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# The Heavy Plough and the Agricultural Revolution in Medieval Europe†

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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 led to increased population density and urbanization. White argued that it was impossible to take proper advantage of the fertile clay soils of Northern Europe before 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 across European regions as well as across Danish historical counties. Consistent with the hypothesis, we find that regions with relatively more fertile clay soil experienced higher urbanization and population growth after the heavy plough had its breakthrough, which was approximately around the closing of the first millennium AD. Our findings suggest that the heavy plough accounts for around 10% of the increase in urbanization and population density during the High Middle Ages.

**Keywords:** Heavy plough, medieval technology, agricultural productivity

**JEL Classification:** J1, N1, N93, O1, O33

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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 ploughshare, 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 into the soil of crop residues, green manure, animal manure, or other substances (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

[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 (Poulsen 1997; 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 in medieval Europe 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 and population density, 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. Our sample contains 268 regions and, to avoid confounding our analysis with the devastating impact of the Black Death, our window of observation is AD 500-1300. We implement our test under two alternative assumptions. The first assumption is that we know exactly when the diffusion of the plough took off in earnest. Under this assumption, a non-flexible model is appropriate. The alternative assumption is that the exact date is unknown but that it happened after AD 500. In this case, a flexible model is called for, as it allows us to assess when the plough began to have a detectable effect on our outcome variables for each century of the Middle Ages. As a supplement to the flexible specification, we also apply rolling regressions to further investigate the timing of the breakthrough of the heavy plough.

While the European data support the heavy plough hypothesis, these data are likely to suffer from measurement error. We have therefore constructed a new dataset for historical Danish counties with more precise measures for both urbanization and fertile clay soils. The Danish data allow us to test the hypothesis on an *independent* high-quality dataset.

We find evidence strongly consistent with White's hypothesis. With respect to the European sample, our estimations show that the heavy plough accounted for around 10% of the increase in population density and urbanization 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 Europe. We subject these findings to a number of checks. For instance, we show that our results are robust to *reasonable* alterations of our measure of soil suitability for using heavy ploughs; *unreasonable* alterations of the soil suitability measure, however, imply a vanishing impact. Specifically, we conduct a placebo-type experiment using soil suitability for growing the potato. This is a crop brought to Europe from the Americas in the Age of Discovery, which strongly influenced urbanization and population density in potato suitable areas after its introduction (Nunn and Qian 2011). Consistent with our identification strategy, potato suitability has no significant effect on local economic development in our sample period. With respect to the Danish sample, we also find strong evidence that counties 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 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. Second, we present evidence that increased agricultural productivity can be a powerful driver of economic development in an agrarian economy. Third, we provide a clear historical example of what Acemoglu et al. (2005a) 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). In particular, these authors stress that living standards became higher in North-West Europe compared to Mediterranean Europe after AD 1500. The paper considers a factor that contributed to regional differences in growth trajectories within Europe and also demonstrates regional differences in development within a particular European country, namely Denmark. In this way, the paper explores economic geography aspects usually not discussed in "the little divergence" literature.

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 in Europe. Section 3 outlines the empirical model. Section 4 describes our data. Sections 5 and 6 present the results. 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 Europe. Doing so provides us with knowledge that helps to guide our econometric 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 (Soil & Tillage 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 we noted above, the heavy plough has a number of advantages on clay soils. We next substantiate these advantages. 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. This has also been stressed by other authors who emphasize regional variation in the use of ards and ploughs even within Northern Europe (Myrdal 1997; Lerche 1994; Fowler 2002).

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). Some evidence on the relative advantage of the heavy plough on clay soils exists in the form of modern mouldboard ploughing tests. These tests 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). We will use this fact in the construction of our measures below.

[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".

## 2.2 Origin and diffusion of the heavy plough[3]

Establishing the origin and timing of the diffusion of the heavy plough is no easy task. It is, however, an important one because our empirical strategy relies on comparing European 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 plough marks, plough remains, and figurative representations as well as the 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.

Comet (1997, p.22) envisions the gradual evolution from ard to heavy plough as follows: "First the ancient ard was fitted with a coulter and a wheeled fore-carriage, which made it heavier and required more draught animals. The farmer could lean on the carriage, so that the ard became easier to steer and could be tilted to one side. With addition of a mouldboard and the development of asymmetric shares, the transition to the plough was made." According to this view, the development of the heavy plough is likely to have been gradual. This is one reason why it is difficult to pinpoint its exact origin and diffusion by relying on the existing evidence. Nonetheless, attempts to do so have been made. White (1962), for example, argues that Slavs may have introduced the heavy plough and that it therefore diffused from east to west starting in the late 6$^{th}$ century. Some of the evidence discussed below is in line with the view that the heavy plough was introduced in some parts of South Eastern Europe. Other authors have argued that it was invented by Germanic tribes and spread to Eastern Europe as part of the eastern expansion of the Germanic tribes (Bartlett 1993; Piskorski 1999).

For the period before AD 500, 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. 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.

[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*.

Other historians hold similar views. Fussell (1966), for example, concludes that for Europe as much evidence suggests that the heavy plough only came into general use as of the $11^{th}$ century and onwards. 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.

*Plough marks*

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 is some doubt as to whether a heavy plough in fact produced them.

First, 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.

Second, as discussed above, mouldboard ploughing is known to create fields with high-backed ridges. Thus, a stronger indicator of the breakthrough of the heavy plough is the presence of high-backed ridges, which—in contrast to the aforementioned furrows—only a heavy plough could have created (Poulsen 1997). Yet there are no high-backed ridges at Feddersen-Wierde (Grau-Møller 1990). High-backed ridges have been observed and dated in several countries, including Britain, Denmark, Germany, Netherlands, and Sweden. 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 around AD 1000. This conclusion is in line with the view of Fowler (2002), Fussel (1966), and others, as stated above.

*Plough remains*

Heavy ploughs and ards consist of different parts, see Figure 1. The most prominent part is the mouldboard, which therefore indicates most clearly the existence of heavy ploughs. Coulters and shares are also of interest but, as discussed below, there are important reasons for doubting whether or not these parts give definite evidence of the presence of heavy ploughs. The archaeological literature discusses discoveries and dating of mouldboards, shares, and coulters, and next we discuss the discoveries of these three parts in turn.

**Mouldboards:** Unfortunately, only few mouldboards have survived. Larsen (2011) discusses two from Denmark, but they have not been dated. 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 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.

The shares found in Feddersen-Wierde are all symmetrical (Felgenhauer-Schmidt 1993). This indicates the use of ards rather than heavy ploughs. The earliest evidence of asymmetrical shares comes from Roman Britain where three such parts have been found (Manning 1964; Wailes 1972). This is consistent with the existence of heavy ploughs, but it has been suggested by Wailes (1972) that asymmetrical ards have existed. Moreover, 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. 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 ploughshares dating back to the 11th century or later are discussed, and also in Larsen (2011), who reviews the evidence for Denmark and parts of present-day Sweden and Northern Germany. These asymmetrical shares can all be dated to the High Middle Ages or later.

Based on the British evidence, Fowler (2002, p. 203) concludes that “cultivating implements with coulters and large shares, but no proven mouldboard, were known in third- and fourth-century Southern Britain, and were probably the source of the similar implements attested in Western Britain and Ireland in the second half of the millennium.” The existing archaeological evidence therefore does not provide definitive evidence of the introduction of the heavy plough, although the evidence provided by Henning (1987) is consistent with a widespread adoption of asymmetrical heavy ploughs in the 7th-10th centuries in some areas.

*Figurative representations*

Depictions may indicate when a technology had its breakthrough, though important caveats are that it is sometimes difficult to date figurative representations and that it is not always clear whether an artist copied what “he saw, or rather what had inspired previous work of art or studio models” as argued by Duby (1968, pp. 390-391).

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 the late 11th century (Grau-Møller 1990; Fowler 2002; Jensen 2010). 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. Still other depictions of ploughing implements are found in the form of church paintings. For example, Larsen (2011) dates paintings depicting heavy ploughs to the 15th or 16th century for the case of Denmark. 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*

As already mentioned, White (1962) argues that the Slavic tribes introduced the heavy plough around AD 568. 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*.[4] 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 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'.[5]

*Summing up*

Our discussion of the evidence demonstrates that there are conflicting time periods for the introduction and 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. In Appendix F we provide further evidence, which shows that for many countries the breakthrough is believed to have happened around this time. Moreover, this particular dating (AD 1000) is corroborated by the presence of high-backed ridges from around this time. 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).[6]

In sum, we use the AD 1000 timing below. However, since there is ample uncertainty regarding this date, we also use estimation methods that allow for an uncertain breakthrough date.

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[4] 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.

[5] 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.

[6] 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.

## 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 adoption of the heavy plough in the Middle Ages and the *cross-sectional* variation arising from differences in regional suitability for adopting the heavy plough.[7] 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.[8] Given our historical period of interest, we focus on the period 500-1300.[9] As mentioned in Section 1, we also implement the test on Danish data, but we defer detailed discussion of these to Section 6.

We implement our test under two alternative assumptions. The first assumption is 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. We therefore estimate non-flexible models in which the post-treatment period is AD 1000 and onwards. The second assumption is that the exact date is unknown but that it happened some time after AD 500. 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 noticeable effect on agricultural productivity. As a supplement to the flexible models, we also apply rolling regressions of 400-year periods to further investigate the timing of the breakthrough of the heavy plough.

### 3.1 Non-flexible model

Our non-flexible model is given by the following equation:

$$\ln\, y_{it} = \beta \ln\left(1 + PloughFraction_i\right) I_t^{1000} + \sum_{j=500}^{1300} X'_i I_t^j \phi_j + \sum_R \lambda_R I_i^R + \sum_{j=500}^{1300} p_j I_t^j + \epsilon_{it} \qquad (1)$$

[7] A similar strategy is applied by Nunn and Qian (2011) in their evaluation of the impact of the introduction of the potato from the new to the old world and by Acemoglu et al. (2005b) in their evaluation of the gains from Atlantic trade opportunities.

[8] NUTS regions are divided into Five levels. Level 0 is the country level, level 1 mixes the regional and country level, and levels 2-4 contain the regional level, but level 4 only exists for Poland; thus, the degree of division increases with the level. The divisions are in most cases based on present national administrative subdivisions. Figure C1 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 28.

[9] 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.

In the equation, $t$ denotes time (centuries from 500-1300), $i$ denotes NUTS regions, $y_{it}$ is economic development, and $ln(1+PloughFraction_i)I_t^{1000}$ measures the interaction between the share of heavy-plough-suitable area[10] in region $i$ and the dummy variable $I_t^{1000}$ being 1 from AD 1000 and onwards, thus indicating our assumption that the heavy plough became widespread after this date. Our main coefficient of interest is $\beta$, which indicates the causal impact of having heavy-plough-suitable area (measured relative to the baseline period AD 500).[11] 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 century dummy variables; regional fixed effects, $I_i^R$; time fixed effects, $I_t^j$; and the error term, $\epsilon_{it}$. We postpone the discussion of control variables to Section 4.

### 3.2 Flexible model

The flexible model is described by:

$$\ln\, y_{it} = \sum_{j=500}^{1300} \beta_j \ln\,(1+PloughFraction_i)\, I_t^j + \sum_{j=500}^{1300} X'_i I_t^j \phi_j + \sum_R \lambda_R I_i^R + \sum_{j=500}^{1300} p_j I_t^j + \epsilon_{it} \quad (2)$$

where the crucial difference from equation (1) is that we obtain an estimate for all centuries, $j = \{600, 700, \ldots, 1300\}$, and hence let the data 'speak' as to when the effect of the heavy plough becomes traceable. 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 AD 500.

## 4. Data

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.

[10] See description in Section 4.1.
[11] Since we have no knowledge of the *take-up rate* of the heavy plough, $\beta$ is an *intention-to-treat* (ITT) type estimate.

### 4.1 Main variables

We employ two different measures of economic development: urbanization and population density. The focus on urbanization is warranted by the fact that historians have linked the heavy plough and urbanization (e.g., White 1962; Jensen 2010). Moreover, Nunn and Qian (2011) and Pounds (1974) argue that urbanization is closely related to per capita income; and Acemoglu et al. (2005a) 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). The heavy plough arguably increased agricultural productivity and the need for markets, and it therefore allowed for urbanization. Moreover, 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. 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).

With respect to urbanization, we construct this measure using historical maps from EurAtlas for the period 500-1300.[13] We build on Pounds (1974) who suggests using the number of cities and towns as an indicator of economic growth for the medieval period. EurAtlas provides information on the locations of cities by century. In the construction of EurAtlas, the researchers relied on historical atlases as well as the historical record to construct maps.[14] The approximate foundation year of cities is the inclusion criterion for a specific century.[15] In the empirical analysis below, we use the number of cities per square kilometer.[16] Bairoch (1991, pp.135-136) stresses that the period from around 900 to 1300 was a period of rapid urban growth in Europe and points out that the way this happened was partly by "the creation of a great many new urban centers" and partly by the expansion of existing cities. He produces

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

[13] Table E4 in appendix E shows a list of the number of cities for each century.

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

[15] 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.

[16] A similar measure of urbanization has been used by historians such as Beresford (1967) for England.

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 in 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.[17] In order to give an impression of the data, we plot our city density measures for each century in Figure C2 in Appendix C.

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,[18] 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 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).[19] 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; see also footnote 32. We calculate the average population density at the NUTS 2 level for each century of our observation period.[20] While

[17] 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 E5 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 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 studied below suggest that we cannot simply replace missing observations by zero values for these years. Thus, we cannot use the Bairoch et al. data.

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

[19] Recent research that uses the McEvedy and Jones's data include Nunn and Qian (2011) and Ashraf and Galor (2011).

[20] See Figure C1 in Appendix C

this variable is constructed, it correlates positively with our measure of urbanization.[21] Given that our urbanization indicator is not a constructed measure, this suggests that the constructed population density measures to some extent track economic development.

We also need a measure on how suitable different soils are to the use of the heavy plough. According to White (1962) and others, it was areas with clay soils that gained from adapting the heavy plough. Yet few of the writers in the historiographical tradition—with the exception of Jensen (2010)—provide precise definitions of "clay soils", "heavy clay soils", or "heavy soils". One challenge is therefore to find a soil type that fits this description in commonly used soil classification systems. 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. 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).[22] As noted in Section 2.1, this type of soil has been shown to benefit from mouldboard ploughing in terms of crop yields.

Fertile luvisol is much more common in Northern Europe than in Southern Europe. 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".[23] For the case of Denmark, many historians have pinpointed the areas dominated by luvisol as areas with "clay soils", "heavy soils" and "heavy, moraine clay" (Jensen 1979; Andersen and Nielsen 1982; Jensen 2010). 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 C3, 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

[21] The correlation coefficient is 0.43.

[22] 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).

[23] Table E6 in appendix E shows the distribution of heavy-plough-suitable soils across present day countries.

the Po Valley, luvisol is highly prevalent.[24] In line with this, Parain (1966) notes that heavy ploughs were used on the clay soils of Lombardy. In section 6 below, we return to the challenge of measuring clay soils by using alternative measures for the case of Denmark.

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.[25] 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. Milthers (1925) notes that the clay soils formed during the ice age in the case of Denmark.

On this background, we identify the areas with high prevalence of luvisol as our baseline measure for clay soil. But in order to identify the areas that would benefit from adapting the heavy plough we need a second condition: We have to adjust for the quality of the soil for growing plough-positive crops, such as wheat, barley, and rye.[26] We must do so 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. The aforementioned crops were also the most common in the High Middle Ages (Pounds 1974).

We construct our measure of the usefulness of the heavy plough from two sources: a soil map from the European Soil Database as mentioned above and a map indicating the suitability for growing plough-positive crops. The suitability map comes from the Global Agro-ecological Assessment 2002 by FAO, which classifies the soil using thresholds on a soil suitability

[24] A soil map has been constructed for the subregion of Lombardy. In this region, luvisol is the most common type of soil (see http://www.ersaf.lombardia.it/upload/ersaf/suoli/eng/soilmap.asp).

[25] 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.

[26] 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.

index denoted by SI.[27] The corresponding classification divides soil suitability into categories ranging from "very marginal" to "very high", see Figure C4 in Appendix C for details. The measure, which we denote *PloughFraction*, is constructed as the fraction of the area of each region which contains luvisol with SI greater or equal to a certain threshold for a plough-positive crop.[28] We construct a baseline measure of *PloughFraction* using luvisol with $SI \geq 55$ for wheat. In terms of soil suitability classification, this corresponds to using luvisol with at least good suitability for growing wheat, but we also investigate other crops and different thresholds for SI.[29] 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 29. In some estimations we also include areas with (fertile) gleysol. This is a wetland soil (FAO, 2006), which is described as being poorly drained by Edwards (1990). *PloughFraction(55)* is visualized in Figure 2. This map confirms that relatively more heavy-plough-suitable land is found in Northern Europe and the northern parts of Italy.[30]

**<Figure 2 about here>**

### 4.2 Control variables and threats to identification[31]

A first step in controlling for potentially omitted factors is to add regional fixed effects and time dummy variables for each century. Regional fixed effects capture time-invariant characteristics such as soil quality and other geographical factors,[32] while time dummies essentially control for underlying aggregate changes that affect economic development.

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[27] Again we need to justify the use of present-day suitability data. In Figure C4 in Appendix C we show a map of wheat suitability and a description of the suitability index. Figure D1 confirms a positive correlation between historic wheat production and our wheat suitability measure based on present-day FAO data. Moreover, sub-national data from Denmark confirm a relation between yields and soil suitability for the three crops considered; see appendix D.

[28] 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.

[29] *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 C4 in Appendix C for further details.

[30] The map does not change substantially if areas with fertile gleysol are included.

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

[32] Regional fixed effects also serve to capture the time-invariant geographical factors, which were used in the construction of population density data.

While regional 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 Europe, and which at same time both (ii) correlate with plough suitability and (iii) affect urbanization and/or population density. We next discuss some changes that potentially fulfill conditions (i) to (iii) as well as ways of dealing with them.

A first potential concern relates to the climatic changes that occurred throughout the so-called Medieval Warm Period. Specifically, the period from AD 950 to 1250 is considered to have been warm (Guiot et al. 2010) and it is not implausible that this may have been beneficial for agricultural productivity (e.g. Koepke and Baten, 2008). If higher temperatures correlate with the prevalence of heavy clay soil, we risk confounding the 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.

A second concern derives from the presence of universities. A recent study finds that the establishment of medieval universities played a causal role in expanding regional economic activity (Cantoni and Yuchtman 2012).[33] 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.

A third concern derives from the work of Mitterauer (2010), who 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 given the Malthusian regime may have led to higher population density and plausibly 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.[34] Nevertheless, the introduction of rye is unlikely to be completely independent of the adoption of the heavy plough. Rye itself is a plough-positive crop, and the introduction of rye as a winter crop may have been made possible only by the heavy plough. Grau-Møller

[33] The majority of medieval universities were only "opened" 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.

[34] We do so in order to identify regions that would benefit *strongly* from the adoption of rye, since regions 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.

(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 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.[35]

The discussion of rye adoption logically directs attention to another set of changes, which occurred as a result of adoption of the heavy plough. These heavy-plough-induced changes fulfill conditions (i) to (iii), but they are *not* unrelated to the heavy plough. And 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. For example, the plough required a number of oxen to pull it. As very few peasants could afford their own team of oxen, they combined their oxen to pull one plough. It is therefore quite possible that the heavy plough in this way instigated a more cooperative peasant society, which may in turn have exerted a positive direct impact on local economies (White 1962; Mokyr 1990). We have essentially no way of controlling for this chain of events. Therefore, while we are convinced that we 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 effects (e.g., a more cooperative peasant society) of the invention and widespread adoption of the heavy plough. That being said, in some of our regressions below we will control for two important additional (and partly) indirect effects: institutions and trade.

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

[35] When we examine the Danish data in Section 6, we note that rye had been grown there long before the Middle Ages.

plough itself may have induced institutional change, as suggested by White (1962).[36] To deal with this possibility, we control for a time-varying effect of institutional heritage. In practice, we interact a dummy variable for being a part of the Roman Empire at some point in the past with time dummies. Landes (1998) argued that Roman presence in an area left important cultural and institutional footprints that may have had lasting effects, and this may shape future institutional changes given that institutions are known to persist.

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 population density.

## 5. Main results

The discussion in this section is organized as follows: Sections 5.1 and 5.2 report the results from the estimation of, respectively, the non-flexible and the flexible model, whereas Section 5.3 reports on the robustness of our findings.

### 5.1 Non-flexible model

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 1 about here>**

Table 1 presents the results for the non-flexible model. Turning first to urbanization as the dependent variable, 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

[36] 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.

control variables. In columns 3 and 4 we check our results using population density as our measure of economic development. In this case, the effect is also positive and significant.

In order to measure the size of the economic impact of the heavy plough, we calculate regional urbanization and population densities in a counterfactual setting where the plough was never introduced. That is, we first use the urbanization and population densities from our last period of observation and subtract the estimated effect of adopting the heavy plough:[37] $\ln\left(1 + urbanization_{i,1300}\right) - \hat{\beta} \cdot \ln\,(1 + PloughFraction_i)$. We then aggregate over all regions and calculate the average urbanization in a world without the heavy plough, which is found to be 0.000305 cities per square-kilometer. This should be compared to the actual urbanization of 0.000321. In AD 900, before the heavy plough became widespread, the urbanization rate had reached 0.000205. Hence, in the counterfactual setting the increase would have been 0.000100 compared to the actual increase of 0.000117; or, to put it differently, the increase would have been only 85.7% of the actual increase. This means that the heavy plough explains 14.3 % of the increase in urbanization from AD 900 to 1300 holding everything else constant. Calculating the same for population density yields smaller but yet comparable results; the heavy plough explains 7.7% of the increase in population density over the same period. That the heavy plough explains in the neighborhood of 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.[38]

### 5.2 Flexible model

Turning to the flexible model, where the timing of the widespread diffusion of the plough is assumed unknown, we report results in Table 2. The four columns correspond to the same columns in Table 1. As is evident upon inspection the table, the plough's effect on urbanization increases as of AD 900, and the precision of the estimated effect also rises; see

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[37] We use the estimated effects from the models in columns two and four of Table 1. In a few cases the counterfactual population density or urbanization becomes negative. This happens when the estimated effect of the heavy plough exceeds the actual level of development in AD 1300. In those cases we set the counterfactual equal to zero. Still, using the negative counterfactual creates nearly identical results.

[38] An alternative way to gauge the economic effect is to evaluate the marginal effects at mean values. For urbanization, the formula is $\Delta Urbanization = \beta \cdot \frac{1+\overline{Urbanization}}{1+\overline{PloughFraction}} \cdot \Delta PloughFraction$. If we consider moving from having no heavy-plough-suitable land to having the mean share, we obtain (upon inserting values from Appendix B and Table 1): $\Delta Urbanization = 0.00024 \cdot \frac{1+0.000342}{1+0.103053} \cdot 0.103053 = 0.0000224$. This means that the relative increase is 0.0000224/0.000342 = 6.54%. Doing a similar calculation for population density gives a relative increase of 0.6246/10.52863= 5.93%.

columns 1 and 2. With respect to population density, we see the same increasing effect but with the precision of the estimated effect rising even faster over time; see columns 3 and 4.

**<Table 2 about here>**

The picture that emerges is thus one showing that the heavy plough had a significant effect on population density after AD 900 and that over time its impact became increasingly important. This is fully consistent with the view that the plough started to spread across Europe in earnest at the closing of the first millennium AD. In earlier centuries, before the breakthrough of the heavy plough, there was no effect of having fertile, heavy clay soil.[39] 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. Figures 3 and 4 show graphs of the estimates for each century (based on columns 2 and 4 of Table 2, respectively). 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.[40]

**<Figures 3 and 4 about here>**

Comparing the two graphs, we see a similar pattern. In both cases we see effects around zero in the first centuries, but from around the turn of the millennium and onwards the effects

[39] We note that the dummies for AD 600 and 700 are 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 5 below 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.

[40] When we use the Conley adjusted standard errors, significance is not affected for our urbanization measure. For population density, significance drops below conventional levels with p-values of 0.123 and 0.102 for respectively the non-flexible models without and with the full set of controls. This is unsurprising as our population density measure, to a large extent, is derived from country-level estimates which should induce spatial dependence by construction. Moreover, for both the urbanization measures in the European and Danish datasets, this adjustment to standard errors matters little for results. Thus, our results are unlikely to be driven by spatial autocorrelation.

increase significantly. Also the precision with which they are estimated increases. Notice that the effect on urbanization becomes significant approximately one to two centuries later, which may indicate a lagged effect of population density on urbanization.[41]

### 5.3 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 3. 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 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 3 about here>**

By and large, the rolling regressions reveal an increasing effect over time. In panel A1 and A2, where urbanization is used, the point estimate of the 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. In the third specification the picture is largely the same except that the effect comes two centuries earlier. However, in Panel B2 the excess effect is highest around the turn of the millennium; subsequently, the size and significance of the effect diminishes. This could indicate that it became harder to keep increasing output even more as the plough was already widespread and the best soils were already being cultivated. It is also consistent with the view that the effect on population

[41] Urbanization may lead to pressure for adoption of the heavy plough. If so, our results indicate that it is only the regions with fertile, clay soil that are successful in using the heavy plough to support new cities. 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 (see footnote 11), reverse causality is not a concern.

density started earlier than the effect on urbanization. Again this could be a result of a lagged effect of population density on urbanization. Of course, we should beware not to interpret too much into this, as we cannot reject the null hypothesis that all statistically significant point estimates in Panel B are equal.

### 5.4 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. In this section we report on the sensitivity of our results with respect to permutations of the main independent variable. First, in Section 5.4.1, we check whether the results are robust to alternative measures of heavy-plough-suitable land. Second, in Section 5.4.2, we conduct a placebo type experiment. Finally, Section 5.4.3 discusses additional robustness checks.

#### 5.4.1 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 wheat.[42] This particular choice of soil, suitability level, and crop may be questioned. Consequently, we first look into the consequences for our results of using alternative crops, such as barley and rye, as well as alternative suitability levels for growing the crops. Second, we add another soil type, gleysol, in order to broaden our measure of soils that may benefit from the heavy plough.

*Alternative crops and suitability levels*

The results for the non-flexible model when using alternative crops and suitability levels are shown in Table 4. Our baseline result is the one in the middle of the first column. We see that the results are highly stable to alternative plough-positive crops. The change in suitability level and crop slightly affects the magnitude and the significance of the results. The size of the effect increases as the suitability increases. This is an intuitive result: More suitable conditions would make it even more beneficial to be able to cultivate the land.

**<Table 4 about here>**

Figure 5 investigates exactly the same issue for the flexible model. So we estimate the model using different alternative crops and suitability levels for growing the alternative crop. The

[42] Specifically, we have worked with *PloughFraction(55)*, see footnote 29.

graphs reveal a similar picture across crops and suitability level. Again the effect increases with the suitability level for the same reasons as mentioned above. At the same time precision decreases, probably due to the fact that areas that in reality are suitable are included as unsuitable. Given the results in table 4 and figure 5, we conclude that our results are stable to the use of alternative measures of suitability.[43] Next, we turn to the sensitivity of our choice of soil type.

**<Figure 5 about here>**

*Measure including gleysol*

As we discussed above, luvisol fits well with the soils that historians point to as being suitable for the heavy plough. But there may be other soils that would gain from the heavy plough. Gleysol, which is a wetland soil (FAO, 2006), is described by Edwards (1990) 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, both in order to test the sensitivity of our choice of luvisol but also to test for a potential impact in these areas. Figures 6 and 7 show that the overall picture is the same and, in fact, including gleysol increases the effect especially so in the period around and after the breakthrough of the heavy plough. Whether the extra gain in these areas stems from the heavy plough is difficult to say; they could have gained a lot from improved drainage using the heavy plough, but perhaps other effects are in operation as well given the size of the effect. At any rate, nothing changes qualitatively.

**<Figures 6 and 7 about here>**

*All plough-positive crops*

We also try to include all three plough-positive crops simultaneously in our plough measure; that is, the suitability for at least one of the crops wheat, rye, or barley, should be at least "good" suitability. The effect of the heavy plough is not isolated to one crop and this test allows the effect to be independent of the type of plough-positive crop. The results are shown in Figures 8 and 9. Results are very similar to our main results, which show that a single crop does not cause the effect.

[43] Carrying out the same robustness tests for population density using flexible as well as non-flexible models leads to the same conclusion. Results are available upon request.

**<Figure 8 and 9 about here>**

### 5.4.2 Potato placebo test

Is it possible that we are capturing another differential effect that we would have captured with any kind of crop? Given the robustness of the results with respect to choice of crop, a test of this is warranted. 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: We know that the potato strongly influenced urbanization and population density 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 see any effect of potato-suitable soil on population density and urbanization during our observation window, 500-1300. Moreover, potatoes can successfully be grown on many types of soils (Kopsell 2000), including sandy soils on which we know that the heavy plough is not beneficial. Any such effect would imply that we are capturing a more general trend, and it would seriously undermine our identification strategy. The results of the non-flexible model are shown in Table 5, while Figures 10 and 11 show the flexible estimates with, respectively, urbanization and population density as dependent variables.

**<Table 5, Figures 10 and 11 about here>**

Using potato suitability alters the results substantially. In the non-flexible as well as in the flexible model the magnitude of the estimated effect decreases substantially and precision is reduced, rendering estimates insignificant. In fact, for urbanization the effect completely vanishes. Overall, these results substantiate that the effect which we attribute to the heavy plough is not just a general 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.

### 5.4.3 Alternative controls for geography and institutions.

In appendix E, we present further evidence on the robustness of results to alternative controls for geography and institutions. Regarding controls for geography, we replace the control for access to the coast by a dummy for not being landlocked. This has trivial effects on results. While the interpretation of latitude is less clear in a European context—or, for that matter, in a high latitude country such as Denmark, which we analyze below—compared to a world sample, where it may proxy for e.g. climate, we have also investigated whether including latitude affects the results. While precision is decreased, there is still evidence of an effect of the heavy plough; see Table E1 in the appendix. 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; see Table E2 in the appendix.

**6. Test on Danish regional data**

A concern regarding our measures of economic development and our PloughFraction measure is that they are likely to be measured with substantial error. If the measurement error is unsystematic, it only works against our alternative hypothesis by reducing the precision of point estimates. If the measurement error is systematic, the consequences may be less benign. To deal with this concern, we have constructed alternative and more precise measures for both clay soil and urbanization for 25 Danish historical counties.[44] In addition to the advantage of more precise measures, a second advantage is that Denmark contains much regional variation in terms of the presence of clay soils, which makes it an interesting case for testing White's hypothesis. A third advantage is that we can study the effects at a more local level since we can use smaller geographical units. We now use historical counties rather than larger, present day regions and towns rather than cities. Finally, the Danish case allows us to shed some light on the plausibility of our maintained assumptions. For instance, we have assumed that soil maps from the late 20$^{th}$ century capture the location of medieval clay soils well, as they formed during the ice age as noted above. The Danish data allow us to show that the share of clay soil based on a *late* 20$^{th}$ century map correlates positively and significantly with the share of clay soil calculated on the basis of an *early* 20$^{th}$ century geological map for Denmark taken from Harder and Ussing (1913); see Appendix D. We also demonstrate in Appendix D that our modern measure of suitability for growing barley correlates positively and significantly with a measure of peasant payments in terms of barley to landlords from the early 1660s as well as crop yields in the 1830s. This supports the maintained assumption that soil suitability today captures that of the past. Before we turn to the results, we briefly discuss

[44] We use the counties in order to better capture the variation within Denmark. With NUTS regions, we only have 5 large regions and do not capture regional heterogeneities to the same extent. Further estimating with only five regions would give a very small dataset.

the timing of the breakthrough of the heavy plough in Denmark, the construction of the new measures, and the included control variables.

*Timing of the breakthrough*

As in the analysis of the European case, we need to determine the timing of the breakthrough in order to estimate the non-flexible model. Therefore, we briefly review the existing Danish evidence. As for Europe in general, most historians stress that the breakthrough took place around AD 1000 or after. 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. Poulsen (1997, p.116) concurs with this and summarizes the diffusion process as follows: "Probably around 900 to 1100, then the mouldboard plough was introduced into Denmark, gradually diffusing from southern areas." Moreover, and as noted above, the word for plough in Old Norse does not appear before AD 1000. 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.[45] Larsen (2011) argues that the earliest evidence of *introduction* is from AD 200-400 based on two cases from Western Jutland; however, both these two cases remain controversial.[46] He concludes that the introduction in Western Jutland should be dated to this time (Larsen 2011, p. 124). In the rest of Jutland, the plough may have been used in the early medieval period. While this evidence is suggestive of an early adoption in some places, it does not provide solid evidence for the breakthrough. Given that we used AD 1000 in the European case, and given that some evidence for this year is present, we stick to this timing in the non-flexible model, but we do investigate the timing in the flexible model in order to evaluate this choice.

*Empirical model and data*

We implement an empirical specification along the lines of equations (1) and (2) but modify the measures accordingly. The cross-sectional dimension is now the 25 Danish historical counties with urbanization data available for every 25 years.

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[45] Porsmose (1988) mentions that the Danish word for plough (plov) was introduced into Danish history as the man who killed King Erik Emune in 1137 was named Black Plough.

[46] For the first case, Larsen (2011) grants that the dating is problematic, and whether the ridges are proper high-backed ridges has been questioned by other experts (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 the furrows could have been produced by a heavy plough.

As our new urbanization measure we construct the town density for each county based on Jensen's (2010) dating of the approximate establishment of Danish medieval towns.[47] He uses, among other things, information on when the town had main streets, a town centre with a market square, and a town church in order to give an approximate earliest date of when the town was established (Jensen 2010). 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. This measure is analogous to our city density measure in the European sample.[48]

We also construct a new PloughFraction measure. We have digitized the soil map from Frandsen (1988), which gives the locations of clay soils in Denmark (see Figure 12).[49] Jensen (2010) used this map to pinpoint the location and types of soil that would benefit from the heavy plough. This measure is more precise than the luvisol-based measure used above and captures all clay soils. 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 new measure.[50] We also note that most of the remaining Danish soils are classified as sandy soils. PloughFraction is constructed as the share of clay soil in a county in the baseline, but we also construct a version using the share of clay that has good suitability for growing barley. We use barley, which, in contrast to wheat, was grown in Denmark throughout the period; see footnote 51.

**<Figure 12 about here>**

*Control variables and threats to identification*

As in our test based on the European data, we control for time fixed effects and county level fixed effects. In Denmark, rye has been cultivated since the early Iron Age (Mikkelsen and Nørbach, 2003),[51] but it was introduced as a winter crop (Grau-Møller, 1990) in the Middle

[47] See table E3 in appendix E for a complete list of the Danish towns and cities.

[48] Note that this measure also 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.

[49] We use the three categories (clay soils, sandy clay soils and clayey sandy soils) as suggested by Jensen (2010) to measure clay soils. We also add clay soils and heavy clay soils from Frandsen's original map, which Jensen (2010) left out, although there is relatively little soil of these types in Denmark.

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

[51] The same is true for barley and oats. Apparently, 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.

Ages, as noted above. 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. We therefore add the interaction between our measure of suitability for growing rye as used above and time fixed effects. We also include an interaction with the distance from the center of a county to the coast for the same reasons as discussed above. The temperature data at the aggregate level suggest little variation within Denmark, and we therefore trust that time fixed effects capture these changes well.[52] They will also capture changes to institutions common to the whole country. There could also be regional effects of institutional change. From the late 900s, Denmark was ruled by one king, and this may have influenced regional development. Jutland (the peninsular which shares a border with Germany) had proved difficult to defend, and it has been argued that Zealand (see Figure 12) was more easily defended. This may have led to a shift in gravitational center towards the eastern part of Zealand. In fact, some eastern towns were founded by the second Danish king around AD 1000 (Sawyer 2002). We address this by testing whether our results still hold within Jutland. The test within Jutland also helps to address that different regions had different provincial laws. Jutland's provincial law (known as "Jyske lov")—a law that among other things regulated the distribution of farmland within a village and that 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.

*Results*

In order to save space, we report mainly non-flexible estimations, see Table 6. We calculate both standard errors corrected for clustering at the county level as reported in Table 6 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 the type of the standard errors. 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, as in the European analysis. Both regressions show a positive and significant effect of clay soils from AD 1000. Using the quality-adjusted measure has little impact on our results; in fact, it only strengthens them. It turns out that the fertile soils (in terms of plough-positive crops) largely coincide

[52] Hybel (2002) argues that the warm period in the Middle Ages only lasted from the 1000s to the beginning of the 1100s in Scandinavia. If there is an effect of clay soils after this in the flexible estimates, we can plausibly rule out that this is driving our results. In fact, the effect is also present in the 1200s; see below.

with the clay soils of Denmark, and unsurprisingly we therefore find that there is little effect of making this correction. In column 3, where we add extra covariates, we find that 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 the shift towards Zealand explains our result by testing solely on Juttish counties. Doing this shows that the effect still emerges, though with a smaller but still significant coefficient. This suggests that the effect of clay soil areas is not merely gravitational shift towards Zealand; see column 4. The inclusion of time fixed effects captures potential regional institutional shocks.

In columns 5 and 6, we use the luvisol measure both unadjusted and adjusted for quality. While we find similar results, the coefficients are smaller and less precisely estimated. We already mentioned above 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, it suggests that we may miss some clay soil in the luvisol based measure above.[53] Still, the fact that we obtain similar, albeit weaker, results suggests that this choice is a reasonable starting point. Finally, 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.[54] Nevertheless, we investigate the importance of this soil type by excluding it from our measure in column 7, and we reach a similar conclusion as in the baseline measure.

When we evaluate the effect of the heavy plough in a counterfactual setting similar to the one for the European case, we find that 70.6% of urbanization can be attributed to the heavy

[53] 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, increasing to the 1 % level for urbanization. Thus, these results are in line with what we find for Denmark.

[54] We have re-estimated the models in Table 6 using a clay soil measure based on the older map and obtain similar results. We prefer the modern map since it covers all counties. In the period 1864-1920, the three counties near the Danish-German border were under German control.

plough based on the model in column 1 of Table 6. This is a large effect, but hardly surprising given the amount of clay soil in Denmark and our use of towns rather than cities.

**<Table 6 and Figure 13 about here>**

Turning finally to the flexible regressions, we obtain similar results. We show one representative example in Figure 13, 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. This suggests that a cut-off after AD 1150 is reasonable; and if we use this cut-off in our non-flexible model, we obtain larger estimates.[55] We also note that the timing of the effect is later than both the warm medieval period in Denmark and the shift to rule by one king. In sum, the Danish case provides strong evidence that the breakthrough of the heavy plough mattered for development.

## 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. Based on the European data, we find that the heavy plough accounts for roughly one tenth of the increase in urbanization and population density experienced in the High Middle Ages. 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;

[55] One could posit that the result in Figure 13 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 mentioned above, and one would expect that settlement takes place on the best soils first. In fact, anything that would make the soils more prone for settlement would lead to a reverse timing of what we see. One may also wonder about the role of cattle in the Danish in economy in this period, and the discussion in Frandsen (1988) and Porsmose (1988) indicate that cattle was more important in Jutland though far from absent in the rest of the country, and that milk productivity was relatively low in the period. Importantly, shocks to this sector is not observed in this period

however, once the heavy plough arrived, access to the fertile clay soils provided advantages in terms of productivity, access to new and fertile land, etc.

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. 2005a). 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 Europe, and at the same time both correlate with plough suitability and affect urbanization and/or population density. Third, we have to assume that the geology of the period from AD 500 to 1300 is similar to that of later periods. For the Danish case, we can show that present day soil suitability matches that of the 17th and 19th centuries, but for the rest of Europe we have to rely on modern geology. We leave attempts to improve the analysis along the said dimensions for future research.

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## Figures and Tables

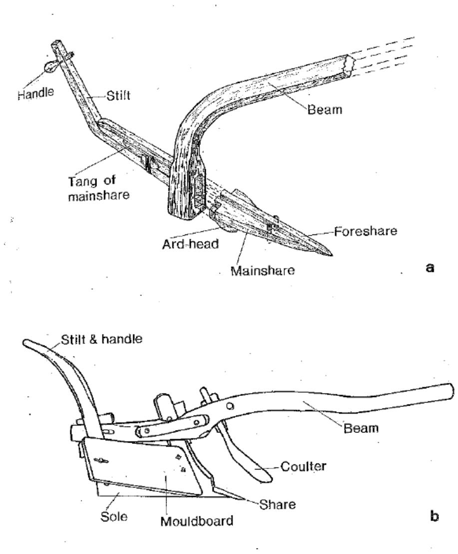



Figure 1: The ard (a) and the heavy plough (b). Source: Fowler (2002).

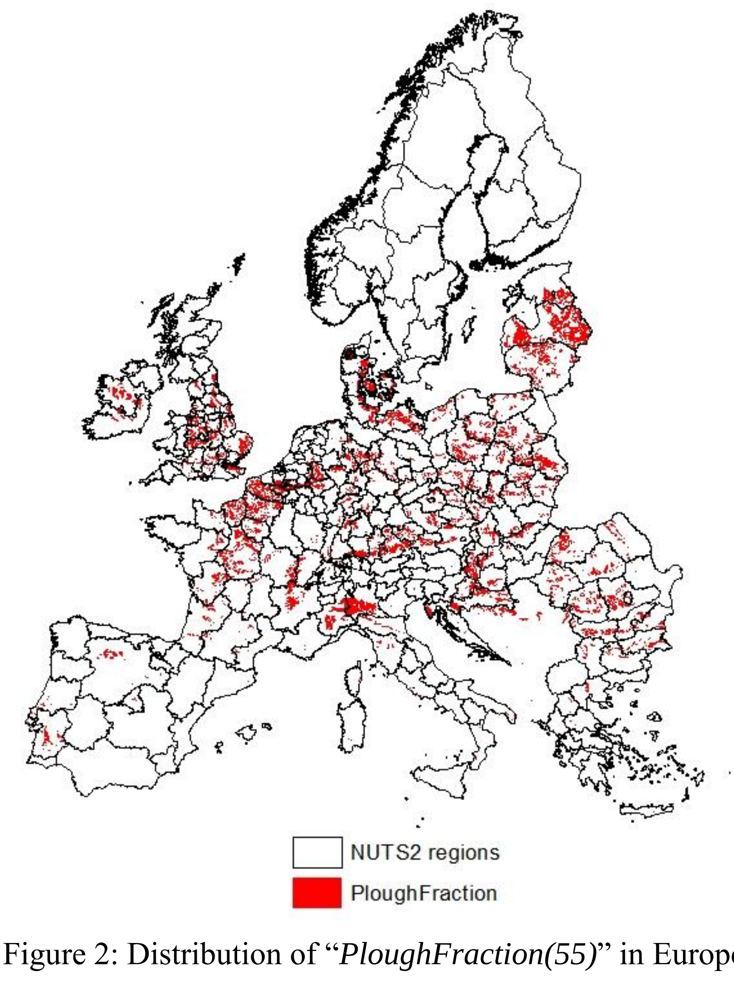



Figure 2: Distribution of "*PloughFraction(55)*" in Europe

Table 1: Results of the non-flexible model

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | Dependent variable: | | | |
| | ln(1+urbanization) | | ln(population density) | |
| ln(1+PloughFraction(55))*$I^{Post}$ | 0.00029*** | 0.00024** | 0.601*** | 0.635*** |
| | (0.00011) | (0.00011) | (0.216) | (0.211) |
| Controls (x Year fixed effects): | | | | |
| Roman heritage | No | Yes | No | Yes |
| ln(1+rye) | No | Yes | No | Yes |
| Universities | No | Yes | No | Yes |
| ln(1+distance coast) | No | Yes | No | Yes |
| ln(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 |

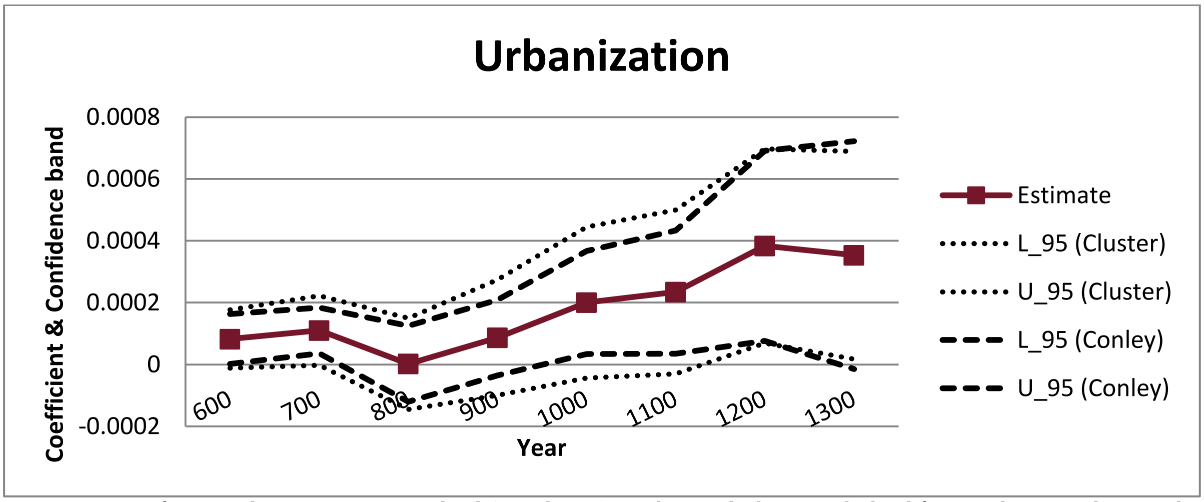
Notes: PloughFraction(55) = fraction of region with luvisol and good wheat suitability ($SI \geq 55$). $I^{Post} = 1$ if year $\geq$ 1000. Clustering on NUTS 2 level. Cluster-robust standard errors in parentheses with corresponding significance levels: *** p<0.01, ** p<0.05, * p<0.1.

Table 2: Results of the flexible model

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | Dependent variable: | | | |
| | ln(1+Urbanization) | | ln(Population density) | |
| ln(1+PloughFraction(55)) *$I^{600}$ | 0.00006 | 0.00008* | -0.129 | -0.226 |
| | (0.00005) | (0.00005) | (0.151) | (0.143) |
| ln(1+PloughFraction(55)) *$I^{700}$ | 0.00008 | 0.00011* | -0.134 | -0.313** |
| | (0.00006) | (0.00006) | (0.133) | (0.121) |
| ln(1+PloughFraction(55)) *$I^{800}$ | 0.00002 | 0.00000 | 0.076 | -0.015 |
| | (0.00006) | (0.00007) | (0.102) | (0.081) |
| ln(1+PloughFraction(55)) *$I^{900}$ | 0.00011 | 0.00009 | 0.324** | 0.338** |
| | (0.00009) | (0.00009) | (0.154) | (0.152) |
| ln(1+PloughFraction(55)) *$I^{1000}$ | 0.00022* | 0.00020 | 0.447** | 0.527** |
| | (0.00012) | (0.00012) | (0.210) | (0.213) |
| ln(1+PloughFraction(55)) *$I^{1100}$ | 0.00029** | 0.00023* | 0.499** | 0.555*** |
| | (0.00013) | (0.00013) | (0.212) | (0.208) |
| ln(1+PloughFraction(55))*$I^{1200}$ | 0.00041*** | 0.00038** | 0.717*** | 0.628*** |
| | (0.00015) | (0.00016) | (0.237) | (0.233) |
| ln(1+PloughFraction(55))*$I^{1300}$ | 0.00045*** | 0.00035** | 0.848*** | 0.658** |
| | (0.00017) | (0.00017) | (0.274) | (0.264) |
| 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 |

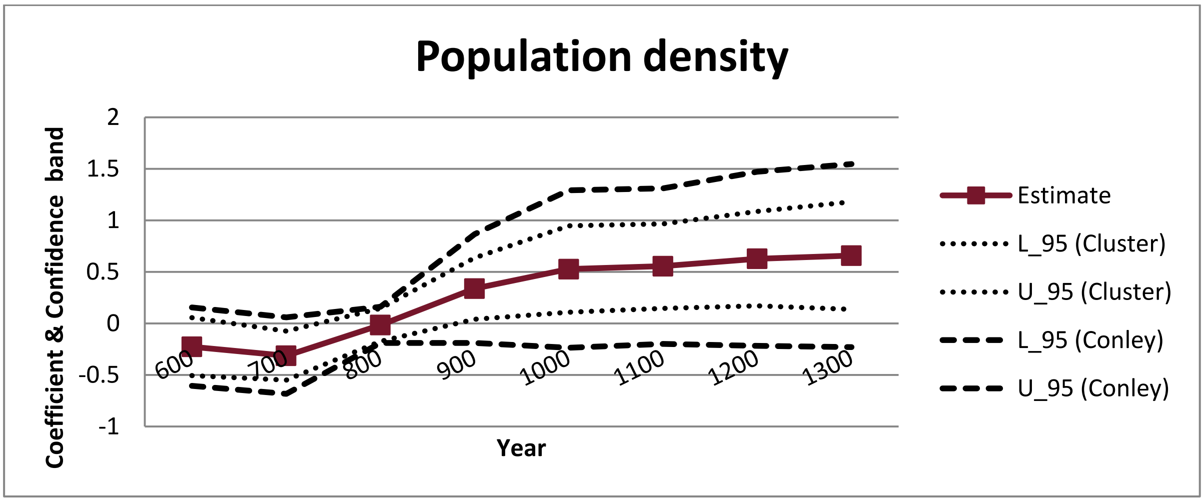
Notes: PloughFraction(55) = fraction of region with luvisol and good wheat suitability ($SI \geq 55$). $I^{Post} = 1$ if year $\geq$ 1000. Clustering on NUTS 2 level. Cluster-robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Figure 3: The effect of the plough on urbanization




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

Figure 4: The effect of the plough on population density




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

Table 3: 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: No covariates | | | | | | |
| ln(1+PloughFraction(55))*$I^{Post}$ | 0.00002 | -0.00000 | 0.00012 | 0.00019** | 0.00018** | 0.00018** |
| | (0.00005) | (0.00006) | (0.00008) | (0.00008) | (0.00008) | (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))*$I^{Post}$ | 0.00002 | -0.00005 | 0.00008 | 0.00017** | 0.00016** | 0.00015 |
| | (0.00005) | (0.00007) | (0.00008) | (0.00009) | (0.00008) | (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 |
| | Dependent variable: ln(Population density) | | | | | |
| Panel B1: No covariates | | | | | | |
| ln(1+PloughFraction(55))*$I^{Post}$ | 0.035 | 0.332** | 0.415* | 0.273* | 0.222** | 0.309*** |
| | (0.073) | (0.168) | (0.214) | (0.142) | (0.107) | (0.114) |
| Observations | 1,076 | 1,076 | 1,076 | 1,076 | 1,076 | 1,076 |
| R-squared | 0.99 | 0.98 | 0.98 | 0.98 | 0.99 | 0.99 |
| Panel B2: Main specification | | | | | | |
| ln(1+PloughFraction(55))*$I^{Post}$ | -0.051 | 0.405** | 0.542** | 0.380*** | 0.164* | 0.125 |
| | (0.073) | (0.177) | (0.217) | (0.136) | (0.089) | (0.094) |
| Observations | 1,076 | 1,076 | 1,076 | 1,076 | 1,076 | 1,076 |
| R-squared | 0.99 | 0.98 | 0.98 | 0.99 | 0.99 | 0.99 |

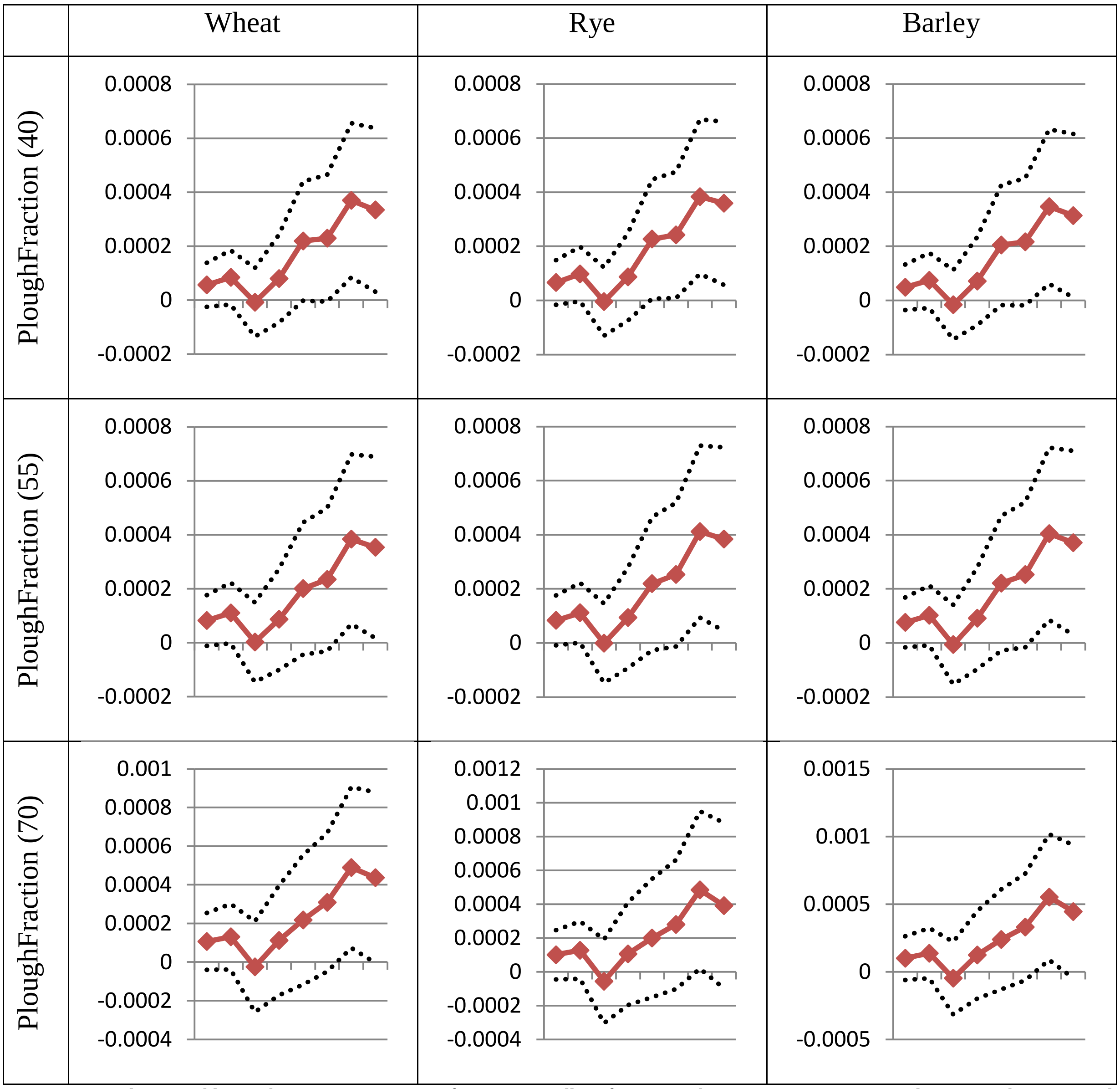
Notes: The dependent variable in panel A is urbanization and in panel B population density. For each dependent variable panel 1 shows estimates with no covariates and panel 2 our main specification controlling for Roman heritage, rye, universities, distance to the coast and mean temperature. Dummies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

Table 4: Non-flexible estimates for different crops and suitability levels

| | | Crop | | |
|---|---|---|---|---|
| | | Wheat | Rye | Barley |
| Suitability at least | PloughFraction (40) | 0.00025** | 0.00025** | 0.00023** |
| | | (0.00011) | (0.00010) | (0.00011) |
| | PloughFraction (55) | 0.00024** | 0.00026** | 0.00026** |
| | | (0.00011) | (0.00011) | (0.00011) |
| | PloughFraction (70) | 0.00030** | 0.00028* | 0.00033** |
| | | (0.00014) | (0.00016) | (0.00016) |

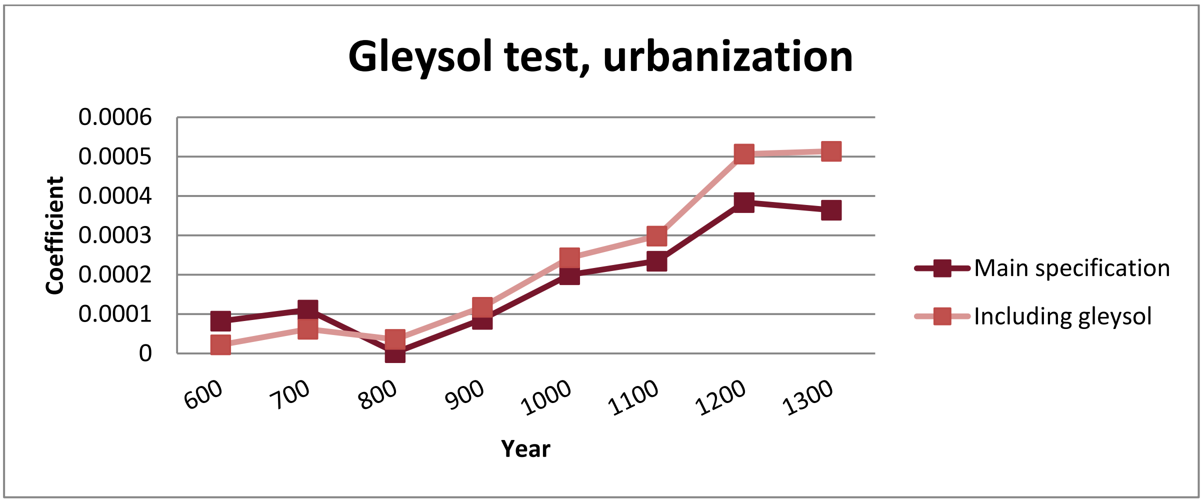
Notes: Dependent variable is urbanization. Main specification controlling for Roman heritage, rye, universities, distance to the coast and mean temperature. Dummies capturing time and regional fixed effects (FE) are included. PloughFraction(SI) = fraction of region with luvisol and crop suitability according to the table. Clustering at NUTS 2 level. Cluster-robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Figure 5: Flexible estimates for different crops and suitability levels



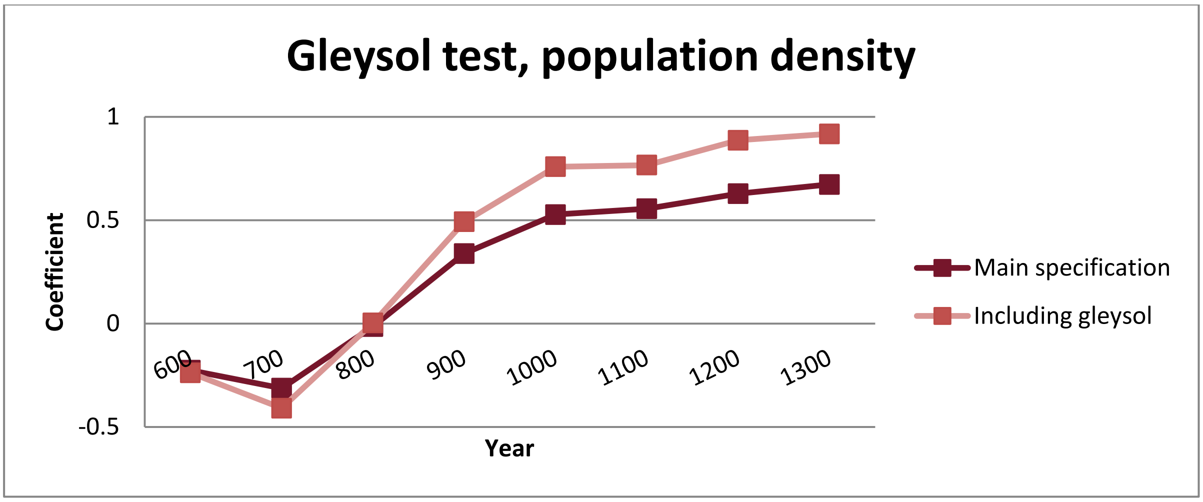

Notes: Dependent variable is urbanization. Main specification controlling for Roman heritage, rye, universities, distance to the coast, and mean temperature. Dummies capturing time and regional fixed effects (FE) are included. PloughFraction(SI) = fraction of region with luvisol and crop suitability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

Figure 6: Comparison of urbanization estimates including gleysol



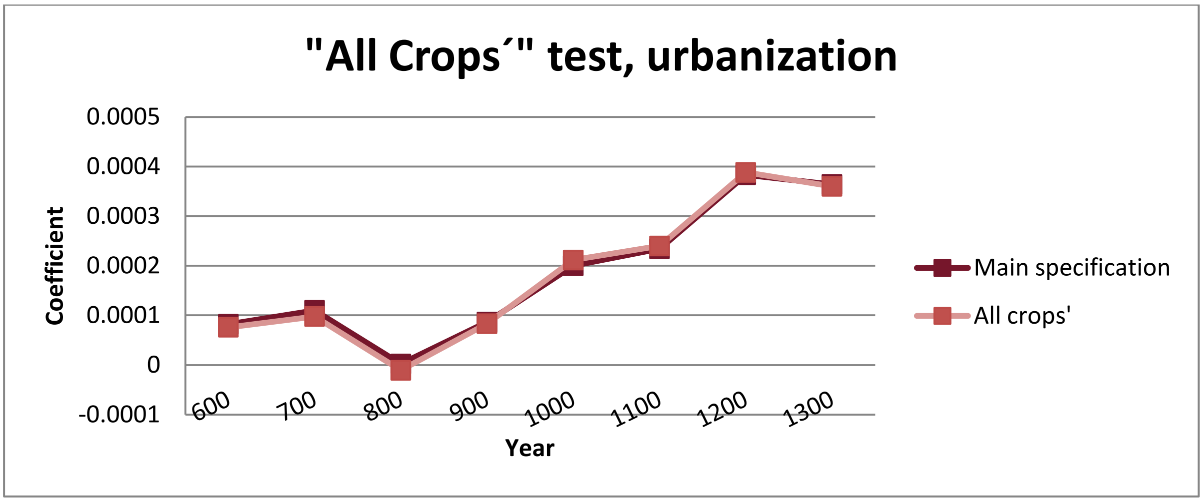

Notes: Dependent variable is urbanization. Main specification. PloughFraction(55) = fraction of region with luvisol or gleysol and good wheat suitability ($SI \geq 55$). Each graph shows the point estimates for each century.

Figure 7: Comparison of population density estimates including gleysol



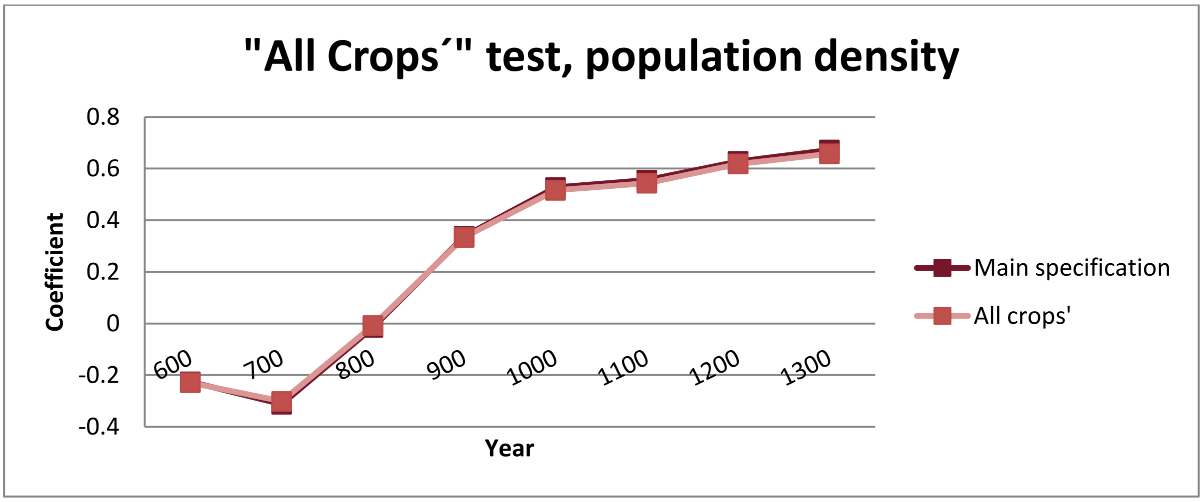

Notes: Dependent variable is population density. Main specification. PloughFraction(55) = fraction of region with luvisol or gleysol and good wheat suitability ($SI \geq 55$). Each graph shows the point estimates for each century.

Figure 8: Comparison of urbanization estimates using all crops




Notes: Dependent variable is urbanization. Main specification. PloughFraction(55) = fraction of region with luvisol and good wheat, rye, or barley suitability ($SI \geq 55$). Each graph shows the point estimates for each century.

Figure 9: Comparison of population density estimates using all crops



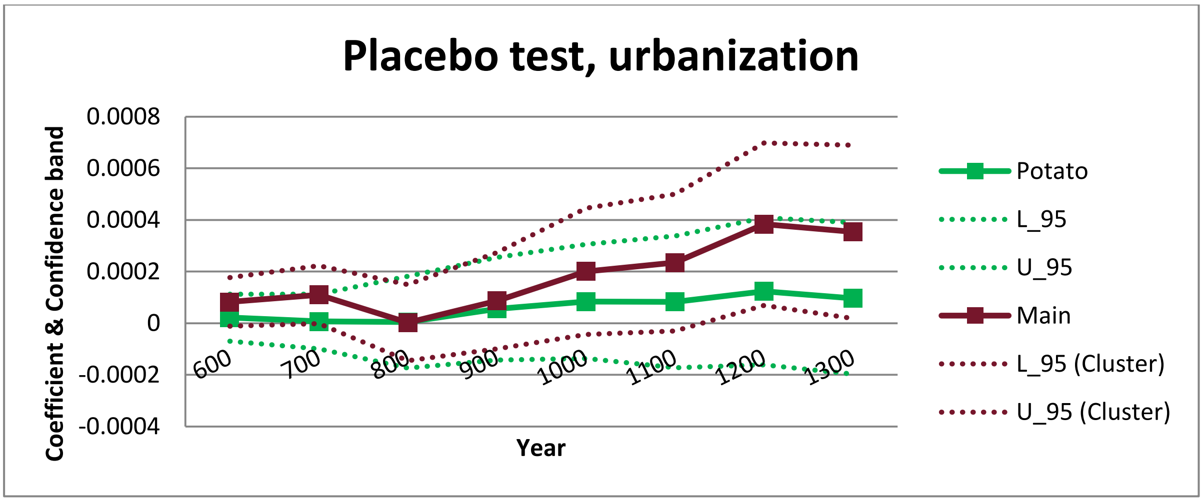

Notes: Dependent variable is population density. Main specification. PloughFraction(55) = fraction of region with luvisol and good wheat, rye, or barley suitability ($SI \geq 55$). Each graph shows the point estimates for each century.

Table 5: Placebo test

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | Dependent variable | | | |
| | ln(1+Urbanization) | | ln(Population density) | |
| ln(1+PotatoFraction(55))*I^Post | 0.00008<br>(0.00010) | | -0.00534<br>(0.17300) | |
| ln(1+PloughFraction(55))*I^Post | | 0.00024**<br>(0.00011) | | 0.638***<br>(0.21) |
| Observations | 2,421 | 2,421 | 2,421 | 2,421 |
| R-squared | 0.89 | 0.89 | 0.97 | 0.97 |

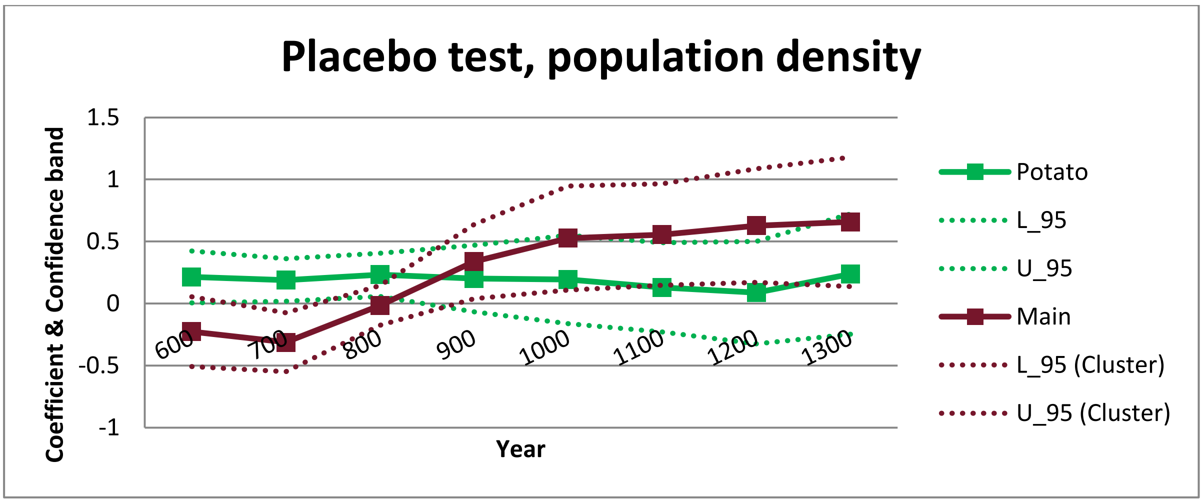
Notes: Main specification controlling for Roman heritage, rye, universities, distance to the coast and mean temperature. Clustering at NUTS 2 level. Dummies capturing time and regional fixed effects (FE) are included. PotatoFraction(55) = fraction of region with good potato suitability ($SI \geq 55$). PloughFraction(55) = fraction of region with luvisol and good wheat suitability ($SI \geq 55$). $I^{Post}$ = 1 if year ≥ 1000. Cluster-robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Figure 10: Comparison of urbanization estimates using potato suitability




Notes: The dependent variable is urbanization. Controlling for Roman heritage, rye, universities, distance to the coast and mean temperature. Clustering at NUTS 2 level. Dummies capturing time and regional fixed effects are included.

Figure 11: Comparison of population estimates using potato suitability




Notes: The dependent variable is population density. Controlling for Roman heritage, rye, universities, distance to the coast, and mean temperature. Clustering at NUTS 2 level. Dummies capturing time and regional fixed effects (FE) are included.

Figure 12: Clay soils and medieval towns in Denmark

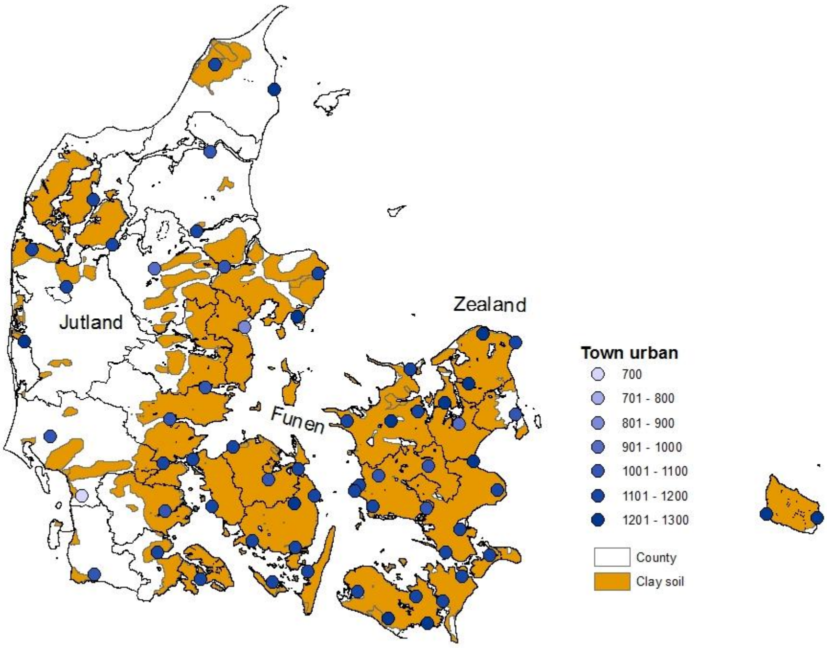
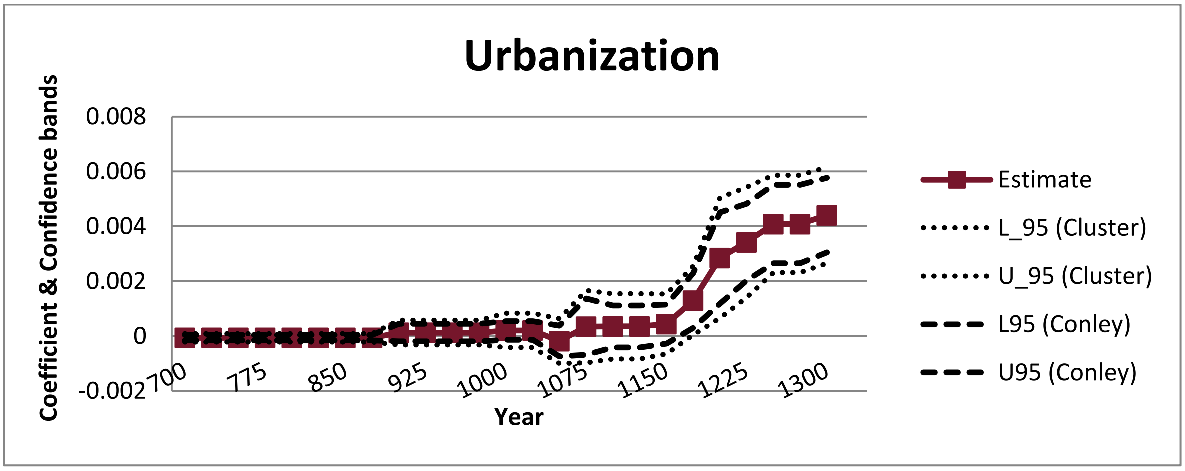



Table 6: The results for the Danish dataset

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| | Dependent variable: ln(1+Urbanization) | | | | | | |
| | Clay | Clay with good barley suitability | Clay with all covariates | Clay for subsample Jutland | Luvisol | Luvisol with good barley suitability | Clay without clayey sand soil |
| ln(1+PloughFraction(55)) *$I^{Post}$ | 0.00169***<br>(0.00031)<br>[0.00028] | 0.00164***<br>(0.00030)<br>[0.00029] | 0.00168***<br>(0.00049)<br>[0.00038] | 0.00063*<br>(0.00031)<br>[0.00021] | 0.00097*<br>(0.00050)<br>[0.00035] | 0.00105*<br>(0.00054)<br>[0.00037] | 0.00163***<br>(0.00024)<br>[0.00020] |
| Distance Coast | No | No | Yes | Yes | No | No | No |
| ln(1+rye) | No | No | Yes | Yes | No | No | No |
| FE (Time and county) | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 650 | 650 | 650 | 364 | 650 | 650 | 650 |
| R-squared | 0.71 | 0.71 | 0.75 | 0.82 | 0.68 | 0.68 | 0.72 |

Notes: PloughFraction = fraction of county with clay (columns 1, 3, and 4), = fraction of county with clay and good rye suitability (column 2), = fraction of county with luvisol (column 5), = fraction of county with luvisol and good wheat suitability (column 6), = fraction of region with clay but not clayey sand (column 7). Column 4 only includes counties in Jutland. $I^{Post} = 1\ if\ year \geq 1000$. 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 13: The effect of the plough on urbanization in Denmark



**Appendices A-G for**

**"The Heavy Plough and the Agricultural Revolution in Medieval Europe."**

**(Supplementary material).**

## Appendix A: Control variables

### Roman heritage

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

### Rye

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

### 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 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.

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

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:

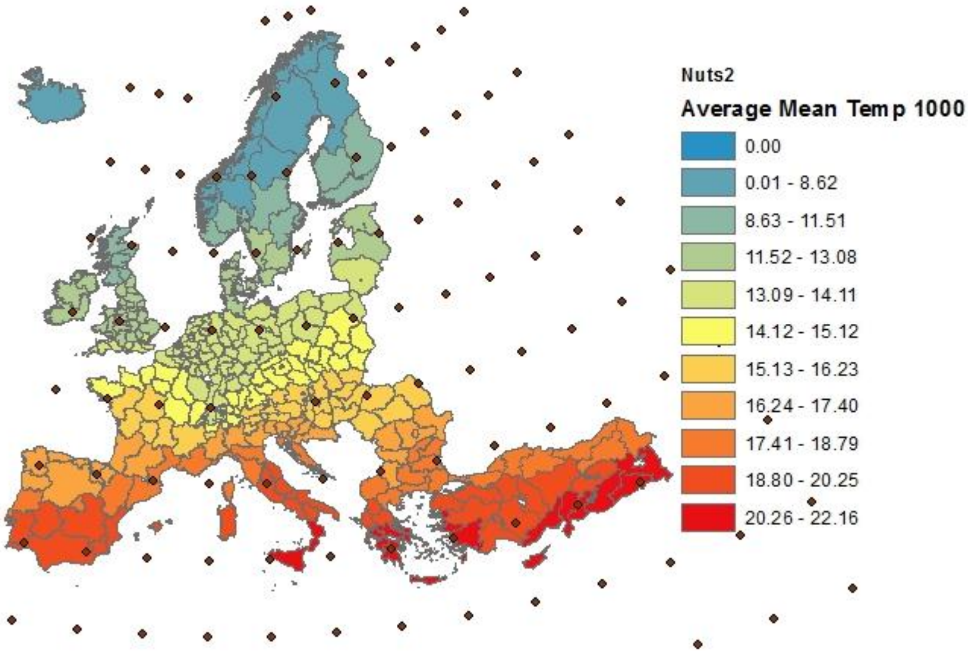



Figure A1: IDW average temperature in AD 1000 on NUTS 2 level

**Distance to the coast**

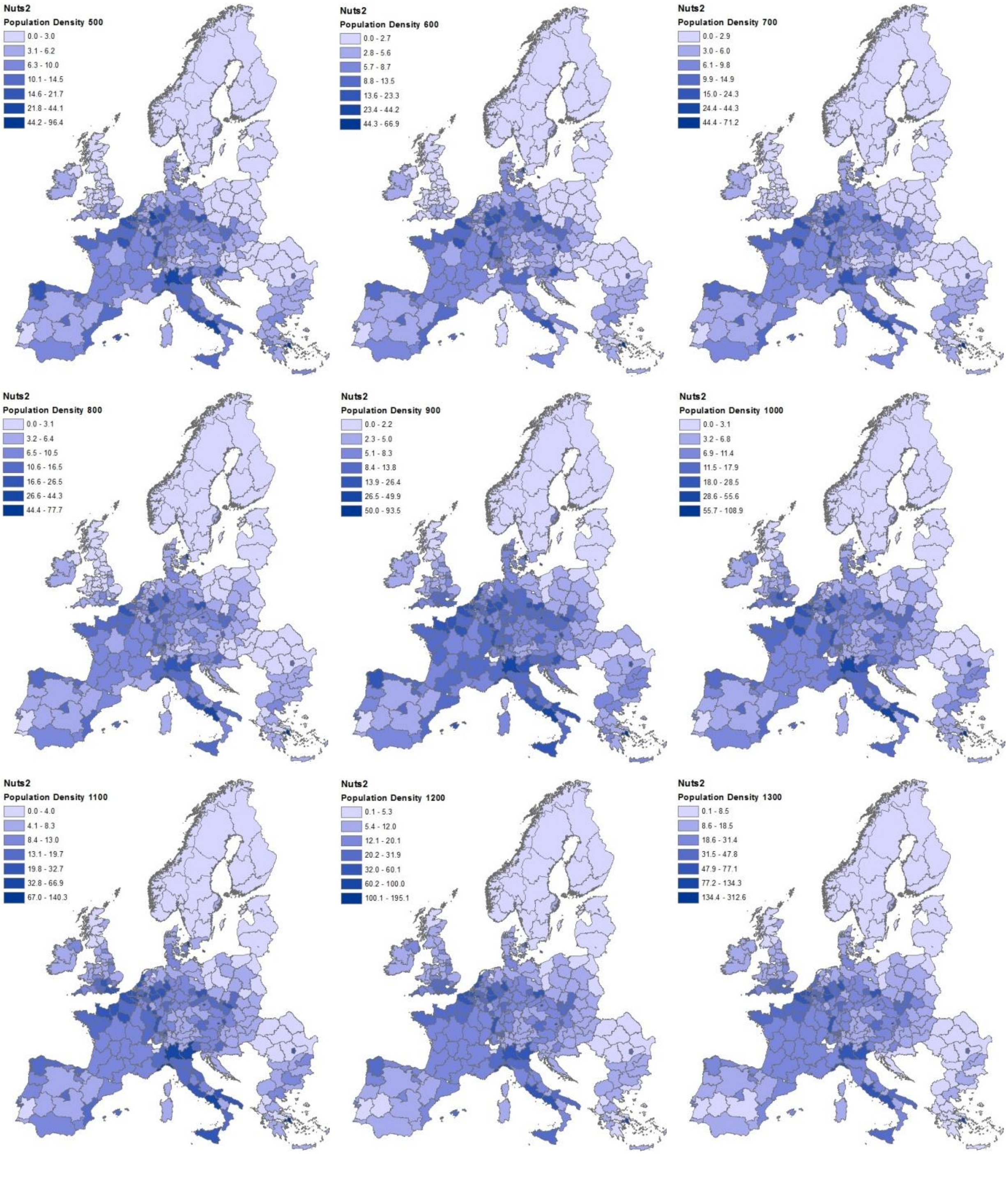
The variable is constructed as the distance from the centroid of each NUTS region to the nearest coast calculated in ArcGIS.

## Appendix B: Descriptive Statistics

| Variable | Number of observations | Mean | Standard deviation | Min | Max | Definition |
|---|---|---|---|---|---|---|
| **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 | 0.103053 | 0.135026 | 0 | 0.933611 | Fraction with luvisol and good suitability for growing wheat |
| PloughFraction (55, Wheat + gleysol) | 2421 | 0.131534 | 0.160615 | 0 | 0.933611 | Fraction with luvisol or gleysol and good suitability for growing wheat |
| 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 |
| **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 | 29454.0000 | 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 |

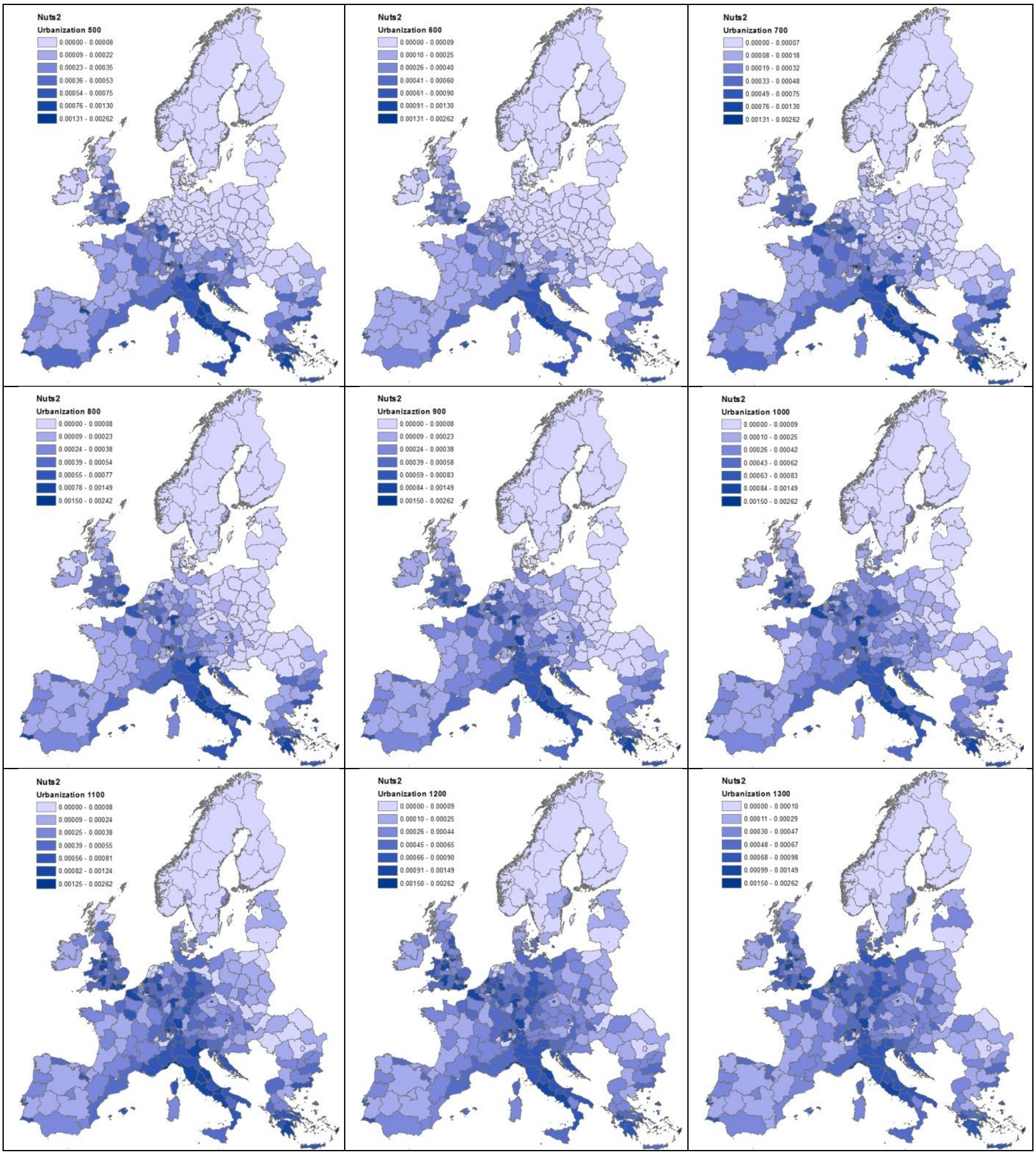
## Appendix C: Population density, soil and suitability maps

## Figure C1: Average population density in Europe AD 500-1300 at NUTS 2 level



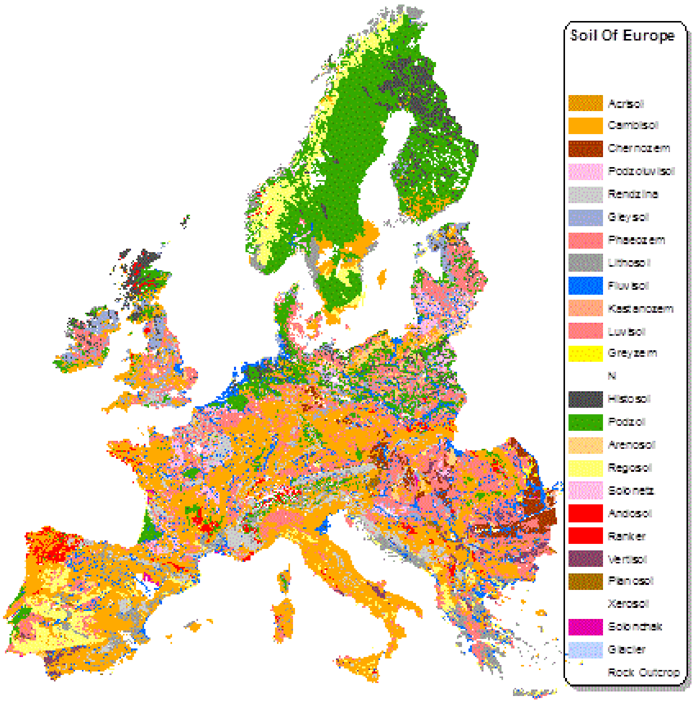

Source: Goldewijk (2010) and own calculations

**Figure C2: Average urbanization in Europe AD 500-1300 at NUTS 2 level**



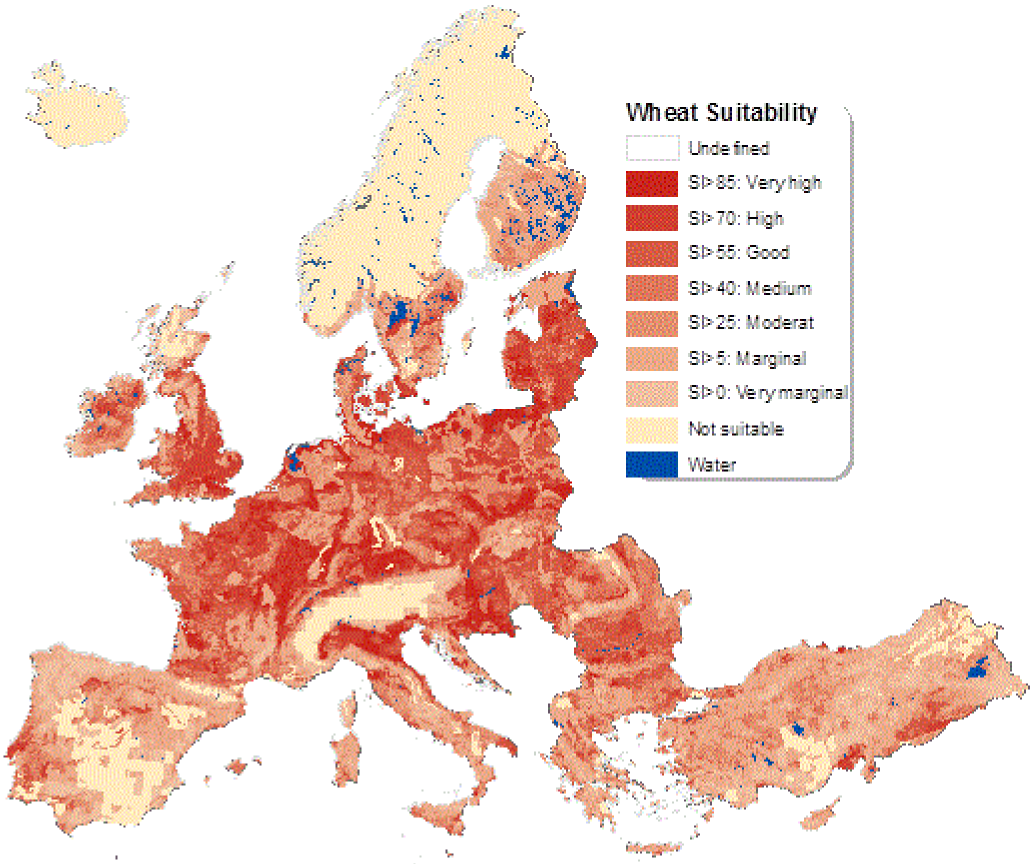

Source: EurAtlas and own calculations

**Figure C3: Distribution of soil in Europe, dominant soil**




Source: The European Soil Database

**Figure C4: Wheat 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%.

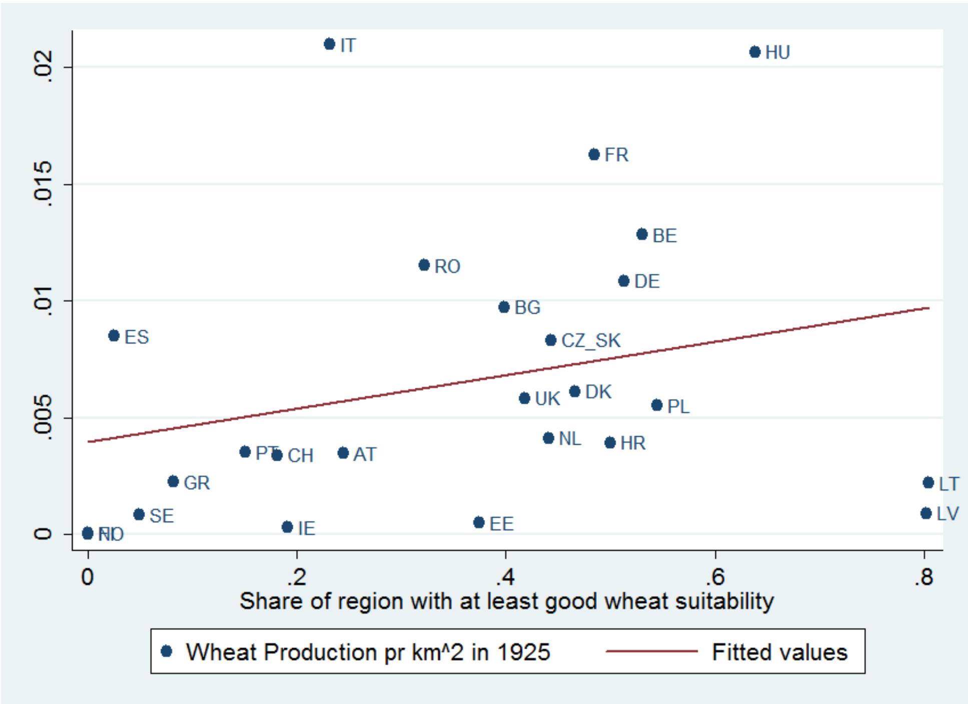
**Appendix D: Modern and historical soil maps.**

In this appendix, we probe into 1) the use of present-day suitability for growing plough-positive crops and 2) the use of modern soil maps 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 wheat production in metric tons in 1925 per square kilometer from Mitchell (2007).[2] The scatter plot shows a positive but insignificant correlation between the two; see figure D1. While the relation is not very strong at the national level, we expect it to be much stronger in sub-national data given the regional variation present in the map shown in figure C4. Unfortunately, such data are unavailable for the whole of Europe, but we have tracked down sub-national data for Denmark, to which we turn next.

**Figure D1: Actual wheat production in 1925 and FAO suitability**



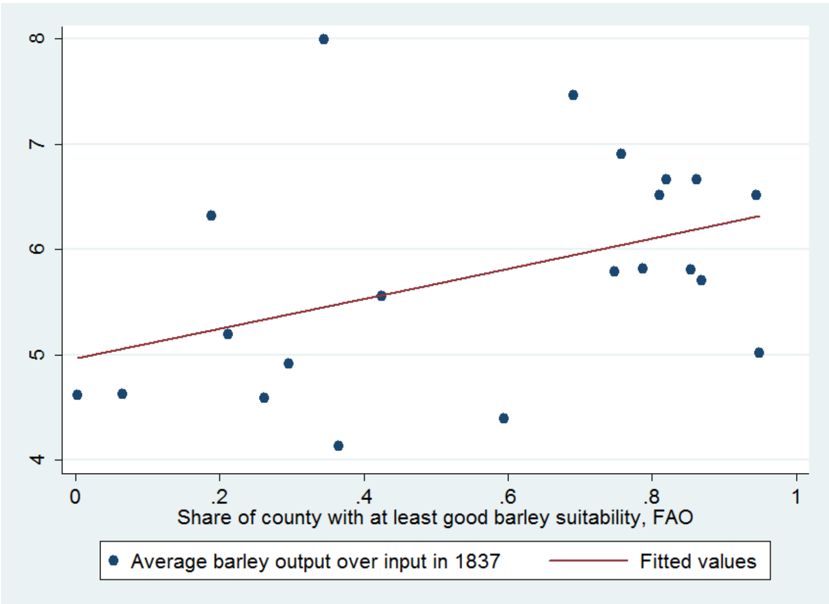

Note: Coefficient $= 0.0072, t\text{-stat} = 1.35, N = 25, R^2 = 0.074$.

We have data on historical soil fertility in the form of barley, rye and wheat yields[3] from 1837 and payments of tenants to landlords (known as "*Landgilde*") for the 1660s, available at

[2] Entries nominated in hectoliter have been converted into 'metric tons' by multiplying with 0.077.
[3] 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.

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 D2 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.[4] Moreover, Frandsen (1988) conjectures that the geographical distribution of tenant barley payments in the 1660s reflects soil fertility.[5] To test this, we regress the payment density at the county level on the FAO barley suitability measure, leaving out regions completely or partly without data on payments.[6] We find a positive and strongly significant relationship between the payments and FAO's suitability measure; see Figure D4. These results are in line with the conjecture that the relation would be stronger at the sub-national level, and it indicates that present day soil suitability resembles past suitability.

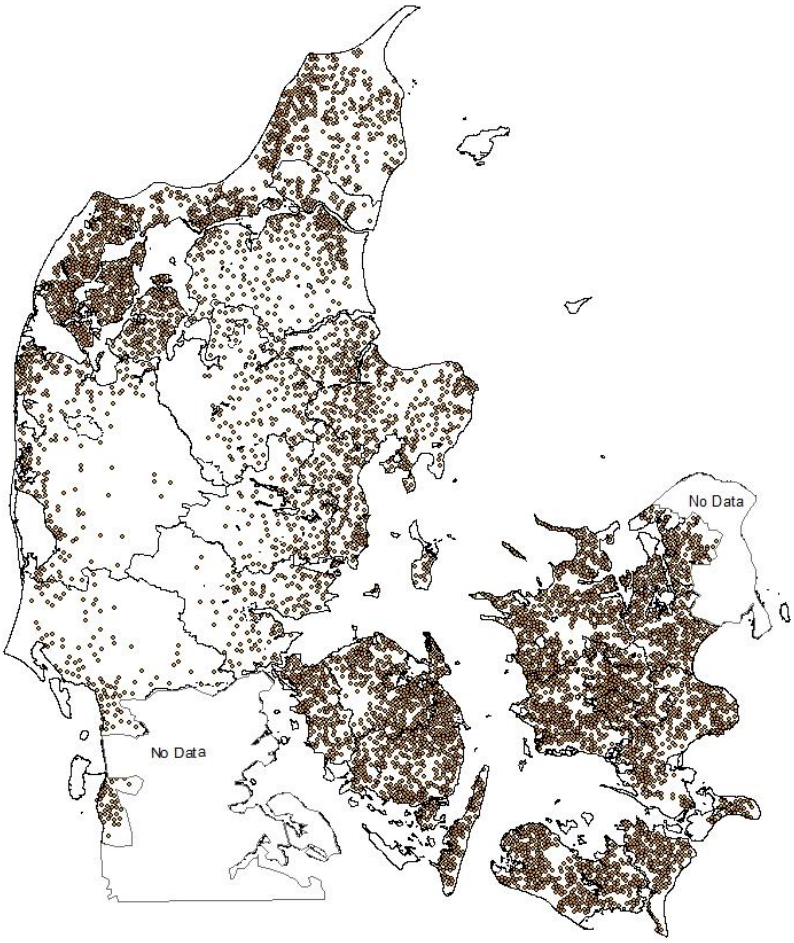
**Figure D2: Barley yields and FAO suitability in Danish counties**




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

[4] Similar pictures emerge for rye and wheat.
[5] We use the map in Figure D3 to construct the measure. Each point on the map represents 20 toender barley in payment. Toender is an old Danish measure.
[6] Keeping counties only partly represented in the payment data only increases the significance.

**Figure D3: Tenant barley payments in 1662**



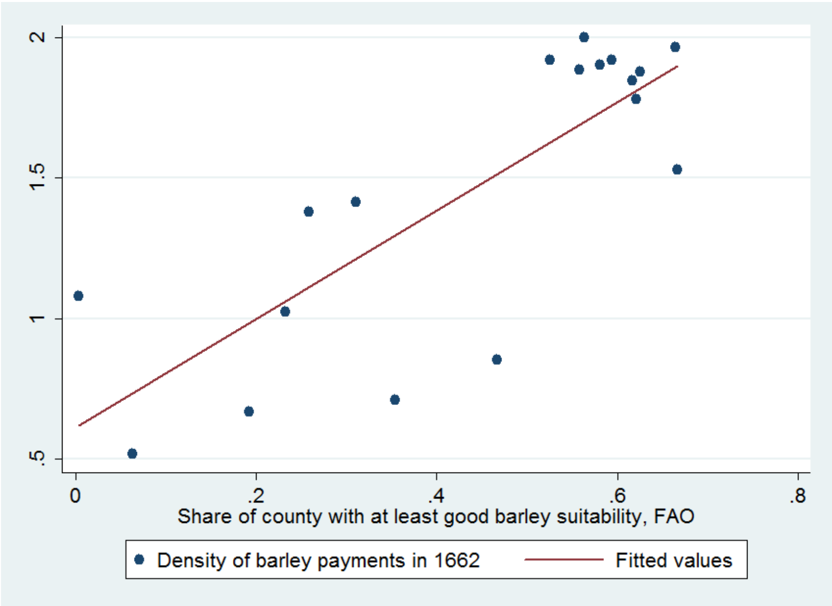

*Use of present day soil maps for identifying the location of clay soils*

To investigate whether the use of present day soil maps captures historical soils, we have digitized an older soil map which dates back to 1912.[7] To the best of our knowledge, this is the oldest soil map for Denmark. Correlating the share of clay soil in 1912 with our present-day soil measure reveals a strong positive correlation; see Figure D5.[8] This suggests strong persistence in the location of clay soils, and it adds further credibility to our maintained assumption that the present-day location of clay soils accurately reflects the past.

[7]As explained in the main text, the map is 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.

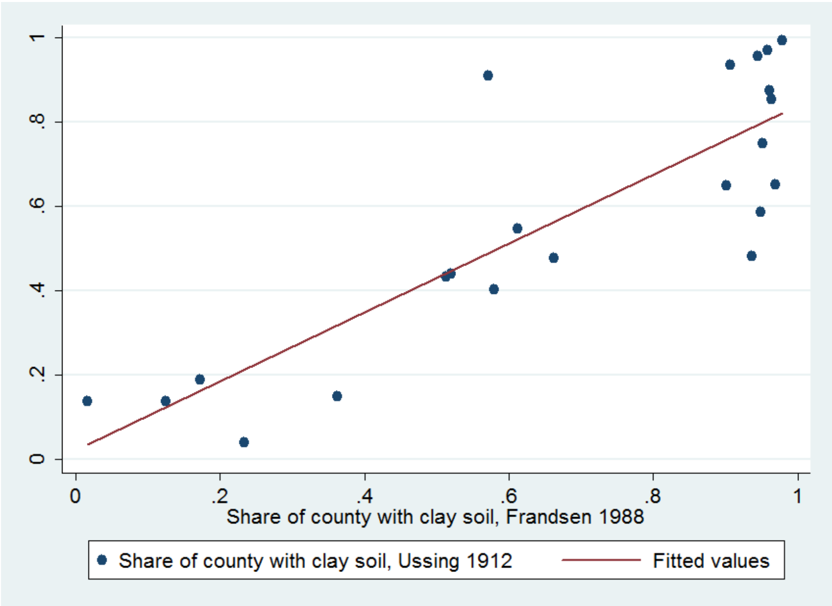
[8] Three counties are left out due to missing data. Data are partially available for two counties, and if we keep them we obtain similar results.

**Figure D4: Barley payments in 1662 and FAO barley suitability**




Note: Coefficient $= 1.9352, t\text{-stat} = 5.31, N = 18, R^2 = 0.63$

**Figure D5: Historical and present day clay soil**




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

**Appendix E: Further robustness and information on urbanization data.**

In this appendix we supply additional tables on robustness and data. Robustness to changes in the definition of variables and additional variables are discussed.

*Additional controls*

Table E1 and E2 add alternative geographical and institutional controls respectively. First, Table E1 examines the robustness of our measure of proximity to the coast by using a dummy for being non-landlocked. This change is inconsequential for results, see columns 2 and 6. Studies of cross-country differences in GDP per capita across the world often include latitude as a control for geographical differences. Across countries, this variable captures differences in e.g. agricultural productivity or disease environment between temperate and tropical zone countries; see e.g. Acemoglu et al. (2005a). In the European case we present below, it is less clear what it presents. For example, since clay soils are more present in the north, latitude would arguably capture this variation within a European context. Nonetheless, we have investigated whether including latitude matters for results, and we find that the coefficient to our urbanization measure change little for the European (and the Danish) case, but precision decreases with significance at the ten and five percent level respectively, see column 3. For population density, the coefficient drops substantially and significance drop to the 10 percent level, see column 7. These results suggest that latitude and the presence of fertile, clay soil may capture some of the same variation within Europe, but a role for the plough still remains. For the Danish case, latitude hardly matters except for reducing precision. Denmark is in itself a high latitude country, and the fact that we find a role for the clay soils within Denmark is strong evidence that we are not merely capturing unobserved heterogeneity associated with the latitude of a region. Columns 4 and 8 show results including regions with a share of undefined soil above 20%, which we leave out in our main analysis for uncertainty reasons. Including them increases the estimated effect as well as standard errors, hence leaving the significance largely unchanged.

Table E2 adds a number of countries to the Roman heritage measure again with little effect on the results; see columns 2 and 5. While we do not have strict exogenous variation in institutions, we are able to control for whether a region was a part of the Carolingian empire where feudalism originated; see Blaydes and Chaney (2013). We use the part of a region that was a part of the Carolingian empire in AD 800. This variable may be interpreted as measuring effects of early feudalism. Controlling for this has little impact on the results, see columns 3 and 6.

## Table E1: Robustness to alternative geographical controls

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
|---|---|---|---|---|---|---|---|---|
| | Dependent variable | | | | | | | |
| | ln(1+Urbanization) | | | | ln(Population density) | | | |
| ln(1+PloughFraction(55))*$I^{Post}$ | 0.00024** | 0.00021* | 0.00020* | 0.00033* | 0.635*** | 0.664*** | 0.367* | 0.701*** |
| | (0.00011) | (0.00011) | (0.00011) | (0.00018) | (0.211) | (0.219) | (0.189) | (0.208) |
| Alt. coast measure | No | Yes | No | No | No | Yes | No | No |
| Latitude | No | No | Yes | No | No | No | Yes | No |
| Full set of controls | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| FE (Time and Region) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 2,421 | 2,421 | 2,421 | 2,511 | 2,421 | 2,421 | 2,421 | 2,511 |
| R-squared | 0.89 | 0.89 | 0.89 | 0.82 | 0.97 | 0.97 | 0.98 | 0.97 |

Notes: Colums one and five report main results for reference. Columns two and six show the results using the robust coast measure constructed as a dummy variable for not being land locked. Columns three and seven show results controlling for latitude. Columns four and eight show results including regions with a share of undefined soil above 20 %. PloughFraction(55) = fraction of region with luvisol and good wheat suitability (SI >=55). $I^{Post}$ = 1 if year >= 1000 Clustering at NUTS 2 level. Robust t-statistics in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

## Table E2: Robustness to alternative institutional controls

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | Dependent variable | | | | | |
| | ln(1+Urbanization) | | | ln(Population density) | | |
| ln(1+PloughFraction(55))*$I^{Post}$ | 0.00024** | 0.00024** | 0.00024** | 0.635*** | 0.646*** | 0.596*** |
| | (0.00011) | (0.00011) | (0.00011) | (0.211) | (0.220) | (0.186) |
| Alt. roman heritage | No | Yes | No | No | Yes | No |
| Carolingian empire | No | No | Yes | No | No | Yes |
| Full set of controls | Yes | Yes | Yes | Yes | Yes | Yes |
| FE (Time and Region) | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 2,421 | 2,421 | 2,421 | 2,421 | 2,421 | 2,421 |
| R-squared | 0.89 | 0.89 | 0.89 | 0.97 | 0.97 | 0.97 |

Notes: Colums one and four report main results for reference. Columns two and five show the results using a robust Roman heritage measure constructed as: Roman Heritage plus Bulgaria, Greece, and Romania. Columns three and six show results controlling for Carolingian empire constructed as the share of the region that was under Carolingian control in 800 AD. Before 800 AD (the peak of the Carolingian empire) the variable is coded as zero for all regions. PloughFraction(55) = fraction of region with luvisol and good wheat suitability (SI >=55). $I^{Post}$ = 1 if year >= 1000 Clustering at NUTS 2 level. Robust t-statistics in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

*Additional Information on urbanization datasets*

**Table E3: 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 E4: 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 E5: 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 E5 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 E6: 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 E6 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 $12^{th}$ and $13^{th}$ century from Germany. |
| Czech Republic | Duby (1968, p. 18) cites evidence that the plough was introduced in Moravia between the $7^{th}$ and $8^{th}$ 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 6. 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).<br>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)<br>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 $\lambda_i$ 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, 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.