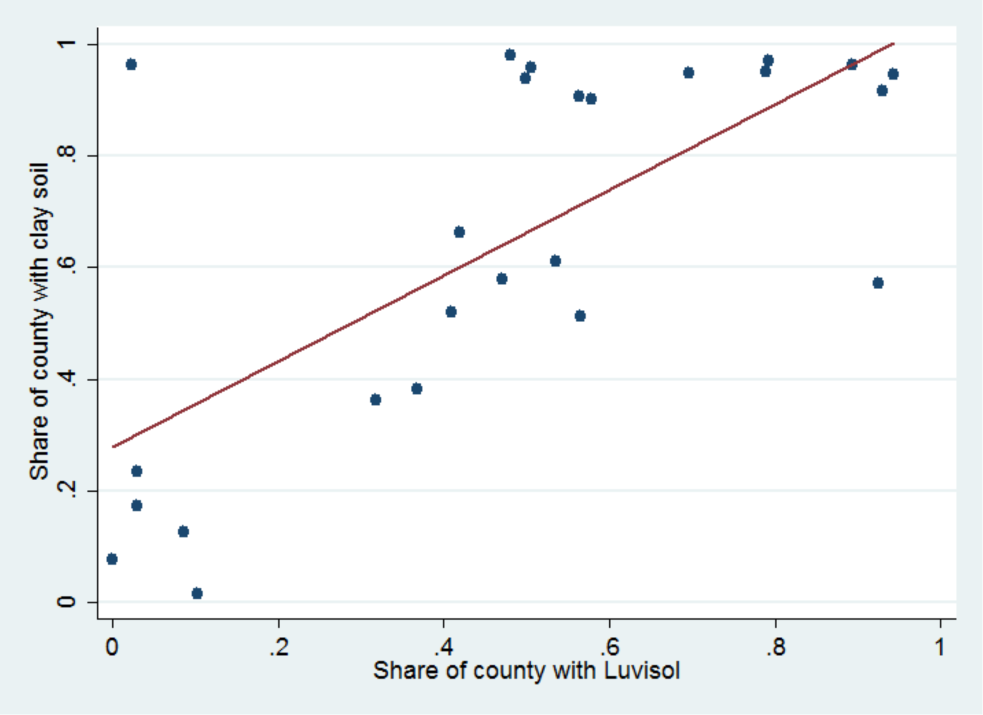


Note: Coefficient $= 3.2935$ t-stat $= 6.09, N = 431, R^2 = 0.078$.

Use of luvisol for identifying clay soils

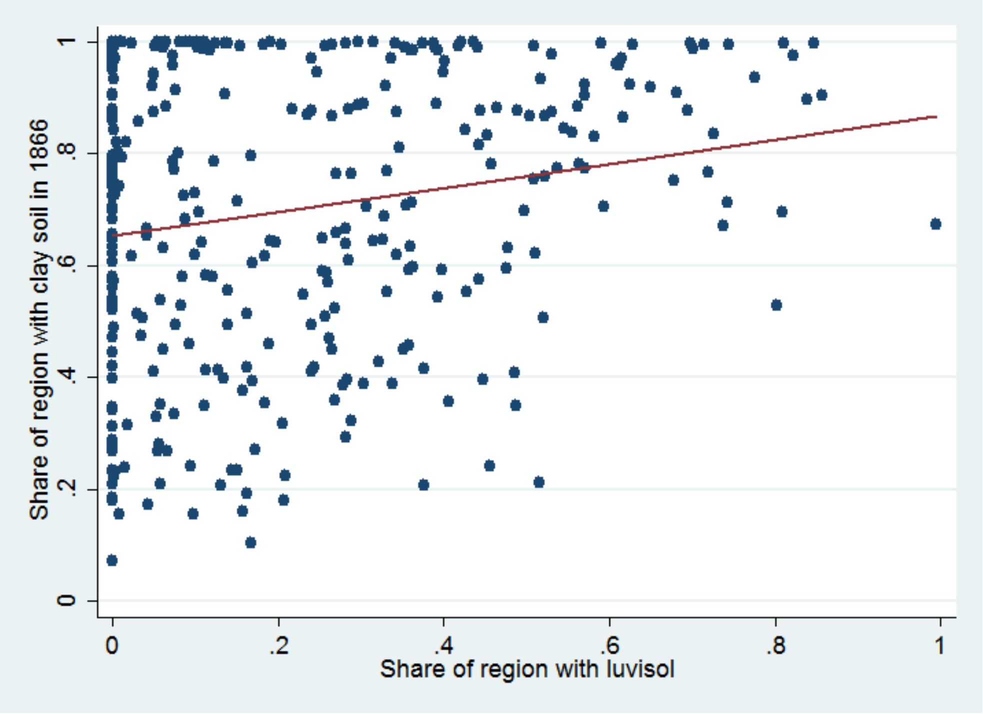
We have already reported some results on the location of clay soils and luvisol for the case of Denmark. Figure D3 shows that the relationship is positive and statistically significant. As mentioned in the text, one county Sorø is an outlier. We have also investigated this using data for the Prussian Economic History Database, which has data for 334 counties in Prussia. These data also confirm at positive association between clay soils and luvisol, see figure D4.

Figure D3: Luvisol and historic clay soil in Denmark



Note: Coefficient $= 0.768$, t-stat $= 4.01$, $N = 25$, $R^2 = 0.497$.

Figure D4: Luvisol and historic clay soils in Prussia

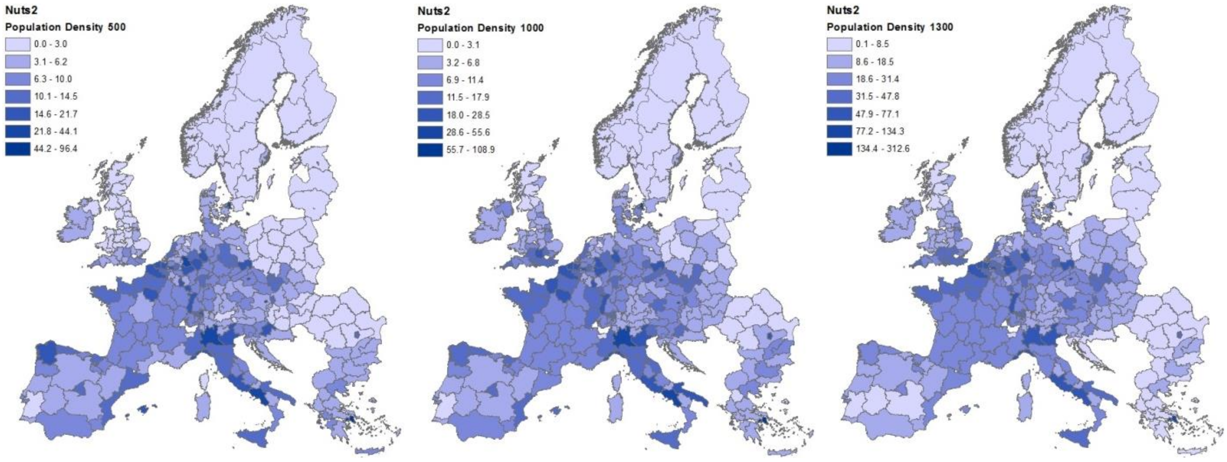


Note: Coefficient $= 0.2156$, t-stat $= 4.19$, $N = 334$, $R^2 = 0.036$.

Appendix E: Further robustness and information on urbanization data.

In this appendix we consider whether the results are robust to replacing urbanization measures by population density as visualized in Figure E1. We also include some more flexible estimation results. We finally include additional information on the urbanization data and the *PloughFraction* measure used in the European case.

Figure E1: Average population density in Europe AD 500, 1000 & 1300 at NUTS 2 level



Source: Goldewijk (2010) and own calculations

Population density data

The focus on population density is usually rationalized by invoking Malthusian thinking (Nunn and Qian 2011). In a Malthusian model, a one-off positive productivity shock—as brought about by the heavy plough—is fully offset by fertility increases. Income per person may increase in the short run; in the long run, however, any such increase is completely offset by increased fertility and income per person therefore stays constant and population levels are permanently higher (Ashraf and Galor 2011).

Obtaining population density data at the regional level is possible but not unproblematic for reasons that will be discussed below. We use gridded population density data from the HYDE database,[3] which was developed under the authority of the Netherlands Environmental Assessment Agency. The measure is based on historical national population data such as McEvedy and Jones (1978), Livi-Bacci (2007), Maddison (2001), and Denevan (1992), supplemented by historical subnational data (Klein Goldewijk et al. 2010; 2011). The first problem with these data is that for periods before the 18th century they are not constructed on

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[3] Klein Goldewijk (2010), Hyde Database: http://themasites.pbl.nl/en/themasites/hyde/index.html

the basis of national censuses. The first census in continental Europe was that of Sweden in 1749, and data before this time are scarce meaning that some data are "guesstimates" (McEvedy and Jones 1978).[4] The second problem is that to construct gridded data, the researchers who produced the HYDE database relied on various geographical weights. They stress that these weights are unchanged over time and that only population density and the amount of agricultural area change over time, which suggests that geographical weights could be captured by regional fixed effects. We calculate the average population density at the NUTS 2 level for each century of our observation period.[5] While this variable is constructed, it correlates positively with our measure of urbanization.[6] Given that our urbanization indicator is not a constructed measure, this suggests that the constructed population density measures to some extent track economic development.

Regarding the results with this measure, Table E1 shows that the coefficient on *PloughFraction* is positive and significant in the non-flexible model with and without control variables. We observe a positive effect from AD 900 onwards, which increases over time. While, the quality of these data should be kept in mind when interpreting the results, they are largely in line with our general findings with the urbanization measures.

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[4] Recent research, which uses McEvedy and Jones's data include Nunn and Qian (2011) and Ashraf and Galor (2011).

[5] See Figure C3 in Appendix C

[6] The correlation coefficient is 0.43.

Table E1: Results for population density

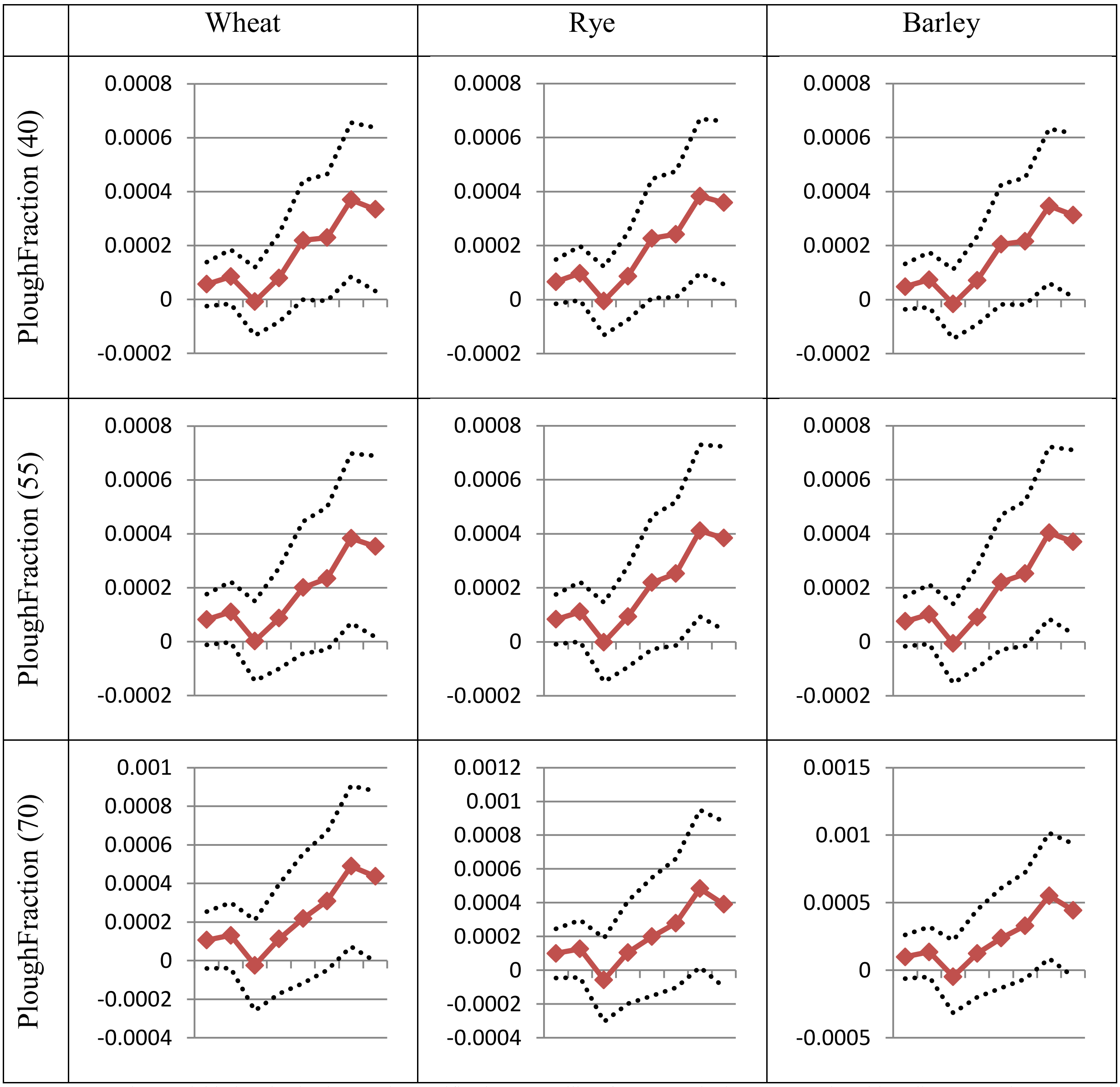
	(1)	(2)	(3)	(4)
	Dependent variable:			
	ln(Population density)		ln(Population density)	
ln(1+PloughFraction(55))*I^{Post}	0.557*** (0.215)	0.612*** (0.210)		
ln(1+PloughFraction(55)) *I^{600}			-0.123 (0.151)	-0.249* (0.142)
ln(1+PloughFraction(55)) *I^{700}			-0.115 (0.133)	-0.322*** (0.120)
ln(1+PloughFraction(55)) *I^{800}			0.081 (0.102)	-0.025 (0.081)
ln(1+PloughFraction(55)) *I^{900}			0.310** (0.153)	0.324** (0.152)
ln(1+PloughFraction(55)) *I^{1000}			0.418** (0.209)	0.505** (0.213)
ln(1+PloughFraction(55)) *I^{1100}			0.459** (0.210)	0.527** (0.207)
ln(1+PloughFraction(55))*I^{1200}			0.669*** (0.237)	0.585** (0.232)
ln(1+PloughFraction(55))*I^{1300}			0.803*** (0.274)	0.616** (0.263)
Controls (x Year fixed effects):				
Roman Heritage	No	Yes	No	Yes
Rye	No	Yes	No	Yes
Universities	No	Yes	No	Yes
Distance Coast	No	Yes	No	Yes
Mean Temperature	No	Yes	No	Yes
FE (Time and Region)	Yes	Yes	Yes	Yes
Observations	2,421	2,421	2,421	2,421
R-squared	0.89	0.89	0.96	0.97

Notes: PloughFraction(55) = fraction of region with luvisol and good barley suitability ($SI \geq 55$). $I^{Post} = 1$ if year $\geq$ 1000. Clustering on NUTS 2 level. Cluster-robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Flexible models with different measures of PloughFraction

Figure E2 shows that the results shown in Figure 10 in the paper are robust to changing soil suitability and crop type.

Figure E2: Flexible estimates for different crops and suitability levels



Notes: Dependent variable is urbanization. Main specification controlling for Roman heritage, rye, universities, distance to the coast, and mean temperature. Dummies capturing time and regional fixed effects (FE) are included. PloughFraction(SI) = fraction of region with luvisol and crop suitability according to the figure. Clustering at NUTS 2 level. Dashed lines show upper and lower 95 % confidence bands.

Additional Information on urbanization datasets

Table E2: List of Danish towns and the year of establishment from Jensen (2010)

Town	Year	County	Town	Year	County
Ribe	700	Ribe	Nykøbing M.	1200	Thisted
Århus	900	Århus	Lemvig	1200	Ringkøbing
Viborg	1000	Viborg	Grenå	1200	Randers
Roskilde	1000	Roskilde amtsrådskreds	Holstebro	1200	Ringkøbing
Aalborg	1050	Ålborg	Helsingør	1200	Frederiksborg
Odense	1050	Odense amtsrådskreds	Nykøbing S.	1200	Holbæk
Tønder	1050	Tønder	Kolding	1200	Vejle
Varde	1075	Ribe	Middelfart	1200	Assens amtsrådskreds
Ringsted	1075	Sorø	Kerteminde	1200	Odense amtsrådskreds
Slagelse	1075	Sorø	Tårnborg	1200	Sorø
Randers	1100	Randers	Store Heddinge	1200	Præstø
Horsens	1100	Skanderborg	Korsør	1200	Sorø
København	1100	København amtsrådskreds	Skælskør	1200	Sorø
Vejle	1100	Vejle	Præstø	1200	Præstø
Haderslev	1100	Haderslev	Stege	1200	Præstø
Næstved	1100	Præstø	Rudkøbing	1200	Svendborg
Hjørring	1150	Hjørring	Ærøskøbing	1200	Svendborg
Svendborg	1150	Svendborg	Sakskøbing	1200	Maribo
Hobro	1175	Randers	Sæby	1225	Hjørring
Skive	1175	Viborg	Ebeltoft	1225	Randers
Holbæk	1175	Holbæk	Ringkøbing	1225	Ringkøbing
Kalundborg	1175	Holbæk	Køge	1225	Roskilde amtsrådskreds
Bogense	1175	Odense amtsrådskreds	Herrested	1225	Svendborg
Nyborg	1175	Svendborg	Rønne	1225	Bornholm
Assens	1175	Assens amtsrådskreds	Nysted	1225	Maribo
Fåborg	1175	Svendborg	Rødby	1231	Maribo
Aabenraa	1175	Åbenrå	Søborg	1240	Frederiksborg
Vordingborg	1175	Præstø	Slangerup	1240	Frederiksborg
Sønderborg	1175	Sønderborg	Skibby	1240	Frederiksborg
Stubbekøbing	1175	Maribo	Stigs Bjergby	1240	Holbæk
Nakskov	1175	Maribo	Neksø	1300	Bornholm
Nykøbing F.	1175	Maribo			

Table E3: Number of European cities for each century, based on EurAtlas

Century	Number of cities
500	804
600	748
700	772
800	851
900	948
1000	1100
1100	1205
1200	1358
1300	1492

Table E4: Bairoch city data

Country	800	900	1000	1200	1300	All Bairoch cities
Austria	.	.	.	1	3	17
Belgium	.	.	4	8	17	72
Bulgaria	1	1	3	2	10	22
Suisse	.	.	1	3	6	19
Czechoslovakia	.	.	1	1	17	36
Germany	9	2	14	20	74	245
Denmark	.	.	.	.	1	10
Spain	9	4	23	11	46	265
Finland	.	.	.	.	.	8
France	9	2	21	31	85	341
Greece	1	1	2	1	7	24
Hungary	.	.	1	.	2	47
Ireland	1	1	2	5	13	22
Italy	5	5	14	31	115	406
Luxemburg	.	.	.	.	.	1
Nederland	.	.	.	1	16	60
Norway	.	.	.	.	3	10
Poland	.	.	.	4	7	55
Portugal	1	1	1	3	10	53
Romania	.	.	.	1	8	34
Sweden	.	.	.	2	8	20
United Kingdom	.	.	15	5	27	165
Sum	36	18	113	138	499	2204

Table E4 demonstrates that there are many years for which there are no city population data available as indicated by "." which denotes missing. Even so, the EurAtlas and the Danish data on foundations of cities and towns demonstrate that urbanization was going on.

Table E5: Distribution of PloughFraction(55) across present day countries

Country	PloughFraction(55)	Country	PloughFraction(55)
Austria	5,9	Italy	6,4
Belgium	20,7	Liechtenstein	0,0
Bulgaria	10,8	Lithuania	19,4
Suisse	2,7	Luxemburg	0,8
Czech Republich	13,6	Latvia	41,6
Germany	14,2	Macedonia	0,0
Denmark	27,3	Nederland	4,8
Estonia	13,8	Norway	0,0
Spain	0,5	Poland	16,4
Finland	0,0	Portugal	4,7
France	10,3	Romania	10,3
Greece	1,2	Sweden	0,0
Croatia	17,9	Slovenia	3,2
Hungary	12,5	Slovakia	7,3
Ireland	8,9	United Kingdom	11,8

Table E5 shows higher shares of fertile heavy clay soils in the temperate zone of Europe and significantly lower shares in the Mediterranean zone and in the Snow Forrest climate of the very Northern parts of Europe. Although significantly lower shares in the Mediterranean zone suitable areas did exist.

Appendix F: Introduction and breakthrough of the heavy plough across modern states

The table below describes the historical evidence on the introduction and breakthrough of the heavy plough on a present country level, and in some case at sub-national level.

Countries	Break-through/introduction of heavy ploughs in Europe
Austria	David B. Grigg (1974, p. 163) argues that settlement in Austria was part of German expansion and Austrian settlements were founded in 800-1100.
Gaul: Belgium, Switzerland, Luxembourg, France, Northern Italy.	Evidence from Gaul: Raepsaet (1997, p. 59) argues that ”the complete plough, with its three fundamental parts-coulter, symmetrical or asymmetrical ploughshare, and mouldboard-is well attested in the thirteenth century, so it was probably known well before. […] a ploughing instrument with coulter was known in Roman Gaul.”
Bulgaria, Estonia, Latvia, Lithuania, Romania, Slovenia, Slovakia.	Bartlett (1993, pp. 148-152) suggests that the heavy plough was introduced into Eastern European during the 12th and 13th century from Germany.
Czech Republic	Duby (1968, p. 18) cites evidence that the plough was introduced in Moravia between the 7th and 8th century. In contrast, Pounds (1974, p. 196) notes that a thirteenth-century fresco at Znojmo (Moravia) show King Premysl of Bohemia with a simple hooked plough pulled by two oxen. On the introduction he argues that “There can be little doubt that that the heavy wheeled plough with mouldboard was introduced from the west”. The latter point is also made by Bartlett (1993). The painted evidence may have been deliberately archaic (Pounds 1974).
Germany	Earliest evidence of heavy ploughs in Feddersen-Wierde south of the Elbe dated till the last century before the birth of Christ (Grau-Møller 1990, p. 94; Hardt 2003:p. 26). May have spread to Schleswig in Northern Germany and Southern Denmark (Hardt, 2003, pp. 28-29). Poulsen (1997, p. 127) notes that “the diffusion north to Denmark and to the rest of Northern Germany at any rate clearly took place much later. From radiocarbon dates of parts of Danish ploughs found in Moors, the earliest is the Navndrup beam from Jutland with a calibrated date of 1285.” As in other places where evidence exists of high-backed ridges, these date back to the Middle Ages or early Middle Ages (Ehlers 2011, p. 325, Felgenhauer Schmidt 1993, p. 167).
Denmark	We summarize the Danish case in Section 2.2. As we note there, the earliest Danish high backed ridges date back to the year AD 1000 or later. The most certain case dates back to the 1100s, Grau-Møller (1990, pp.103-104).
Spain	”There may have been some wheeled, heavy plows in humid areas of the North (Catalonia, Galicia) as early as the eleventh century, but the evidence is inferential” Glick (1979, Chapter 7). Otherwise the ard was the main ploughing implement used in Spain (Fussell 1966, p. 183).
Finland	Knut Helle (2003, p. 266) notes that the plough was introduced from Estonia and Novrogod in the 13th century.

France	Heavy ploughs were known from ”at least the thirteenth century” Comet (1997, p. 24). See also Gaul. Ard was the main ploughing implement used in southern France (Fussell 1966, p. 183).
Greece	Alan Harvey (2003, p. 122) contends that the heavy plough was never introduced to Byzantium. Further, Laiou and Morrison (2007, p. 99) notes that the non-adoption of the heavy plough has been used to explain the relative decline of the Byzantine empire. This suggests that heavy ploughs were not adopted in Greece. They also note that an ard was more suitable for the soils of the Eastern Mediterranean region.
Hungary	“An important aspect of Hungary’s economic development was the adoption of new agricultural techniques. Here, too, the western part of the kingdom was most favored, for the innovations appeared first in western counties and from here slowly spread eastwards. The earliest example of an asymmetric heavy plough was found near Zemendorf in modern Burgenland” (Engel et al. 2005, p. 111). It follows from this that heavy ploughs reached Hungary later than Austria since Zemendorf is located in Austria. See also the reference to Bartlett in other entries. However, evidence by Henning (1987) of asymmetric shares in the Danube era suggests an earlier adoption.
Ireland	May have been introduced in Ireland around AD 600 (Hall, 1990, p. 380).
Italy	May have been used in the Po Valley (e.g. Pounds, 1973, p. 149). Otherwise the ard was the main ploughing implement used in Italy (Fussell 1966, p. 183).
Netherlands	Hoppenbrouwers (1997, p. 91) links the introduction of the heavy plough with the growth period 1000-1300. See also Belgium.
Norway	“In southern Norway the plough was adopted in the Viking Age (ninth to tenth centuries)” (Myrdal 1997, p. 155)
Poland	Bartlett (1993, pp.148-152) suggests that the heavy plough was introduced into Eastern European during the 12th and 13th century from Germany. Piskorski (1999) and Wedski (forthcoming) agree with this though Wedski notes that there is some controversy about this. According to Pounds (1974, p. 112): “The heavy plough, with its coulter and mouldboard, was essential if the heavy clays of the Polish plain were to be cultivated.”
Portugal	The ard was the main ploughing implement used in Portugal (Fussell 1966, p. 183). Payne (1973) notes that the heavy plough may have been introduced by the Suevi (a small Germanic tribe before 500)
Sweden	Myrdal (1997, 1999) argues that there is regional variation in adoption rates. Southern Sweden had the plough around AD 800-1000. Other areas of Sweden had adoptions from 1400-1500 and 1800, Myrdal (1999, p.52). The Earliest high-backed ridges are dated till the Middle Ages (Grau-Møller 1990, p. 6). In our main measure of PloughFraction, Sweden has no values, but if we use a broader definition as suggested by the Danish data, southern Sweden has some heavy-plough-suitable soils. As noted in footnote 53, this makes results stronger.
United Kingdom	“Seven (English) manuscript illustrations of ploughing dating to the late tenth and eleventh century exist. […] The archaeological evidence is scarce and entirely consists of iron shares and coulters.” (Astill 1997, p. 201) Earliest date of high backed ridges around AD 1000 (Grau-Møller 1990, p. 110). Medieval high backed ridges are also mentioned by Eyre (1956).

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Appendix G: Interpolation using inverse distance weights

When interpolating temperature data we have used the inverse distance weighted interpolation method. All interpolation methods are about defining the way to weight information from neighboring observations in order to obtain an estimate in each cell. The inverse distance weight method uses distance as the weight based on the presumption that closer information is more accurate. The estimate of the value in cell x_0 is calculated as

$$\hat{x}_0 = \sum_{i=1}^{N} \lambda_i x_i$$

where N is the number of neighbors taken into account, x_i is the value of observation i and λ_i is the weight of cell i given by

$$\lambda_i = \frac{d_{i0}^{-p}}{\sum_{i=1}^{N} d_{i0}^{-p}}$$

$$\sum_{i=1}^{N} \lambda_i = 1$$

The distance from observation i to the present cell is given by d_{i0}. Hence the weight is determined by the distance from the present cell to observation i, relative to the distances of all the other observations taken into account. The power parameter p determines how high a weight nearby observations should have. The higher the power parameter, the higher the weight on nearby observations.

Another way to interpolate is using the kriging method. The problem using this method is that it assumes stationarity; that is, the relation between points is the same given the distance. Ordinary kriging also assumes an unknown but constant mean. These assumptions are unlikely to hold given the geographical barriers and the geographical distribution, so relying on a more local approach such as the inverse distance weighted approach seems more appropriate.

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