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Abstract

Does the prosperity of medieval manors depend on their position in the feudal system? How large are these effects? And what are the economic mechanisms behind it? To answer these questions, we estimate an econometric interactions model on data derived from the Domesday Book, a unique country-wide survey conducted by William the Conqueror two decades after the Battle of Hastings. Domesday Book presents researchers with a unique insight into the feudal structure of a medieval society and the functioning of manorial economies. Using this source, we reinterpret the 11th-century English feudal system as a network in which manors are linked to one another based on their common ownership structure. Our results reveal the existence of external economies of scale: manorial prosperity was closely intertwined with the fortune of their feudal peers, even after including rich agricultural and geographic controls. We decompose these significant, positive interaction effects into two mechanisms: scale and productivity spill-overs. The latter are interpreted as common management structures and knowledge transfers in an information-constrained feudal world.

JEL Codes: L14, N33, O33

Keywords: Domesday Book, medieval economic history, network economics

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1 Introduction

The most characteristic feature of the civilization of feudal Europe was the network of ties of dependence, extending from top to bottom of the social scale.

— Marc Bloch in *Feudal Society* (1968, 282)

Few authors have described the pervasive nature of feudalism as vividly as French historian Marc Bloch in his seminal work. For centuries, feudalism has been one of the most prominent features of European economies, shaping economic behaviour through institutionalized interactions among land ownership. Accordingly, this paper presents first empirical evidence on the economy-wide significance of the 11th-century English feudal system, facilitating agricultural cooperation and information sharing among feudal landowners and their managers.

The possibility of such interdependencies between Anglo-Norman manors has been coined before by medieval historians. It is hypothesized that inter-manorial connections led to efficiency gains in the production of grain and livestock, leading to a rise in the prosperity of these manors relative to their unconnected counterparts. For instance, Wareham (2005, 107) hypothesizes that inter-manorial connections, among other factors, could have led to efficiency gains in the production of grain, livestock and other agricultural produce, “thereby leading to a rise in the valuation of the estates relative to their counterparts”.

There are credible reasons to believe this was indeed the case in the High Middle Ages. Scholars working on later periods have found evidence on economic cooperation across English manors with respect to cattle management and transportation.¹ Also, historical reconstructions of agrarian productivity have highlighted the importance of inter-manorial coordination in management decisions (Biddick & Bijleveld, 1991; Karakacili, 2004). Such interactions plausibly led to information transfers along the feudal network. In his seminal work on English medieval agriculture, Campbell (2006, 421) writes that “much information and advice must also have been exchanged between manors belonging to the same estate and estates belonging to the same religious order”.

¹This is mostly based on ecclesiastical manorial accounts from the Late Middle Ages. Biddick (1989, 86) documents how Peterborough Abbey in the early 14th century used inter-manorial transfers to and from specialized breeding manors to correct for cattle shortages and surplus elsewhere on the estate. Also, Slavin (2012, 107) highlights how Norwich Cathedral Priory authorities in the 14th century established cooperation across its respective manors in the transportation of their agricultural produce.

Quantitative evidence is limited, however, as all econometric research on Domesday Book proceeds by modelling the manors as independent entities, ignoring these rich patterns of interactions². In the ensuing analysis, we take a different approach and allow for two plausible interaction mechanisms: scale and productivity spill-overs. In the former, production costs are cut by agglomeration effects, such as the efficiency gains arising from large-scale transport among feudal peers. The latter are interpreted as productivity gains through common experiences with regards to successful management practices. Both mechanisms are reminiscent of Marshall's (1890) external economies of scale, but now applied to feudal instead of geographic distance.

To disentangle these two mechanisms, we reinterpret the feudal system as a network in which manors are linked to one another based on their common ownership structure. Making use of this feudal network, our empirical interactions model provides a rich yet parsimonious description of the interdependencies between manors, while also controlling for spatial autocorrelation through the geographic network. We argue that the sparse and non-overlapping nature of both networks allows us to separately identify the two economic mechanisms at hand and to assess the relative contributions of feudalism and location. To construct the feudal network, we make use of the Hull Domesday Project database (Palmer, 2010), which provides the most up-to-date identification of landowners in 11th-century England. Identification of manors' tenants-in-chief and lords allows us to link manors to one another based on their common ownership structure. The database also contains the monetary value, resources, and location of each manor. The latter is used to construct the geographic network, which allows us to control for spatial clustering. In addition, we also impute environmental determinants of manorial wealth such as agricultural suitability from the Global Agro-Ecological Zones project (Fischer et al., 2012) using geographic information system (GIS) methods.

Our results reveal that a manor's prosperity, as expressed in terms of its value, was closely intertwined with the fortune of its feudal peers³. While we highly strongly

²For example, see McDonald and Snooks (1986), McDonald (1998), McDonald (2015) and Walker (2015).

³We use the terms value, wealth and production interchangeably. In Domesday scholarship, it is commonly accepted that the manorial monetary valuations reflect their productive capacity and are, by extension, (part of) the landowners' wealth accumulation. In this context, this paper defines observed productivity as the ratio of a manor's value and resources.

significant results for both mechanisms, the productivity spill-overs clearly dominate the scale spill-overs in terms of economic importance. Including rich geographic controls, we also report evidence for external economies of scale through the geographic network. To account for the obscurities in Domesday Book, we perform multiple sensitivity assess to mitigate the impact of sample and variable selection, outliers, and network mismeasurement. Under all these sensitivity checks, our results remain remarkably robust.

Our contribution to the literature is threefold. First, we are the first to model the feudal system as a network of interactions that is suitable for econometric analysis. In doing so, we establish the existence of feudal coordination in the management of agricultural activities in the England of William the Conqueror. From a more broad perspective, we also contribute to the strand of research on how socio-economic and political networks played a role in economic history. It is now widely recognised that such networks are central to the understanding of historical interactions in trade, business and the diffusion of knowledge and technologies (see the recent overview by [Esteves & Mesevage, 2019](#) and references therein). Although being a prime example of a network in economic history, no formal econometric analysis has ever been undertaken on feudal interactions.

Second, our analysis adds to the understanding of how information played an important role in medieval economies. The existence of inter-manorial coordination across the kingdom suggests that transaction costs in 11th-century economies were not excessively high. It has long been believed that information was scarce in pre-industrial economies, with transaction and information transmission costs being exacerbated by limited means of communication and transport. Over the past decades, however, economic history research has rehabilitated the role of medieval markets and commerce, establishing the idea of a commercial revolution in the long 13th-century (for a notable example on England, see [Britnell, 1993](#)).⁴ Reductions in transaction costs are considered to be an important driver of market activity in medieval times ([Hatcher & Bailey, 2001](#), 155).

Nevertheless, it is only when literacy became more widespread in the 13th-century, that historical sources started to emerge to document such claims. Indeed, 14th-century

⁴This commercialization hypothesis is still subject to academic debate. For a more critical appraisal, see [Schneider \(2014\)](#).

purveyance accounts reveal that transport costs were “remarkably low” (Masschaele, 1993, 266).⁵ Furthermore, building on 13th-century price data, Clark (2015) has recently emphasized that grain markets were more integrated and efficient than previously thought. Evidence regarding transaction costs in the early periods of the High Middle Ages is, however, more scarce.⁶ Our findings shed first light on the idea that 11th-century transaction costs might also not have been as high as previously assumed.

Third, we provide a more nuanced view of medieval institutions. While feudalism might be detrimental for aggregate welfare, it also provided a platform through which common experiences on successful management practices and the efficient exploitation of their production factors, be it their lands or their labor, were exchanged.⁷ Others have successfully shifted attention away from the predominantly pessimist views of medieval institutions. For instance, Epstein (1998) famously argues how medieval guilds emerged to provide a framework in which skills and technological innovations could be transferred. Such an argument draws analogies with our interpretation of feudal interactions, which allow for the transmission of best-practice agricultural techniques. A contrasting view, however, emphasizes the inefficient nature of guilds, giving rise to rent-seeking and other economic growth-detering behavior (Ogilvie, 2004, 2019). Interestingly, a similar dichotomy lies at the root of the intense debate on whether feudal institutions were an efficient outcome or rather a rent-seeking construction (for notable examples, see North & Thomas, 1973 and Brenner, 1976 respectively).

Recently, economists have typically adhered to the latter, more negative appraisal, pointing at the feudal system as the culprit for centuries of limited economic development in medieval Europe. Most notably, Acemoglu and Robinson (2012, 176) claim that feudal institutions “formed the basis for a long period of extractive and slow growth in Europe during the Middle Ages”. The main idea is that these institutions were designed to extract wealth from the many peasants to the few elite landholders. The results in this paper provide first evidence on how feudal networks facilitated wealth accumulation of well-connected landowners within the institutional framework

⁵See also the discussion and references in Langdon and Claridge (2011).

⁶An early contribution on the accomplishments in early medieval transport and communication can be found in Leighton (1972). The lack of material for the historian to work with is emphasized, asserting that this period “provides little grist for the scholar’s mill” (Leighton, 1972, 10).

⁷In other words, our results do not conflict with either view on feudalism in the aforementioned efficiency debate. Domesday Book only presents information on the seignorial economy and, as a consequence, does not allow for claims on the aggregate welfare effects of feudalism.

of feudalism.

The remainder of the paper is structured as follows. In Section 2, the Domesday Book and its historical background are introduced. Section 3 provides reduced-form evidence on the determinants of manorial prosperity and argues for the need to incorporate the feudal network, a key and pervasive feature of the medieval economy, in the econometric model. Results of this exercise are presented in Section 4, in which we find significant and positive external economies of scale across the geographic and feudal network alike. In Section 5, we discuss the driving factors of the latter productivity effect. Section 6 contains a sensitivity analysis. Finally, Section 7 concludes.

2 Domesday Book

2.1 Historical background

The Norman conquest of England was a landmark event in the history of Medieval Europe. Following the death of the childless Anglo-Saxon king Edward the Confessor on 5 January 1066, William, Duke of Normandy, made a claim to the English throne. King Edward was, however, succeeded by Harold, his brother-in-law. This pressed William to gather an invasion fleet of French and Flemish soldiers, which landed in Sussex, southern England, on 28 September. On 14 October 1066, the English army of King Harold, who himself was killed in battle, suffered a decisive defeat to the Norman army. The decades that followed were characterized by a long and difficult period of consolidation. English lordship loyal to the former king were replaced by those who fought alongside William.

The 11th-century England of King William I, later hallmarked as William the Conqueror, was organized by a feudal system in which landowners, i.e. the *tenants-in-chief*, received land directly from the king in return for financial and military support. While this concept of knight service has long been believed to be a Norman innovation (Round, 1895, 225-314), it is now established that the Anglo-Norman feudal system was strongly built on the foundations of the ownership structures which were already in place (see Roffe, 2007, ch. 5 for a discussion). These landowners, which comprised both nobility as clerics, could in turn sublease their land to others, i.e. the *lords*, or operate the landholdings themselves. This hierarchical network of landowners played

a defining role in the workings of medieval economies. Agricultural activities were organized around the landowners' manors and were performed by various types of workers. Peasants were typically bound to the land at which they resided, and often also to its lords, to which they owed labor service.

Almost twenty years after his coronation, William the Conqueror announced an inquiry into the state of affairs his kingdom. What followed was a remarkable exercise of central administration for its time. The kingdom was divided in (presumably) seven circuits, which were all visited by a team of commissioners. Tenants-in-chief were interrogated on the present and past ownership of their holdings, its values, its population and the available economic resources, such as ploughs and livestock. Before their submission to the Exchequer in Winchester, local boards of four English and four Norman jurors were tasked to verify the landowners' answers.⁸ The pervasive nature of the feudal hierarchy presents itself in the structure of the book, which was organized not on a geographic but on a feudal basis (Darby, 1977, 4-9).

The result is a historical document which showcases a uniformity and geographic coverage incomparable to any other historical source in medieval Europe. Due to its definite character, this 'Book of Winchester' earned the name 'Domesday Book' in the century to come (Harvey, 2014, 271-273).⁹ Domesday Book presents researchers with a unique insight into the feudal structure of a medieval society and the functioning of contemporary rural economies. Nevertheless, it should be emphasized that Domesday Book is far from a straightforward document. The original source is recorded in Latin and requires careful translation. Its presentation based on the feudal structure makes it challenging to reconstruct the regional character of England's population and agricultural activities. These challenges have brought forth a large literature of Domesday scholarship ever since the end of the 19th-century.¹⁰ In what follows, we showcase how these fundamental contributions can be employed to construct a database fit for our econometric interactions model.

⁸Not all stages of the data collection process can be easily reconstructed by current-day research. See Harvey (2014) for a comprehensive discussion of the organization of the inquest and its obscurities.

⁹Domesday Book actually consists of two parts: Great or Exeter Domesday book, which is the definite version compiled by the Exchequer clerics, and Little Domesday Book, a preliminary and unabbreviated version. The former covers the first six circuits, while the latter contains information on a seventh circuit covering eastern England.

¹⁰Round (1895) is typically considered to be the founding father of modern Domesday scholarship. The references in this section only serve as an illustration of the vastness of the available literature.

2.2 Data description

Domesday database We rely on the work of [Palmer \(2010\)](#) and his team of the Hull Domesday Project (HDP). This data set provides a comprehensive overview of all manors in 1086 England, their resources and their value in shillings at the time of the conquest, 1066, and at the time of the inquest, 1086. To achieve this, the recorded resources of all seven circuits were carefully distributed across manors. While other translated and digitized versions of the Domesday Book exist, the HDP database is the only version which is constructed with statistical analysis in mind.

The HDP database also contains a comprehensive list of all Domesday landowners in 1066 and 1086. Importantly, they identified and standardized a majority of the 1086 landholders.¹¹ In the presence of inconsistent reporting of personal names, a phenomenon which should be expected given the historical nature of the source at hand, this is of crucial importance. In this effort, the Hull team was supported by decades of work of preceding Domesday scholars.¹² Using this database, we constructed a unique identification variable for every identified landowner. It is safe to assume that this is the closest one will ever come to reconstructing a complete feudal system for economic analysis.¹³ Nevertheless, it is still worth emphasizing that network mismeasurement and selection bias are important considerations in this context. We will return to these issues in Section [6](#).

Manors' resources Economic activities in English manors around 1086 were mainly organized around growing crops and raising animals. Domesday Book illustrates that especially arable farming, i.e. the cultivation of crops,¹⁴ was of crucial importance: the number of ploughteams and the amount of ploughs needed to bring the manor to full production capacity received a central place in the inquiry. In contrast, the livestock

¹¹The coverage of the 1066 landowners is incomplete at best.

¹²A comprehensive list of this literature is supplemented to the electronic version of the database. The impressive work of [Keats-Rohan \(1999\)](#) deserves special credit, as [Roffe \(2007, 164\)](#) describes how she “has identified almost all the holders of land in 1086”.

¹³[Lowerre \(2016, 227\)](#), for example, claims that “Palmer’s identifications are doubtless among the best and most comprehensive currently available”.

¹⁴Efforts were mainly concentrated on the cultivation of grain (wheat, rye, barley and oats), with legumes (mostly peas and beans) being less important ([Dyer, 2009, 14](#)).

counts were redacted out of the final version of the Great Domesday Book.¹⁵ In this context, we specify the resources which could explain the variation in wealth across manors.

A first resource important to production was the availability of labor. Domesday Book provides an intricate categorization of laborers depending on their legal status, ranging from the *liberi homines* (free men, not bounded to land) to slaves (serfs). Following Walker (2015), we simplify this subdivision by making the distinction between slave labor and all other forms of labor.

The high reliability on the cultivation of crops implies that ploughs and land were capital goods of high importance. Recent empirical research has highlighted the crucial impact of plough technologies on long-run agricultural productivity (Andersen, Jensen, & Skovsgaard, 2016). Domesday Book records the number of ploughs available at each manor. In addition, both the quantity and quality of its land were essential to the determination of a manor's value. Domesday Book is the only medieval source which casts a light on the amount of arable land, albeit a very oblique one (Campbell, 2006, 386-387). Landowners were asked the extent of their manors, expressed as land for so many ploughs. In theory, this is a straightforward measure of arable land. Despite its simpleness, the ploughlands variable is one of most disputed pieces of information in Domesday Book, with scholars pointing at inconsistent reporting and the infamous phenomenon of 'overstocking' (i.e. manors where the amount of ploughs exceed the number of ploughlands). Moreover, little consensus exists on whether the ploughlands should be considered as a measure of land, or rather as a fiscal measure (Roffe, 2007, 203). For the purpose of our analysis, we propose two ways forward. First, we take the ploughlands variable at face value in our main estimates. Second, we propose a robustness check in which we assume that land was a perfect complement to the other two key determinants of manor wealth, capital and labor, discarding the need for a

¹⁵The relative importance of crop cultivation is supported by both our and earlier empirical analyses for subsamples of Domesday Book for which figures survived: livestock contributed little to the Domesday value of the manor (McDonald & Snooks, 1985; Walker, 2015). In this context, we are bound to follow many traditional historians in the assumption that agricultural performance in the cereal and livestock sectors are highly intertwined. However, it must be said that due to its difficult-to-quantify nature, the role of husbandry in medieval agriculture remains a contentious topic (for a discussion, see Biddick, 1989, 1-4).

land quantity variable.¹⁶

With respect to the quality of the land involved, we link the locations of the Domesday manors with a contemporary GIS database on the suitability of English lands for agriculture. The former are identified by the Palmer team, with their coordinates being approximated to the nearest kilometre. For the latter, the Global Agro-Ecological Zones (GAEZ) project (Fischer et al., 2012) provides environmental suitability indices for a variety of crops. To approximate 11th-century agricultural conditions as closely as possible, we use the GAEZ classification for barley suitability under the assumption of traditional management, i.e. the usage of only labor intensive techniques without the application of nutrients, irrigation or other contemporary techniques.¹⁷

As far as we are aware, no-one has ever attempted to empirically investigate the relationship between the wealth of feudal landowners and the geological characteristics of their lands, despite that authors have argued that 20th-century soil maps are informative of past conditions (for a discussion, see Andersen et al., 2016, 143).¹⁸

Sample selection Finally, we impose a series of plausible sample conditions. First, as this analysis only concerns landholdings which are economically active, we drop manors that did not generate any value. In other words, we are solely concerned with economic decisions on the intensive margin, rather than the extensive margin. Second, we require that both labor and capital resources are recorded in the data. Likewise, we drop observations with missing and zero values for the ploughlands variable in our main analysis. Third, a manor sometimes refers to more than one place. For our main analysis, we restrict the sample to single-location manors. Finally, the landowners of

¹⁶For further discussion, see Section 6. Other than ploughlands, Domesday Book also reports meadow, pasture and woodlands. McDonald and Snooks (1986) use this information as a measure of land in their regional study of the counties of Essex and Wiltshire. These variables are, however, inconsistently reported. Moreover, the heterogeneous use of all kinds of measures make the standardization to a common denominator, such as acres, impossible (see, for example, Darby 1977, 142, 190). As a result, it is impossible to incorporate these variables into an analysis at the national level.

¹⁷We also considered a similar suitability index for wheat cultivation. This index is, however, highly correlated with the measure for barley and consequently adds little to the analysis.

¹⁸As Lowerre (2016) recently emphasized, the full richness of the Domesday England's geography has never been utilized in the literature. An exception is the local study of McDonald (1998) on the county of Essex, which found an insignificant connection between manorial efficiency and soil type. However, he only considered soil types and did not address the issue of agricultural suitability.

about 15% of all manors in Domesday Book are unidentified. As these manors' lords were presumably less important landholders, we assume that these are unique to the manor and therefore do not have other possessions. The impact of alternative sample selection and identification rules is discussed in Section 6.

3 Relationship between manorial values and resources

We establish the relationship between the values y_i of manors i and its aforementioned resources \mathbf{x}_i (both expressed in logarithms)¹⁹ For now, we assume that manors in 11th-century England operated as separate, individual entities, regardless of their position in the feudal system. The following baseline equation can then be estimated using Ordinary Least Squares (OLS):

$$y_i = \alpha + \mathbf{x}_i\boldsymbol{\beta}' + \varepsilon_i, \quad \mathbb{E}[\varepsilon_i | \mathbf{X}] = 0. \quad (1)$$

The left-hand side of Equation (1) is expressed in shilling prices, in contrast to the right-hand side which is expressed in quantities. In the case of a constant ratio of prices of capital and labor across the Anglo-Norman kingdom, however, this does not affect our estimate of $\boldsymbol{\beta}$. If one assumes that a manor's value is determined by its agricultural production, it is easy to interpret Equation (1) as a Cobb-Douglas production function, in which $\boldsymbol{\beta}$ then represents output elasticities of the respective resources.²⁰

Table 1 presents the correlations between the manorial values and the resources recorded in the Domesday Book. Our results can be easily compared with earlier analyses at the local level, such as the ones in McDonald and Snooks (1986) for the counties of Essex and Wiltshire, as well as with the more recent work of Walker (2015), who was the first to estimate a similar relationship at the national level. Just like these studies, we observe a strong relationship between manorial resources and their values. The availability of ploughs as a capital good played a crucial role in determining

¹⁹In addition, \mathbf{x}_i includes county and soil quality dummies. In the remainder of the paper, we denote vectors in bold lower case (e.g. \mathbf{x}_i) and matrices in bold upper case (e.g. \mathbf{X}).

²⁰A common concern here is the endogeneity of the inputs, i.e. when a manor chooses its inputs based on its (unobserved) productivity ε_i , the OLS estimates might become biased. In a context without developed capital markets and where labor was bound to land, however, it can be argued that inputs were relatively fixed in the short run (McDonald & Snooks, 1986, 116). Consequently, we presume that the effects of this so-called simultaneity bias are limited in our context.

a manor's economic value in each of the respective specifications. Labor that was not fully bound to the lord's ownership, had a somewhat higher contribution to the manorial income than slave labor.

The inclusion of ploughlands as a land quantity measure in specifications (2) and (4) has only a minor impact on the interpretation of our results. This is somewhat to be expected, given the highly collinear nature of the ploughs and ploughlands variables. In addition to previous work, we also include a categorical soil quality variable to all our specifications. These contemporaneous estimates of agricultural suitability do an adequate job in explaining high manorial values, strengthening our prior that the values in Domesday Book represent manorial agricultural activity. The inclusion of county fixed effects in specification (3) and (4), however, appears to absorb most of the geographic environment effect. This explains why our coefficients are relatively comparable to previous estimates that assume a linear relationship.²¹ We also note that in these specifications, the coefficients add up to one, providing evidence for constant returns to scale.

Although informative, specifications that do not allow for interactions between manors like Equation (1) might not reflect the economic reality of England under William the Conqueror. It has already been emphasized that the manorial economy was organized along the foundations of the Anglo-Norman feudal system. In such a context, it is more than likely that the manors which shared similar ownership also shared similar economic outcomes, conditional on the manors' environmental endowments. In the next section we therefore introduce an empirical interactions model that provides a rich yet parsimonious description of this dependency structure between manors. In particular, we hypothesize that every manor is part of both a feudal and a geographic network that might affect its productivity and therefore value. As illustrated by Esteves and Mesevage (2019), such an interactions model is more appropriate to capture these interdependencies than OLS regressions that contain controls for some network summary statistics, like a manor's number of feudal peers or ownership dummies.

²¹Aside from providing a satisfactory way to control for local effects, another advantage of including county fixed effects is that it alleviates concerns of variation in administrative practices across circuits. English counties were grouped in seven circuits with potentially diverging administration practices (cfr. Section 2.1).

Table 1: **Relationship between manorial value and resources (OLS)**

Parameter		(1)	(2)	(3)	(4)	
Labor: non-slaves	β_1	0.23*** (0.01)	0.24*** (0.01)	0.19*** (0.01)	0.18*** (0.01)	
Labor: slaves	β_2	0.17*** (0.01)	0.14*** (0.01)	0.13*** (0.01)	0.10*** (0.01)	
Capital: ploughs	β_3	0.62*** (0.01)	0.54*** (0.02)	0.66*** (0.01)	0.57*** (0.02)	
Land: ploughlands	β_4		0.12*** (0.01)		0.13*** (0.01)	
Land: suitability	High	β_5	-0.02** (0.01)	0.04*** (0.01)	-0.02** (0.01)	-0.01 (0.01)
	Low	β_6	-0.21*** (0.01)	-0.28*** (0.01)	-0.02* (0.01)	-0.02* (0.01)
Constant	α	-0.25*** (0.01)	0.31*** (0.01)	-0.16*** (0.02)	-0.21*** (0.02)	
County FE				YES	YES	
Observations		12,222	9,084	12,222	9,084	
R^2		0.72	0.74	0.81	0.84	

Note: Reference category for the land suitability variable is ‘moderate’.

Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

4 The role of the feudal network

4.1 Network construction

Feudal network To study the feudal interdependencies across Domesday manors, we represent the feudal system of William the Conqueror in one comprehensive network. Such a comprehensive feudal network is composed of various linked neighborhoods. Manor j is defined to be in the feudal neighborhood \mathcal{F}_i of manor i either when they share the same tenant-in-chief (condition *i*) or lord (condition *ii*), or when the tenant-in-chief of one manor is the lord of the other (condition *iii*). Formally, we can write these three conditions as²²

$$j \in \mathcal{F}_i \iff \begin{cases} \text{tenant-in-chief of } i = \text{tenant-in-chief of } j, \text{ or} & (i) \\ \text{lord of } i = \text{lord of } j, \text{ or} & (ii) \\ \text{tenant-in-chief of } i = \text{lord of } j, \text{ or tenant-in-chief of } j = \text{lord of } i & (iii). \end{cases}$$

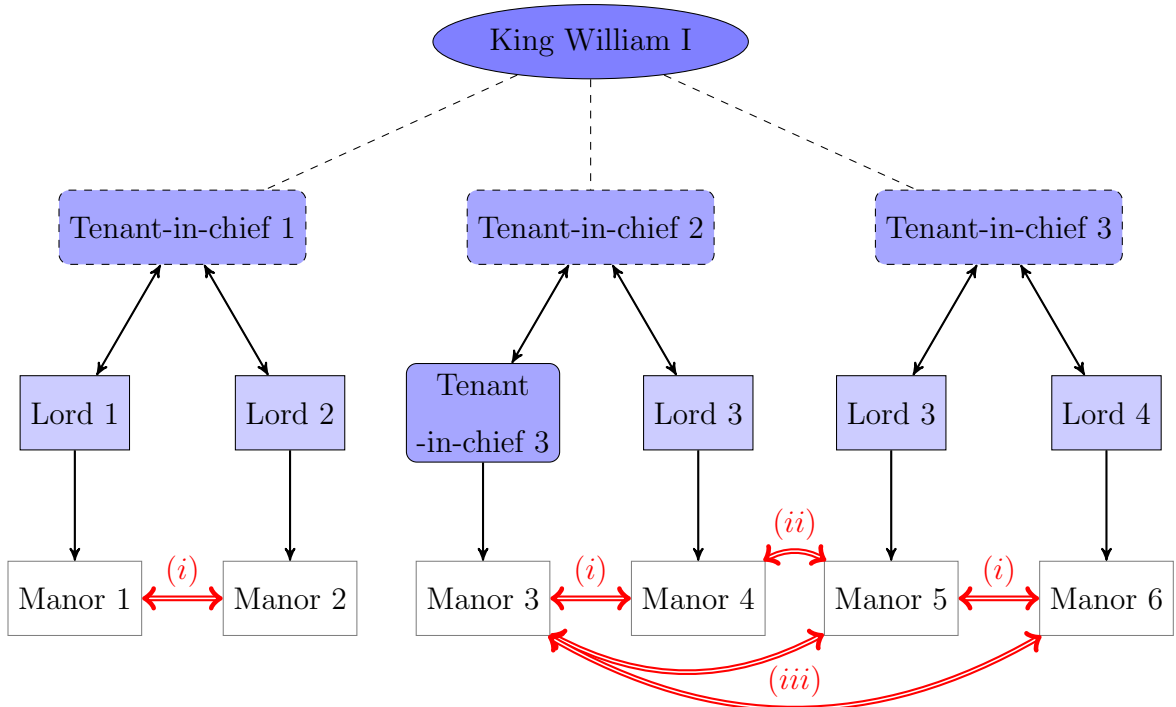
²²In accordance with the literature, we also require that a manor is never part of its own neighborhood: i.e. $i \notin \mathcal{F}_i$. In addition, note that our definition yields undirected network links such that $j \in \mathcal{F}_i$ if and only if $i \in \mathcal{F}_j$.

One can represent the entire feudal network compactly in terms of a symmetric feudal network matrix \mathbf{F} :

$$\mathbf{F} = [f_{ij}], \quad f_{ij} = \begin{cases} 1, & \text{if } j \in \mathcal{F}_i, \\ 0, & \text{if } j \notin \mathcal{F}_i. \end{cases}$$

Example We illustrate these concepts with an example of a simplified feudal system, presented in Figure 1 in which three tenants-in-chief own all of King William's lands. The three landowners in turn sublease their lands to two lords. These could also be tenant-in-chiefs themselves, as is the case for manor 3. Since this construction was not uncommon in 11th-century England, let us consider the neighborhood of manor 3. In our set-up, manors 3 and 4 are connected to each other because of condition (i), i.e. they share the same tenant-in-chief. Because manor 3's lord is also the tenant-in-chief of manors 5 and 6, condition (iii) implies that manor 3 is connected to manors 5 and 6 as well. As a result, elements in the third row (column) of matrix \mathbf{F} will be equal to one in the fourth, fifth and sixth column (row).

Figure 1: A simplified example of the Anglo-Norman feudal network



Note: \Leftrightarrow **arrows** represent links (i.e. edges) in the network.

Applying these definitions to the feudal system as recorded in Domesday Book, we (re)construct the feudal network of 11th-century England. In this network, about 68% of the 1,550,125 links across Anglo-Norman manors are generated by the fact that manors share a tenant-in-chief, i.e. condition (i). Lords were largely dedicated to a specific tenant-in-chief, with only about 2% of the edges rooted in condition (ii). In other words, lords were mostly (but not exclusively) confined to the subtree of their tenant-in-chief. This is intuitive, given that lords were expected to swear an oath of fealty and to attend his vassal’s private courts for advice (Dyer, 2009, 86). Alternatively, tenants-in-chief were connected across subtrees of the network and leased property from other tenants-in-chief in the remaining 30% of the cases.

On the level of the manor, the size of the feudal neighborhood (i.e. degree) shows great variation. On average, a Domesday manor is connected to 136 other manors. Half of the manors, however, have a degree of 59 or less. In other words, the mean degree is skewed by a selection of well-connected manors owned by important landowners such as Robert, Count of Mortain. In Appendix A, Tables A1 and A2 present the most influential tenants-in-chief and lords respectively in terms of the size of their estate. While some regional clustering of manor ownership is to be expected, these networks are not consistently grouped in very specific regions of England.²³ For example, Fleming (1991, 180) describes how Norman holdings in Yorkshire did not form “any sort of compact territory”. This is important, because a perfect overlap of manorial locations and the feudal ownership structure would not allow us to separate the effect of the feudal system from regional determinants of a manor’s value. This regional variation enables us to compare manors with similar location endowments but distinct feudal characteristics to examine the impact of the latter on the holding’s value.

Geographic network To fully account for the importance of regional effects, we also go beyond the inclusion of county fixed effects and construct a geographic network. The resulting matrix \mathbf{G} controls for the distance between all manors in Domesday Book. The idea is that neighboring manors were more likely to interact and could

²³For a visual representation for the major tenants-in-chief and lords, see Figures A2 and A3 respectively in Appendix B. Furthermore, Figure A1 documents that there was considerable regional variation within estates.

more easily observe each others’ successful and failing management practices. Such synergy between two farms i and j becomes less likely when the distance $d_{i,j}$ to one another increases. To capture this, we construct a matrix using double power distance weights,

$$\mathbf{G} = [g_{ij}], \quad g_{ij} = \begin{cases} (1 - (d_{i,j}/d)^2)^2, & \text{if } d_{i,j} \leq d, \\ 0, & \text{if } d_{i,j} > d, \end{cases}$$

in which d denotes the distance from which the influence becomes zero. To obtain our main results, we set this parameter equal to 20km²⁴. The choice of spatial weights is always arbitrary to an extent. Such concerns can fortunately be easily alleviated by a range of robustness checks. These are presented in Section 6. With the construction of matrices \mathbf{F} and \mathbf{G} , we now have the tools to comprehensively incorporate the feudal nature of the manorial economy in our analysis.

4.2 Analysis

Correlational evidence Before extending the model of Section 3, we present some correlational evidence that supports the hypothesis that there was a significant degree of economic interaction across the feudal network. We consider three features of economic activity: the (logarithms of) manorial values, value-to-labor ratios and value-to-capital ratios²⁵. For each of these features, we calculate both regular and partial correlations between a variable containing every manor’s own feature and a variable containing the average feature across the manors in its feudal or geographic neighborhood. The partial estimates exclude the part of the correlation that can be explained by agricultural suitability and county fixed effects²⁶. The results are presented in Table 2.

The high and significant correlation in values across the geographic network reveals the spatial clustering of manors based on their values, an observation which was already established in the seminal geographic study of Darby (1977, 224). Similarly,

²⁴This distance was chosen so it could be covered in a typical day’s journey, as argued in recent historical research (Claridge & Gibbs, 2020, 21).

²⁵We define value to labour as a manor’s value divided by the sum of its non-slave and slave labor, and value to capital as its value divided by the sum of its ploughs and ploughlands.

²⁶We calculate these partial correlations by first regressing both variables on agricultural suitability and county fixed effects and then calculating the correlation between the residuals of both regressions.

we find that that value-to-resource ratios, which can be loosely interpreted as factor productivity, are highly spatially correlated across England. Common determinants of agricultural productivity are a likely explanation for such a pattern, as controlling for agricultural suitability and county level effects absorbs a large part of the correlation.

Crucially, we also find highly correlated features of economic activity across the feudal network. Even conditional on environment, we find a highly significant relationship in the manorial values of feudal peers, as well in value-to-resource ratios. In what follows, we incorporate these feudal interdependencies into our network model to describe the relationship between values and resources in Domesday Book.

Table 2: **Correlations across the feudal and spatial network**

	Feudal connections	Geographic connections
<i>Correlations</i>		
Value	0.490***	0.495***
Value-to-labor ratio	0.381***	0.520***
Value-to-capital ratio	0.517***	0.654***
<i>Partial correlations</i>		
Value	0.352***	0.211***
Value-to-labor ratio	0.125***	0.139***
Value-to-capital ratio	0.224***	0.288***

Note: Values and ratios are in logarithms.

Controls include agricultural suitability and county fixed effects.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

Baseline network model In our baseline network model, we again specify the value y_i of manor i as a linear function of the its resources \mathbf{x}_i and an unobserved error term ε_i . In contrast to reduced-form model (1), however, the manor’s error term is now allowed to be correlated with the error terms of the manors in its feudal neighborhood \mathcal{F}_i and geographic neighborhood \mathcal{G}_i . In particular, we assume this error term to be a linear function of the average error term in both neighborhoods and an independent white noise component η_i . Interpreting the error terms as unobserved productivity,

this set-up allows for spill-overs in productivity between neighbors. Formally, we have

$$y_i = \alpha + \mathbf{x}_i \boldsymbol{\beta}' + \varepsilon_i, \quad \varepsilon_i = \lambda_F \frac{\sum_{f \in \mathcal{F}_i} \varepsilon_f}{|\mathcal{F}_i|} + \lambda_G \frac{\sum_{g \in \mathcal{G}_i} \varepsilon_g}{|\mathcal{G}_i|} + \eta_i, \quad \mathbb{E}[\eta_i | \mathbf{X}, \mathbf{F}, \mathbf{G}] = 0,$$

in which $\boldsymbol{\beta}$ denotes the direct effect of the manor's resources, λ_F captures spill-overs in productivity from feudal neighbors, and λ_G from geographic neighbors.²⁷ Stacking observations, this model can be rewritten compactly in matrix notation:

$$\mathbf{y} = \alpha \mathbf{1} + \mathbf{X} \boldsymbol{\beta}' + \boldsymbol{\varepsilon}, \quad \boldsymbol{\varepsilon} = (\lambda_F \mathbf{F} + \lambda_G \mathbf{G}) \boldsymbol{\varepsilon} + \boldsymbol{\eta}, \quad \mathbb{E}[\boldsymbol{\eta} | \mathbf{X}, \mathbf{F}, \mathbf{G}] = 0, \quad (2)$$

where \mathbf{F} and \mathbf{G} are adjacency matrices as defined in previous section.²⁸ This model can be estimated consistently and efficiently by using the generalized spatial two-stage least squares (GS2SLS) procedure proposed in [Kelejian and Prucha \(2010\)](#) and [Drukker, Egger, and Prucha \(2019\)](#).²⁹

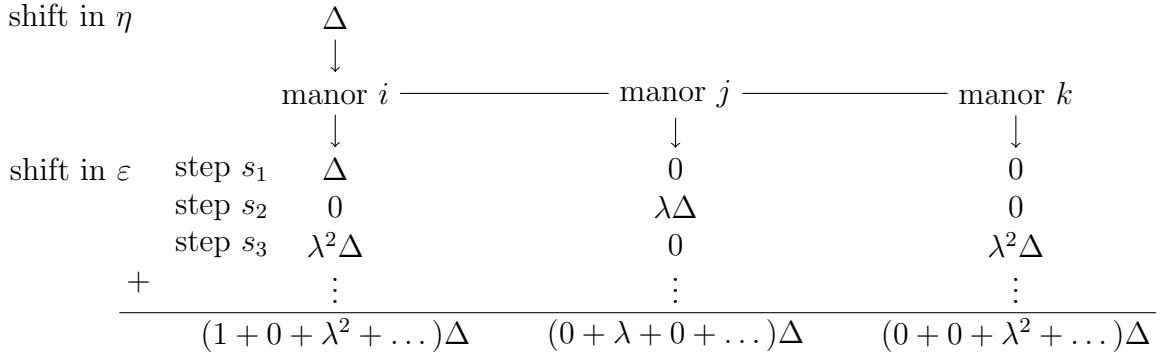
The interpretation of the parameters in our model is less straightforward than those in an OLS regression. In general, these parameters can not be understood as marginal effects, as the former also depend on the underlying network structure. Consider, for example, the simple network with three nodes that is depicted in [Figure 2](#). If an exogenous shock shifts manor i 's innate productivity η_i with Δ , its productivity ε_i initially (in step s_1) also rises with this amount. In the next step, due to the feudal structure, its direct feudal peer j will experience an effect on its productivity ε_j , but now of size $\lambda \Delta$. The same mechanism again induces a productivity spill-over of size $\lambda^2 \Delta$ to manors i and k in step s_3 . This mechanism goes on forever, but the additional terms become negligibly small as the number of steps increases. We also note that the further away a manor is removed in the feudal network, the smaller the effect becomes. That is, the effect on manor j is stronger than on manor k .

²⁷A sufficient condition for this model to have a stable and unique solution is that $|\lambda_F| + |\lambda_G| < 1$.

²⁸In accordance with the literature, we normalize \mathbf{F} and \mathbf{G} such that all rows sum to unity, except for the rows belonging to isolated manors. A manor is called isolated when it has no links with other manors in the network. In other words, its neighborhood is empty.

²⁹For the reader's convenience, we restate the main steps of this estimation procedure in [Appendix C](#).

Figure 2: **An illustration of productivity spill-over in the baseline model**



To overcome this difficulty, we also report the more easy to interpret summary measures that are suggested by [LeSage and Pace \(2009, 39\)](#). These measures divide the average total effect (ATE) into an average direct effect (ADE) and an average indirect effect. In our context, the average direct effect is defined as the expected impact on a given manor i 's value when its innate productivity η_i is increased by 1. It can therefore be interpreted as an average marginal effect of a shock in the latter variable. Alternatively, the average total effect is defined as the expected impact on a given manor i 's value when the innate ability of *all* manors is increased by 1. The average indirect effect is then defined as the difference between the average total and indirect effect.

Table [3](#) presents the estimates for our baseline network model. Overall we find large positive and statistically significant results for the productivity spill-over parameters in all specifications considered. When only one of both networks is included (columns 1 and 2), we have that $\hat{\lambda}_F$ equals 0.81 and $\hat{\lambda}_G$ equals 0.93. In these cases, the feudal and geographic networks capture part of each other's effect due to their previously highlighted correlated nature. As a consequence, modelling both networks simultaneously (column 3) reduces both estimates to 0.43 for $\hat{\lambda}_F$ and 0.71 for $\hat{\lambda}_G$. The inclusion of county and soil quality fixed effects (columns 4, 5, and 6) absorbs some of, but not the complete network effect. The estimates for the resources β are comparable to those of the preferred specification (column 4 in Table [1](#)) in the the reduced form model. The main takeaway from these estimates is that feudal peers' unobserved agricultural performance had a significant positive effect on a manor's value. This effect is sizeable, albeit smaller than the impact of one of a manor's geographic neighbors.

Table 3: **Estimates baseline econometric model (GS2SLS)**

Parameter		(1)	(2)	(3)	(4)	(5)	(6)
Labor: non-slaves	β_1	0.19*** (0.01)	0.15*** (0.01)	0.15*** (0.01)	0.17*** (0.01)	0.15*** (0.01)	0.15*** (0.01)
Labor: slaves	β_2	0.11*** (0.01)	0.09*** (0.01)	0.09*** (0.01)	0.10*** (0.01)	0.09*** (0.01)	0.10*** (0.01)
Capital: ploughs	β_3	0.54*** (0.01)	0.60*** (0.01)	0.57*** (0.01)	0.56*** (0.01)	0.59*** (0.01)	0.57*** (0.01)
Land: ploughlands	β_4	0.13*** (0.01)	0.15*** (0.01)	0.15*** (0.01)	0.13*** (0.01)	0.14*** (0.01)	0.14*** (0.01)
Constant	α	-0.25*** (0.02)	-0.21*** (0.03)	-0.17*** (0.03)	-0.18*** (0.03)	-0.20*** (0.04)	-0.17*** (0.07)
Productivity spill-overs	F λ_F	0.81*** (0.01)		0.43*** (0.07)	0.55*** (0.02)		0.46*** (0.02)
	G λ_G		0.93*** (0.01)	0.71*** (0.01)		0.75*** (0.02)	0.63*** (0.03)
County FE					YES	YES	YES
Soil FE					YES	YES	YES
Observations		9,084	9,084	9,084	9,084	9,084	9,084
<i>ADE productivity spill-overs</i>		1.08	1.04	1.04	1.02	1.02	1.04
<i>ATE productivity spill-overs</i>		4.06	5.65	10.71	2.17	3.44	8.90

Note: Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

Extended network model A possibility with the baseline network model in Equation (2) is that the error structure might not only capture spill-overs in unobserved productivity, but also scale spill-overs (Marshall, 1890). Such external economies of scale arise when the feudal or geographic clustering of large-scale manors induces a reduction in production costs. For instance, neighboring high-value manors could more easily cooperate to provide public infrastructure such as bridges, facilitating even higher agricultural production. While we expect these scale spill-overs to be much more important for the geographic network than for the feudal network, it is not unimaginable that such mechanisms might also arise across feudal peers. This becomes particularly clear in the context of our bridge example, as Cooper (2006, 66) describes how bridgework evolved from a communal obligation under the Anglo-Saxons to a highly feudal affair under the Normans.

The adjacency of manors with large values might thus in itself affect the value of a manor in the presence of scale spill-overs. To separate this mechanism from spill-overs

in productivity³⁰, we propose an extended network model,

$$\mathbf{y} = \alpha\boldsymbol{\nu} + \mathbf{X}\boldsymbol{\beta}' + (\delta_F\mathbf{F} + \delta_G\mathbf{G})\mathbf{y} + \boldsymbol{\varepsilon}, \quad \boldsymbol{\varepsilon} = (\lambda_F\mathbf{F} + \lambda_G\mathbf{G})\boldsymbol{\varepsilon} + \boldsymbol{\eta}, \quad \mathbb{E}[\boldsymbol{\eta} \mid \mathbf{X}, \mathbf{F}, \mathbf{G}] = 0, \quad (3)$$

in which δ_F scale spill-overs through the feudal network, and δ_G through the geographic network.³¹ External economies of scale are thus captured by both δ and λ .

To facilitate interpretation, we also report the ADE and ATE for the extended model. However, as this model now contains two channels of interaction, we also present these statistics for each mechanism separately, such that their relative magnitude can be assessed. These statistics are calculated by putting the parameter(s) of the other mechanism at 0, which effectively shuts down that channel.

Table 4 presents the estimates for this extended network model. In every specification, the $\hat{\lambda}_F$ and $\hat{\lambda}_G$, which capture spill-overs in productivity, are slightly smaller than those for the baseline network model reported in Table 3, although the overall qualitative assessment remains intact. The scale spill-overs through the geographic network are quite substantial, with estimates for δ_G ranging from 0.17 (column 2) to as high as 0.44 (column 3). However, these scale effects are dominated consistently by the dependence in the unobserved productivity term. As we highlighted earlier in this section, there is more potential for scale spill-overs through the geographic network than the feudal network. Our estimates confirm this, with $\hat{\delta}_F$ being comparatively small and averaging around 0.10 in every specification.

Our model also allows to test whether the effects through the feudal network are heterogeneous across different types of manors. Did a manor's amount of feudal peers contribute to the feudal spillover mechanism? And were religious or secular holdings more keen on interacting with its network neighbors? To answer these questions, estimates are derived from the extended model as in column (6) of Table 4, but with the inclusion of an interaction of the relevant source of heterogeneity with peers' av-

³⁰It is not straightforward at first sight, however, that both mechanisms can be separately identified from the data. For example, suppose we observe a cluster of manors with large values given their level of resources. This pattern can be generated by either large productivity spill-overs (a high value of λ_F or λ_G) or by large scale spill-overs (a high value of δ_F or δ_G). In Appendix C we formally show that these two effects can be disentangled whenever the networks under consideration are sparse enough. A sufficient condition is that there exists at least one pair of manors between which the shortest network path is of length four.

³¹A sufficient condition for this model to have a stable and unique solution is that $|\lambda_F| + |\lambda_G| < 1$ and $|\delta_F| + |\delta_G| < 1$.

Table 4: **Estimates extended econometric model (GS2SLS)**

Parameter		(1)	(2)	(3)	(4)	(5)	(6)
Labor: non-slaves	β_1	0.19*** (0.01)	0.15*** (0.01)	0.15*** (0.01)	0.17*** (0.01)	0.15*** (0.01)	0.15*** (0.01)
Labor: slaves	β_2	0.12*** (0.01)	0.09*** (0.01)	0.09*** (0.01)	0.11*** (0.01)	0.09*** (0.01)	0.10*** (0.01)
Capital: ploughs	β_3	0.55*** (0.01)	0.60*** (0.01)	0.58*** (0.01)	0.56*** (0.01)	0.59*** (0.01)	0.57*** (0.01)
Land: ploughlands	β_4	0.13*** (0.01)	0.14*** (0.01)	0.14*** (0.01)	0.13*** (0.01)	0.14*** (0.01)	0.14*** (0.01)
Constant	α	-0.35*** (0.03)	-0.47*** (0.05)	-0.91*** (0.04)	-0.29*** (0.03)	-0.49*** (0.05)	-0.63*** (0.06)
Productivity spill-overs	F λ_F	0.79*** (0.02)		0.38*** (0.04)	0.45*** (0.03)		0.36*** (0.03)
	G λ_G		0.92*** (0.03)	0.65*** (0.02)		0.62*** (0.03)	0.51*** (0.03)
Scale spill-overs	F δ_F	0.08*** (0.02)		0.10*** (0.01)	0.09*** (0.01)		0.10*** (0.01)
	G δ_G		0.17*** (0.03)	0.44*** (0.02)		0.21*** (0.03)	0.25*** (0.03)
County FE					YES	YES	YES
Soil FE					YES	YES	YES
Observations		9,084	9,084	9,084	9,084	9,084	9,084
<i>ADE productivity spill-overs</i>		1.07	1.04	1.03	1.01	1.01	1.03
<i>ADE scale spill-overs</i>		1.00	1.00	1.01	1.00	1.00	1.00
<i>ADE combined</i>		1.08	1.05	1.06	1.02	1.02	1.04
<i>ATE productivity spill-overs</i>		3.83	5.56	7.51	1.81	2.53	6.92
<i>ATE scale spill-overs</i>		1.08	1.21	2.11	1.09	1.27	1.32
<i>ATE combined</i>		4.16	6.74	15.88	1.98	3.22	9.13

Note: Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

erage unobserved productivity (for the productivity spill-overs) and average value (for the scale spill-overs). We find that both effects significantly increase with the size of the feudal neighborhood, although the rise in spill-over effects in productivity is the most outspoken (Figure 3a). This heterogeneity is not unsurprisingly, given that such manors had a higher probability of interacting with the most innovative manors. In addition, we also find that manors with religious ownership also experience much higher spill-over effects than those with secular ownership (Figure 3b). This can be attributed to two factors. First, the organizational hierarchy of ecclesiastical domains might have facilitated closer interactions between its manors, encouraging extensive communica-

tion among its laborers and managers.³² Second, these extraordinary spillover effects can also be interpreted within the long-established idea that ecclesiastical domains were forerunners in the adoption of medieval agricultural innovations³³

5 Drivers of the feudal productivity spill-overs

We have now quantified that manorial economies were characterized by a high and significant level of inter-manorial interactions across the feudal system. This dependence was decomposed into two mechanisms: scale spill-overs and, more importantly, spill-overs in productivity. In what follows, we scrutinize the economic mechanisms underlying the latter.

Common management and communication A prime channel through which the feudal network could influence manorial wealth is through common management or the transmission of agricultural know-how among peers. In his micro-study of medieval farm management techniques, Stone (2001) emphasizes the role of the information constraints that farm managers faced when making crucial economic decisions. It is in such a context, that information sharing among manorial lords could have been very impactful.

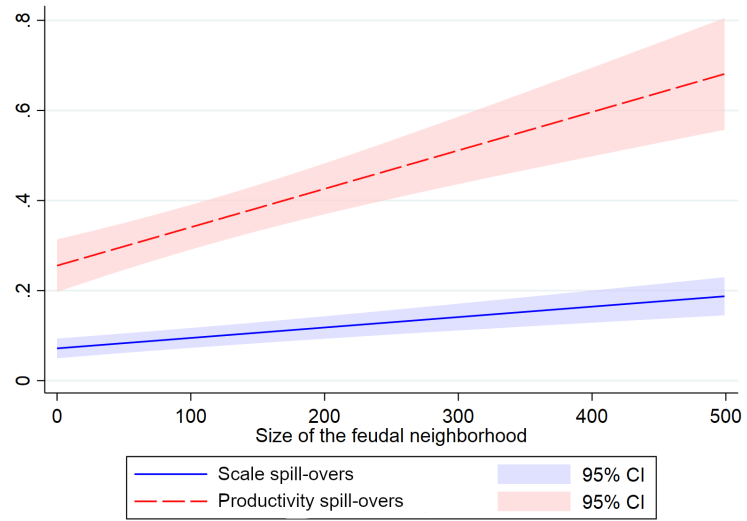
What kind of management practices would have been shared across the feudal network? A first and obvious candidate is the diffusion of innovative technologies across Domesday England. Due to their public nature, innovations can be easily diffused through local and social networks³⁴ As a result, it comes as no surprise that learning from peers has been identified as a key driver in the adaption of new

³²The emergence of the obedientiary system implied increasing specialization among the members of religious organizations. For instance, Farmer (1991, 378) documents how 13th-century monastic estates dispatched their obedientiaries to oversee the reeves of their respective manors in their market purchase decisions. For a discussion of the changing organizational structures of monastic houses and the effects on management and information flows within church estates, see Dobie (2008).

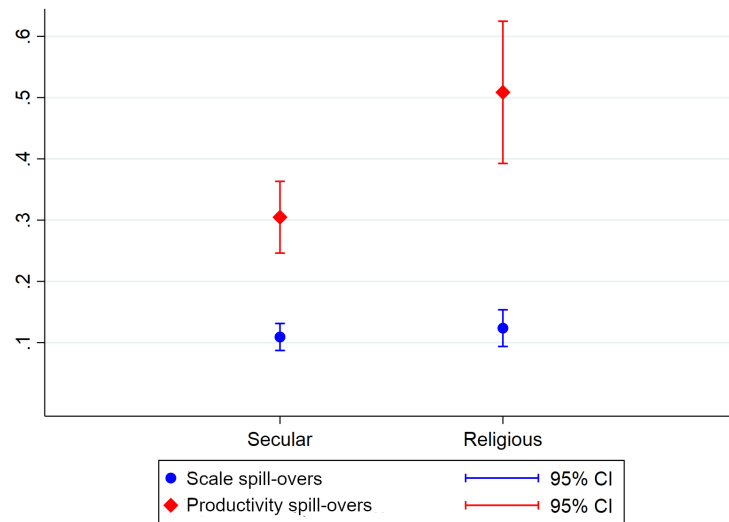
³³This notion is established in several traditional works on medieval history. Pirenne (1969, 11) saw the clergy's superior levels of education as the root of the Church's economic ascendancy (*"l'ascendant économique"*). Boissonnade (2005, 157) described church domains as "centres in which agricultural science was developed, forestry and scientific breeding improved, model farms created, new crops tried, and agricultural production regenerated and stimulated".

³⁴A limiting factor to this could be the site-specific nature of certain agricultural technologies and the lack of general-purpose technologies, as highlighted by Mokyr (1990, 32).

Figure 3: **Heterogeneous feudal network effects**



(a) Size of the feudal neighborhood



(b) Secular versus religious ownership

agricultural technologies.³⁵ Historical evidence on knowledge spillovers in early 20th-century agriculture similarly highlights the importance of interaction among neighbors and social peers alike (Parman, 2012).

It is now generally taken for granted that technological progress in medieval agriculture was a gradual process with little room for macroinventions. Instead, agricultural progress materialized through “a long chain of small improvements” (Persson, 1988, 28), such as the emergence of mixed-farming systems, crop rotation and the supportive use of livestock farming.³⁶ It goes without saying that there must have been great variation in the extent that manorial managers were able to adapt and apply these new best-practice techniques successfully. In such a context, the institutionalized interaction between a heterogeneous set of feudal landholders has great potential to materialize spill-overs of agricultural knowledge. Such human capital transfers are a convincing explanation for our observed network effect.

Second, it should be emphasized that the Domesday Book data does not allow us to differentiate between different levels of production factor intensity. In other words, because we only observe the number of laborers, we do not control for differences in working hours. As a consequence, if one lord requires longer workdays from his peasants than another lord with an identical number of workers, the resulting effect on the manor’s valuation will show up in the error term. This implies that higher levels of labor intensity, or even labor exploitation, are potentially propagated through the feudal network. Such an interpretation would align closely with Marxist theories of feudalism, in which the exploitation of unfree peasants and the disregard for technological progress are inevitable consequences of the feudal class structure. For example, Brenner (1976) (in)famously states that “the lord’s most obvious mode of increasing output from his lands was not through capital investment and the introduction of new techniques, but through ‘squeezing’ the peasants, through raising either money-rents or labour-services”. In the context of our results, this implies that feudal peers

³⁵See Foster and Rosenzweig (2010) for a discussion on the literature of learning spillovers in agriculture.

³⁶To be more precise, Campbell (1997) identifies seven concrete channels through which agricultural change could have been facilitated in the centuries following the Conquest: (1) a renewed focus towards more productive agricultural food chains, such as crops instead of animal products (2) the substitution from less to more productive crops (3) the emergence of mixed-farming systems (4) the diversification of rotations (5) the intensification and rationalization of the labor process (6) improvements to tools and equipment (7) increased specialization due to market expansion. This illustrates in which dimensions production processes could have varied across manors.

share great similarity in the extent to which they “squeeze” their respective manor’s inhabitants.

Regardless of whether feudal spillover effects were facilitated by the transmission of innovative techniques or of exploitative ways to extract surplus from the peasant population, the fact remains that landowners were able to increase their manorial value through their connections in the feudal network. In either sense, our empirical evidence aligns with the common perception of feudal institutions as an extractive device, designed to extract wealth for the well-connected “happy few” (Acemoglu & Robinson, 2012, 98).

The formation of the feudal network A potential factor in explaining the observed feudal dependence in productivity is the formation of the network itself. Cooperation between powerful nobles striving to obtain the wealthiest landholdings could explain the feudal clustering of wealth. This is especially important in the context of King William’s England, as the feudal system under investigation was only put in place twenty years earlier. Such endogeneity concerns are fundamentally inherent to any non-experimental empirical work on interaction effects, but can be mitigated by a deeper understanding of the origins of the Anglo-Norman feudal institutions.

A first argument is that the structure of the feudal system was also strongly influenced by non-economic features, like military and political considerations. In his ‘tenurial revolution’, William the Conqueror structurally reshaped the landscape of England to his own view. Landholdings with great defensive importance close to the borders or the sea were especially sought after by the landed elite (Fleming, 1991, 147). A second argument is that the formation of the feudal system, if actually influenced by economic considerations, was likely to be based on easy observable proxies for the value of manors. Note that although our modelling strategy does not allow for network formation on innate productivity η , it does allow for network formation on the resources \mathbf{X} .³⁷ That is, even if the newly created feudal system was mainly based on population density and the availability of lands and ploughs, our estimates are still

³⁷This follows from the fact that in our model both \mathbf{F} and \mathbf{X} are exogenous matrices whose mutual dependence is left unspecified.

consistent and can be interpreted as actual spill-over effects.³⁸

6 Sensitivity to the obscurities in Domesday Book

It goes without a doubt that Domesday Book presents a unique quantitative insight into an 11th-century economy. Be that as it may, it remains a complex historical document, which was created in a time where centrally organized inquiries of the like were an unseen sight. The resulting obscurities, both in structure and content, have been identified as a prime cause for the surprising neglect of Domesday Book by economists (for an up-to-date discussion on the matter, see Walker, 2015). In what follows, we scrutinize how the unresolved uncertainties in Domesday Book are to be interpreted within the context of our findings.³⁹

Network mismeasurement While we argue that the network which we present in this paper, is the closest one will ever come to comprehensively measuring a feudal network, it is still crucial to scrutinize whether our results are sensitive to the incomplete identification of Anglo-Norman landowners. The mismeasurement of networks is an ever-present concern in empirical work on peer effects. It goes without saying that this is especially relevant in the construction of network matrices of an historical nature.

About 85% of landowners in Domesday Book are identified with reasonable certainty. It is not unlikely, however, that the remaining manors with unidentified ownership structure are somewhat different in an unobserved nature. The mismeasurement of these inter-manorial connections could therefore induce selection bias in our network estimates.

As discussed before in Section 2, we consider manors with missing identification on their lordship as having their own idiosyncratic lord. These manors are only connected to the network through their identified tenant-in-chief. To assess the impact of

³⁸In contrast, if the construction of the feudal network was influenced by unobserved resources, network endogeneity will be present. This might also lead to inflated productivity spill-over estimates.

³⁹The early seminal work of McDonald and Snooks (1986), who were the first to apply econometric analysis to Domesday Book, was built on the premise that Domesday Book was “not a particularly complex document” (McDonald & Snooks, 1987, 252). This stance is, however, difficult to defend given the the large strand of Domesday literature on the peculiarities of the historical source at hand.

this assumption, we reestimate our interactions models on the extreme premise that among the unidentified lords, those with the same name within a given circuit are in fact identical individuals. Tables [A11](#) and [A12](#) in the Appendix show that this leaves our results basically unaltered. Moreover, we run an additional sensitivity check in which all manors with unidentified manors were dropped from the sample. Also this sensitivity check has very little impact on our results (see Tables [A13](#) and [A14](#)). We may therefore conclude that our estimates are most likely not driven by network mis-measurement.

The geography of Domesday Book Our analysis paid close attention to the disentanglement of the feudal and geographic network effects. To achieve this, we relied on the geographic picture of England that is presented by Domesday Book. In the introduction to his seminal study, [Darby \(1977, 13\)](#) claims that this picture “while neither complete nor accurate in all its details, does reflect the main features of the geography of the eleventh century”. The question we ask here is whether these omissions and inaccuracies drive our results in any way.

One such uncertainty lies in the nature of the manorial concept in Domesday Book. In a majority of the cases, these holdings were confined to a single location, making up a small community or being part of a larger village. However, Domesday manors were sometimes scattered across several locations. Until now, these manors were omitted from the analysis, as the disentanglement of feudal and regional peer effects can only be made with less certainty. We can, however, not rule out that this induces a selection effect, because multiple-location manors of the like are typically larger and could differ in their unobservable characteristics. To alleviate such concerns, we devise an alternative strategy, in which we assign these manors to the centroid of their respective locations. To avoid assigning insensible locations to manors, we still drop manors of which one of the locations is further than five kilometres from its centroid. Table [A7](#) and [A8](#) reveal that the inclusion of these manors have little impact on the estimated parameters of our models.

Another aspect of the Domesday geography which deserves special attention is the role of distance. In our baseline analysis, we modelled the interaction with neighboring manors as a function of distance: the further away one’s neighbor, the less

strongly that interactions and the subsequent spillover effects occur. The choice of this distance function is, however, contingent on our assumptions with respect to the role of distances, travel and information in medieval England (for a discussion, see [Langdon & Claridge, 2011](#)). Here, we ascertain that these do not drive our results. In our baseline analysis, we used a double power distance function with a parameter d equal to 20km. In Tables [A9](#) and [A10](#), we evaluate the sensitivity of our models to the choice of d . In particular, we estimate three additional cases, including a low level of $d = 10\text{km}$ and a(n implausibly) high level of $d = 100\text{km}$. The remarkably consistent estimates of the feudal effects $\hat{\lambda}_F$ and $\hat{\delta}_F$ across all four cases reveal that the choice of the distance function parameter d does not alter our findings, both in a qualitative and a quantitative sense.

The meaning of the Domesday variables While the variables in Domesday Book often show great simplicity at first glance, their interpretation is not always as straightforward. The controversial ploughlands variable, which we introduced in Section [2.2](#), is the prime example of this. Despite being typically associated with the statement “land for so many ploughs”, it is uncertain whether this variable effectively measures the amount of arable available for the manor’s agricultural activities. In our baseline analysis, we took this variable at face value and considered it as a control for the amount of land. In Tables [A3](#) and [A4](#), we repeat our analysis but omit the ploughlands variable. In other words, we assume perfect complementarity between land, capital and labor. Doing so, we can extend the sample with manors for which no ploughlands are recorded. It is apparent that our findings with respect to the feudal peer effect are robust to the exclusion of the ploughlands variable and to the inclusion of these manors. The coefficients of interest $\hat{\lambda}_F$ and $\hat{\lambda}_G$ are remarkably unchanged. Somewhat unsurprisingly, we observe the biggest impact on the ploughs effect.

Another important discussion is the open debate on Domesday Book’s manorial valuations. Many historians have interpreted these *valets* (values) as a measure of income which the landowner derived from his or her manor. Evidence in support of this theory originates in [Galbraith \(1929\)](#), who illustrated how a Domesday manor was rented out at the price of its value. Additionally, the well-researched case of Canterbury presents great consistency in how the ecclesiastical grounds were valued across

other, 12th-century sources (Du Boulay, 1966). Or, as Dyer (1995, 198) concludes: “it is on the basis of such evidence that a case can be made for some comparability between Domesday values and annual income deriving from manors in the twelfth and thirteenth century.”

It is, however, an open debate as to whether the *valets* compromise the entire stream of revenue which flows to the manorial lord. Some historians argue that only money rents are accounted for, challenging the now generally held view that “Domesday values are a more or less accurate index of the productive capacity of estates” (Roffe, 2007, 241). The idea is that these values are a measure of the peasants’ cash contributions to the lords, rather than of the manor’s own agricultural activities.

Such an interpretation would sit poorly with another, more quantitative approach to the nature of the Domesday values furthered by McDonald and Snooks (1985). The crux of their argument lies in the close statistical relationship between a manor’s resources and valuation, leaving little room for contributions from the peasant side of the economy.⁴⁰ Additionally, a more recent study finds a much weaker correlation between peasant ploughteams and valuations than between the lord’s ploughs and the latter (Walker, 2015). This does not lend credence to interpretation of values as a cash contribution by the manor’s peasants. Our results on the feudal structure of valuations in Domesday Book add new evidence to the ongoing debate. That is, it is unclear as to why and how agricultural activities of the peasant economy should be inter-connected across the feudal system, compared to the management practices of the lords in their seigniorial holdings.

7 Final thoughts

This paper presents first evidence on the pervasive nature of feudal institutions in the manorial economy. Building on the land ownership data in Domesday Book, we reinterpret the feudal system as a network that facilitates economic interactions. Indeed, we find that landowners’ wealth accumulation was closely intertwined with

⁴⁰Another explanation would be a high correlation between the manor’s and peasants’ agricultural performance. However, this renders the discussion on values irrelevant in the context of our paper (unlike, for example, in the context of the reconstruction of the GDP of the Domesday economy). We are only interested in cross-variation in wealth production and, in this case, the *valets* represent this adequately.

the fortune of their peers. Manorial values in Domesday England were positively and significantly influenced by both the unobserved value productivity and the absolute value levels of their feudal peers. The former can be explained by inter-manorial knowledge sharing mechanisms which were capable of playing a crucial role in a world where agricultural information was scarce. The latter effect is credited to scale spillovers, facilitated by agricultural cooperation across feudal peers. In this process, we empirically establish the presence of economic interactions between manors during the High Middle Ages, which had previously only been documented by manorial accounts from the Late Middle Ages.

We can see the following of avenues for future research. To start with, our approach to network formation was heavily inspired by the feudal structure as presented by Domesday Book, allowing us to model the 11th-century web of ownership structures in a comprehensive manner. Domesday Book is, however, silent on any other network structures that might affect the economic interaction mechanisms described in this paper. For instance, 11th-century England was a highly multilingual society, comprising of many different cultures and languages. It cannot be ruled out that the intensity of interactions across the feudal network was heavily regulated by this polyglot reality. In a similar manner, family relationships, while largely unknown to the historian, could prove relevant. We did not account for such cultural or familial networks, except for the degree to which these relationships are correlated with the feudal structure. Research on the etymological nature of the names in Domesday Book might offer additional insights into the extent to which this was the case.

More research on the underlying economic and social mechanisms is also required. As with all cross-sectional studies on observational data, it is inherently difficult to single out the true underlying mechanisms without the help of theoretical arguments and sound judgement. This is especially true for Domesday Book, where only limited and imperfect data is available to researchers. Be that as it may, this unique historical source reveals a fascinating insight into the feudal interdependencies within medieval economies.

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A Summary statistics of estimation sample

Table A1: Main tenant-in-chiefs by number of manors

Tenant-in-Chief	Manors				Lords	
	Number		Value		Number	Share main (%)
	Total	Demesne	Total	Demesne		
Count of Mortain	675	88	1,810.4	637.5	193	6.6
King William	470	359	8,379.7	6,156.1	149	1.0
Bishop Odo of Bayeux	328	23	2,121.2	506.9	145	7.9
Bishop of Coutances	226	25	755.5	194.9	116	27.1
Earl Roger of Shrewsbury	217	43	1,463.5	611.2	138	7.4
Count Alan	188	51	761.1	440.0	79	6.7
Baldwin the sheriff	167	19	340.0	127.9	90	5.3
Countess Judith	153	41	591.5	351.9	71	5.7
Henry of Ferrers	138	51	431.8	198.5	51	5.7
Roger of Bully	118	65	261.2	170.5	32	8.2
Robert of Stafford	110	15	217.1	73.1	67	4.3
Iudhael of Totnes	100	13	151.2	68.0	58	26.7
Bishop of Lincoln	98	19	730.3	312.6	78	7.0
Earl Hugh	97	20	516.6	133.8	38	11.9
Hugh of Grandmesnil	97	34	369.0	190.0	31	11.0
Average	15.8	6.7	81.4	47.5		

^a The summary statistics for the lords are calculated under the assumption that these lords are all separate individuals.

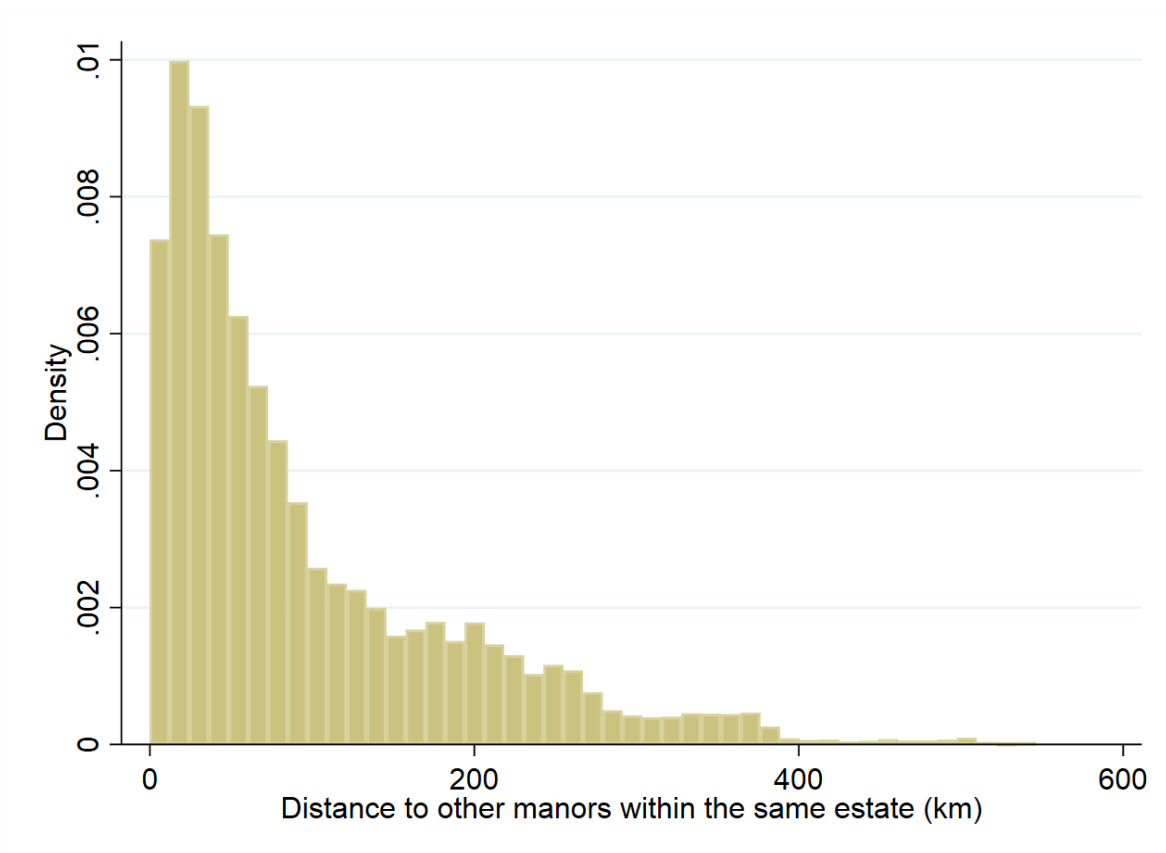
Table A2: Main lords by number of manors (excluding demesne)

Lord	Manors		Tenant-in-chiefs	
	Number	Value	Number	Main (share in %)
Drogo son of Mauger	70	80.7	2	Bishop of Coutances (98.6)
Reginald of Vautortes	48	71.8	1	Count of Mortain (100.0)
Ralph of Pomeroy	41	26.0	5	Iudhael of Totnes (40.9)
Alfred the butler	41	148.1	3	Count of Mortain (95.1)
Urso of Abetot	40	107.7	12	Abbey of Westminster (30.2)
Richard son of Turolf	36	40.1	5	Count of Mortain (82.1)
William of Keynes	35	96.1	3	Count of Mortain (91.9)
Wadard of Cogges	34	117.2	3	Bishop Odo of Bayeux (91.2)
Ilbert of Lacy	32	99.8	3	Bishop Odo of Bayeux (57.4)
Adam son of Hubert	28	239.4	1	Bishop Odo of Bayeux (100.0)
Nigel Fossard	28	28.9	1	Count of Mortain (100.0)
Hugh of Bolbec	27	122.5	3	Walter Giffard (78.8)
Reinbert the sheriff	26	85.3	2	Count of Eu (92.3)
Hamelin of Cornwall	22	21.9	1	Count of Mortain (100.0)
Turstin the sheriff	22	65.2	2	Count of Mortain (95.5)
Average including unidentified lords	1.6	9.9	1.1	(97.3)
Average excluding unidentified lords	3.2	16.9	1.4	(90.0)

^a For manors that have multiple lords, the complete value of the manor was attributed to every lord. As a result, the values in this table should be interpreted as an upper bound.

^b The average including the unidentified lords is calculated under the assumption that these lords are all separate individuals.

Figure A1: Histogram of the distances to manors within the same estate



B Maps with manors main tenant-in-chiefs and lords

Figure A2: Main tenant-in-chiefs by number of manors

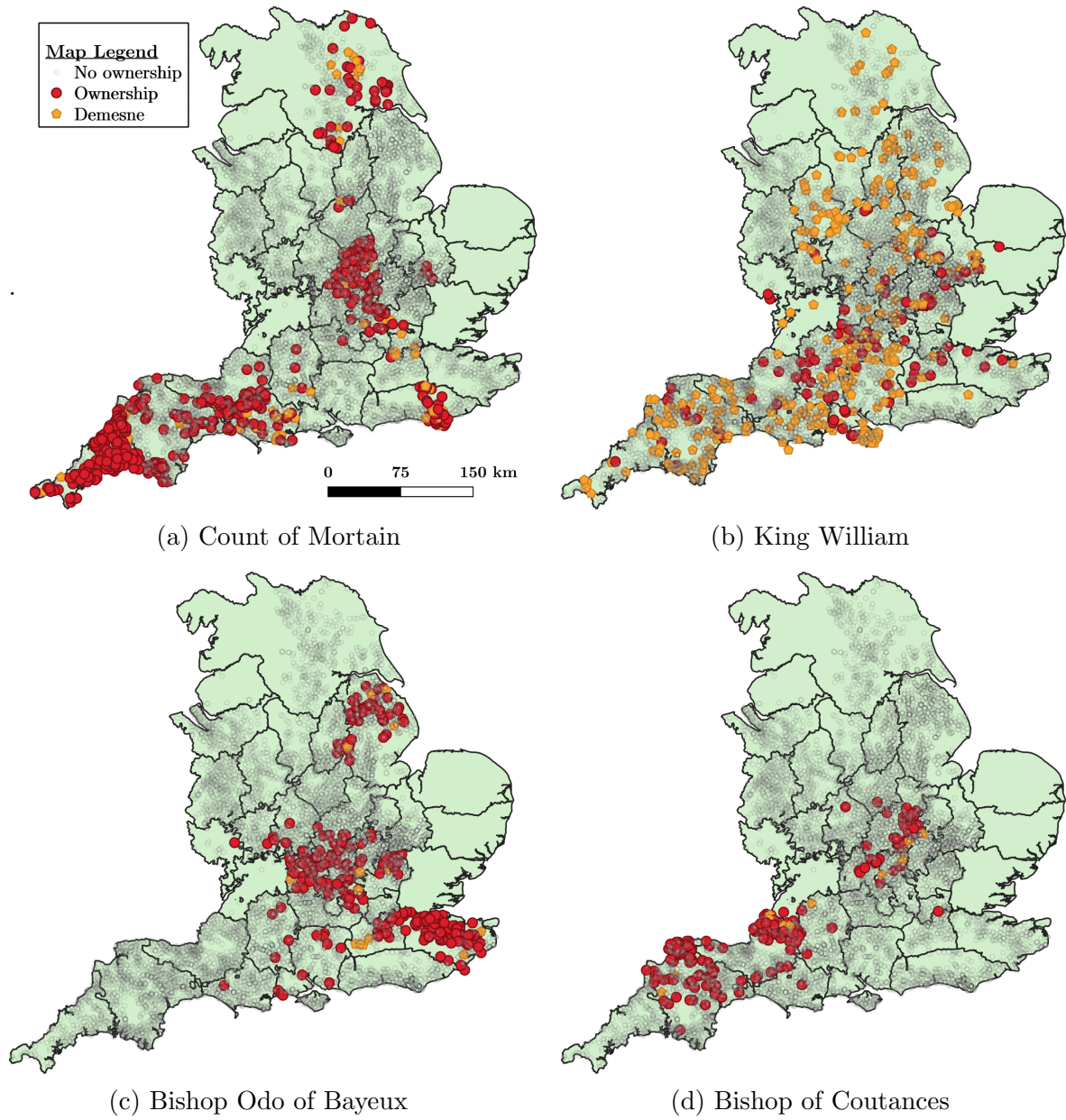
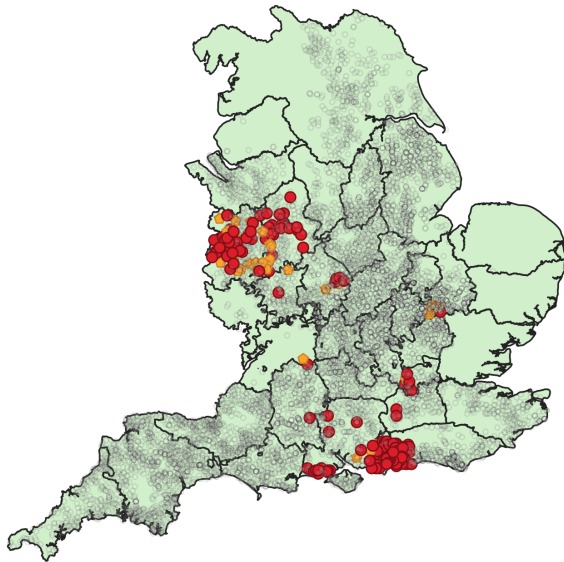
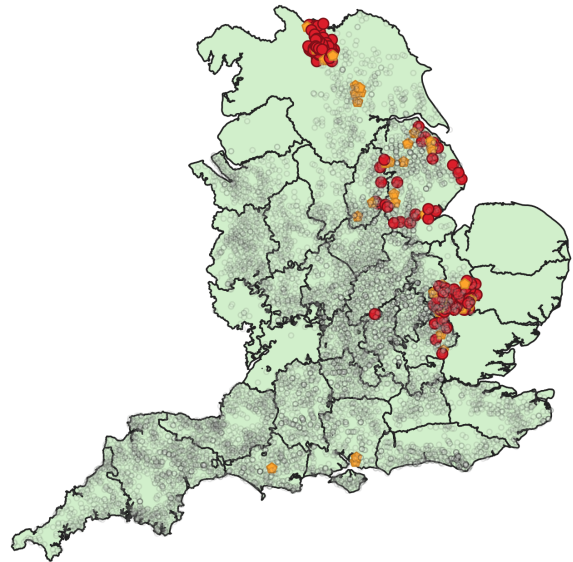


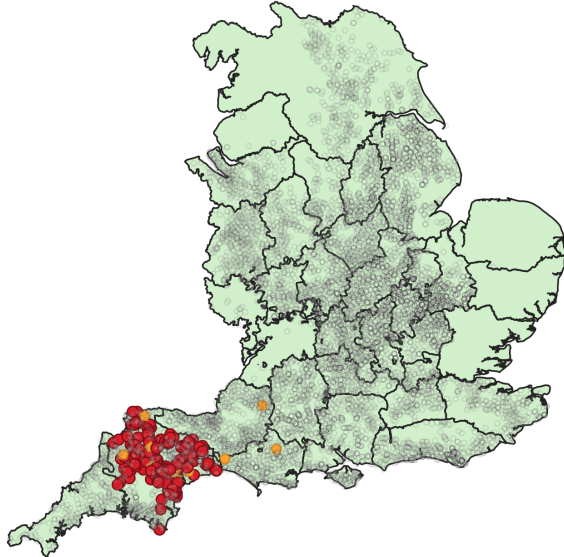
Figure A2: Main tenant-in-chiefs by number of manors (continued)



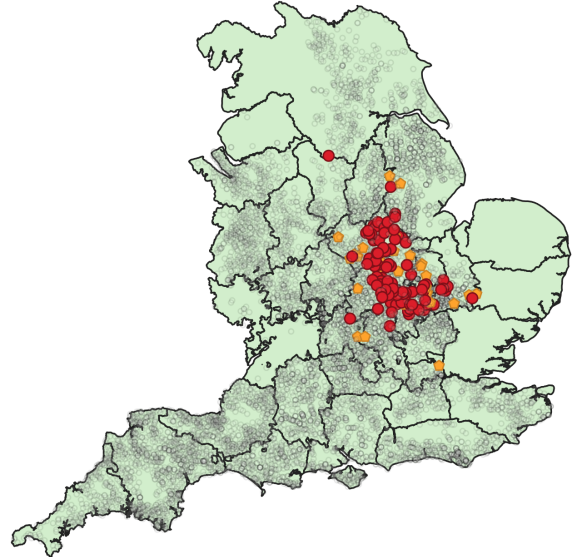
(e) Earl Roger of Shrewsbury



(f) Count Alan



(g) Baldwin the sheriff



(h) Countess Judith

Source: [Palmer \(2010\)](#); historical county borders from [Brookes \(2017\)](#)

Figure A3: Main lords by number of manors

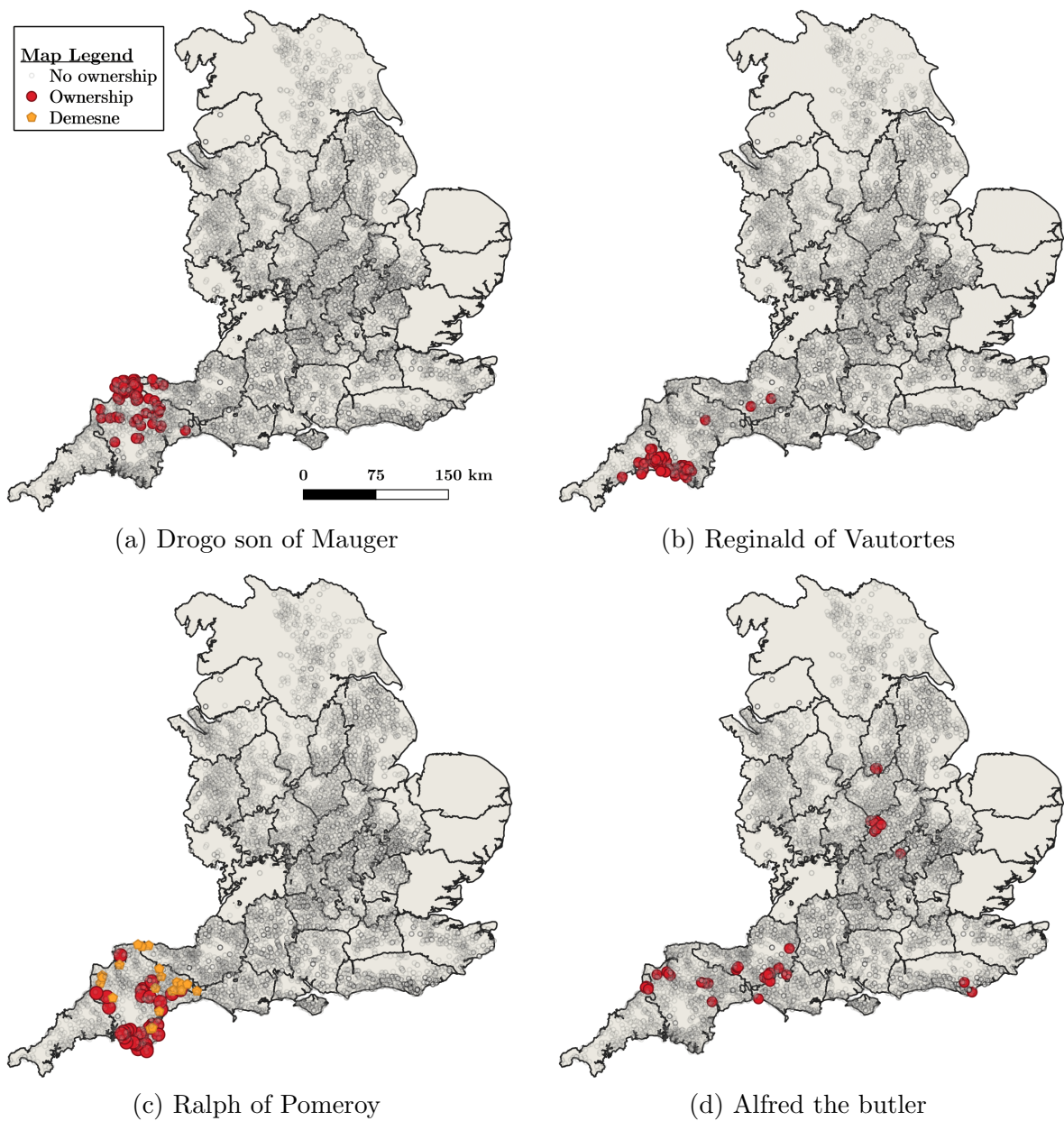
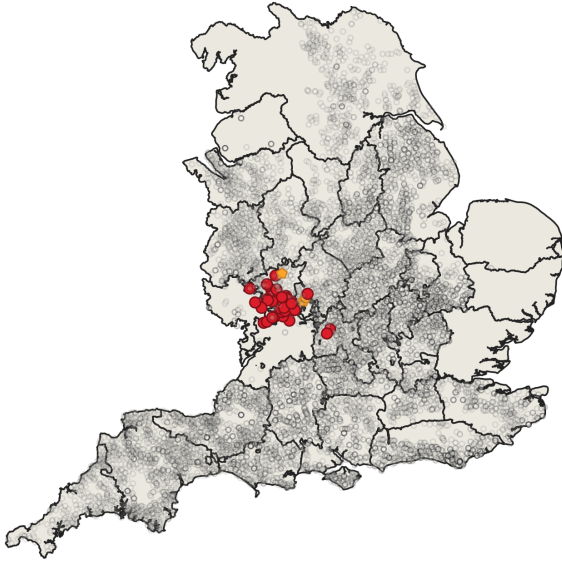
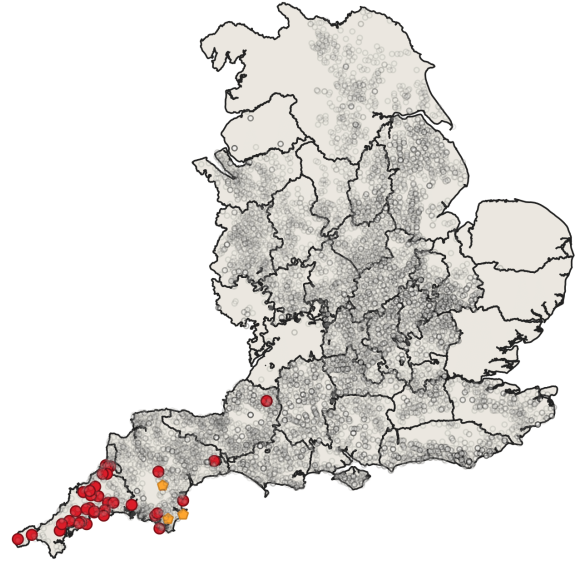


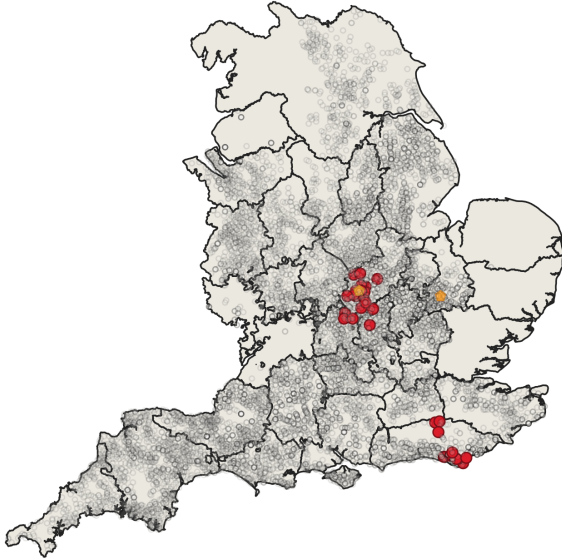
Figure A3: Main lords by number of manors (continued)



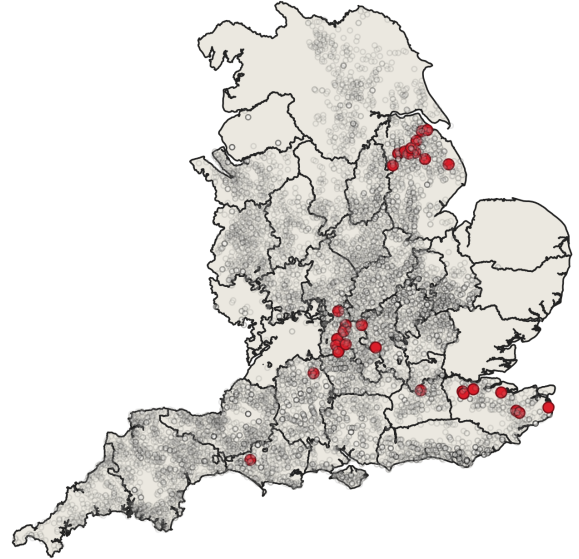
(e) Urso of Abetot



(f) Richard son of Turolf



(g) William of Keynes



(h) Wadard of Cogges

Source: [Palmer \(2010\)](#); historical county borders from [Brookes \(2017\)](#)

C Technical appendix

C.1 Generalized spatial 2SLS estimation

We estimate both the baseline and extended network model using the Generalized 2SLS procedure proposed by Kelejian and Prucha (2010) and Drukker et al. (2019), which has been shown to be asymptotically optimal. This procedure can be summarized as follows for the extended model: (i) in the first step, we estimate the parameters $(\alpha, \boldsymbol{\beta}, \delta_F, \delta_G)$ using a 2SLS estimator with $\mathbf{Z} = [\mathbf{I}, \mathbf{X}, \mathbf{FX}, \mathbf{GX}, \mathbf{FGX}, \mathbf{GFX}, \mathbf{F}^2\mathbf{X}, \mathbf{G}^2\mathbf{X}, \dots]$, which contains (higher order) lags of the exogenous variable \mathbf{X} , as instrument; (ii) in the second step, we estimate the parameters (λ_F, λ_G) with GMM, using moments of the 2SLS residuals; (iii) in the third step, we estimate $(\alpha, \boldsymbol{\beta}, \delta_F, \delta_G)$ again, but now using the Cochrane-Orcutt transformed model, using $(\widehat{\lambda}_F, \widehat{\lambda}_G)$ from previous step; (iv) in the fourth and final step, we estimate (λ_F, λ_G) again with GMM, but now applied on the residuals from previous step. As the baseline model is a special case of the extended model, the estimation procedure is identical.

C.2 Identification of scale and productivity spill-overs

In this section we propose a sufficiency condition to identify both scale and productivity spill-overs. For simplicity, consider first the following simplified version of our extended model,

$$\mathbf{y} = \alpha\boldsymbol{\iota} + \boldsymbol{\beta}\mathbf{X} + \delta_F\mathbf{F}\mathbf{y} + \boldsymbol{\varepsilon}, \quad \boldsymbol{\varepsilon} = \lambda_F\mathbf{F}\boldsymbol{\varepsilon} + \boldsymbol{\eta}, \quad \mathbb{E}[\boldsymbol{\eta} \mid \mathbf{X}] = 0, \quad (4)$$

which only allows for interaction effects through the feudal network. The reduced form of this model can be written as

$$\mathbf{y} = (\mathbf{I} - \delta_F\mathbf{F})^{-1}(\alpha\boldsymbol{\iota} + \boldsymbol{\beta}\mathbf{X}) + \widetilde{\boldsymbol{\eta}}, \quad \widetilde{\boldsymbol{\eta}} = (\mathbf{I} - \delta_F\mathbf{F})^{-1}(\mathbf{I} - \lambda_F\mathbf{F})^{-1}\boldsymbol{\eta}, \quad (5)$$

where $\widetilde{\boldsymbol{\eta}}$ denotes the composite error term.

Using a first order Neumann expansion (see e.g. Meyer, 2000, 527) around $(\mathbf{I} - \delta_F\mathbf{F})^{-1}$ we have that $\mathbb{E}[\mathbf{y} \mid \mathbf{X}] \approx (\mathbf{I} + \delta_F\mathbf{F})(\alpha\boldsymbol{\iota} + \boldsymbol{\beta}\mathbf{X}) = (\alpha + \alpha\delta_F\mathbf{F})\boldsymbol{\iota} + \boldsymbol{\beta}\mathbf{X} + \delta_F\boldsymbol{\beta}\mathbf{F}\mathbf{X}$, which implies immediately that the parameters of interest $\boldsymbol{\beta}$ and δ_F are identified from this conditional expectation whenever \mathbf{X} and $\mathbf{F}\mathbf{X}$ are not colinear.

We now show that λ_F is identified from the variance-covariance matrix of the composite error $\tilde{\boldsymbol{\eta}}$,

$$\begin{aligned}\mathbb{E}[\tilde{\boldsymbol{\eta}}\tilde{\boldsymbol{\eta}}' | \mathbf{X}] &= (\mathbf{I} - \delta_F \mathbf{F})^{-1}(\mathbf{I} - \lambda_F \mathbf{F})^{-1} \mathbb{E}[\boldsymbol{\eta}\boldsymbol{\eta}' | \mathbf{X}] (\mathbf{I} - \lambda_F \mathbf{F})^{-1}(\mathbf{I} - \delta_F \mathbf{F})^{-1} \\ &= \sigma(\mathbf{I} - \delta_F \mathbf{F})^{-1}(\mathbf{I} - \lambda_F \mathbf{F})^{-1}(\mathbf{I} - \lambda_F \mathbf{F})^{-1}(\mathbf{I} - \delta_F \mathbf{F})^{-1}.\end{aligned}\quad (6)$$

In this expression, the second equality follows from the assumption that the innovations $\boldsymbol{\eta}$ are homoskedastic and uncorrelated, i.e. $\mathbb{E}[\boldsymbol{\eta}\boldsymbol{\eta}'] = \sigma \mathbf{I}$. Suppose there exists an other parameter vector $(\sigma', \delta_F, \lambda'_F)$ that generates the same variance-covariance matrix as $(\sigma, \delta_F, \lambda_F)$. That is, $\sigma(\mathbf{I} - \delta_F \mathbf{F})^{-1}(\mathbf{I} - \lambda_F \mathbf{F})^{-1}(\mathbf{I} - \lambda_F \mathbf{F})^{-1}(\mathbf{I} - \delta_F \mathbf{F})^{-1} = \sigma'(\mathbf{I} - \delta_F \mathbf{F})^{-1}(\mathbf{I} - \lambda'_F \mathbf{F})^{-1}(\mathbf{I} - \lambda'_F \mathbf{F})^{-1}(\mathbf{I} - \delta_F \mathbf{F})^{-1}$. By premultiplying both sides by $(\mathbf{I} - \lambda_F \mathbf{F})(\mathbf{I} - \delta_F \mathbf{F})$, postmultiplying both sides by $(\mathbf{I} - \delta_F \mathbf{F})(\mathbf{I} - \lambda'_F \mathbf{F})$, and by using a first order Neumann expansion around the inverses, we have that $\sigma(\mathbf{I} + \lambda_F \mathbf{F})(\mathbf{I} + \delta_F \mathbf{F})(\mathbf{I} - \delta_F \mathbf{F})(\mathbf{I} - \lambda'_F \mathbf{F}) \approx \sigma'(\mathbf{I} - \lambda_F \mathbf{F})(\mathbf{I} - \delta_F \mathbf{F})(\mathbf{I} + \delta_F \mathbf{F})(\mathbf{I} + \lambda'_F \mathbf{F})$. This can be written as

$$\begin{aligned}(\sigma - \sigma')\mathbf{I} &+ (\sigma(\lambda_F - \lambda'_F) - \sigma'(\lambda'_F - \lambda_F))\mathbf{F} \\ &+ (\sigma(-\delta_F^2 - \lambda_F \lambda'_F) - \sigma'(-\delta_F^2 - \lambda'_F \lambda_F))\mathbf{F}^2 \\ &+ (\sigma(\delta_F \delta'_F \lambda'_F - \lambda_F \delta_F \delta'_F) - \sigma'(\delta'_F \delta_F \lambda_F - \lambda'_F \delta'_F \delta_F))\mathbf{F}^3 \\ &+ (\sigma(\delta_F^2 \lambda_F \lambda'_F) - \sigma'(\delta_F^2 \lambda'_F \lambda_F))\mathbf{F}^4 \approx \mathbf{0}.\end{aligned}\quad (7)$$

If the matrices $\mathbf{I}, \mathbf{F}, \mathbf{F}^2, \mathbf{F}^3, \mathbf{F}^4$ are linearly independent only the zero solution satisfies this equation. It therefore follows immediately that $\sigma = \sigma'$ and $\lambda_F = \lambda'_F$ should hold; that is, both parameters of interest are identified from the variance-covariance matrix.

A sufficiency condition for these matrices to be independent can be expressed in terms of the concepts of *node distance* and *network diameter*. The node distance between two manors is defined as length of the shortest network path between both manors. The diameter of a network is defined as the maximum distance between any two manors in the network. Suppose that the network diameter is equal or larger than four. Then there exists a pair of manors (i, j) with node distance equal to four such that $[f^4]_{ij} > 0$ while $[f]_{ij} = [f^2]_{ij} = [f^3]_{ij} = 0$. Let j' be the next to last node on this shortest path. It then holds that $[f^3]_{ij'} > 0$ while $[f]_{ij'} = [f^2]_{ij'} = 0$. Likewise, let j'' denote the second to last node on this shortest path. It then holds that $[f^2]_{ij''} > 0$

while $[f]_{ij''} = 0$. These (in)equalities together imply that $\mathbf{I}, \mathbf{F}, \mathbf{F}^2, \mathbf{F}^3, \mathbf{F}^4$ are linearly independent.

Mutatis mutandis, it follows that in the presence of both the feudal and geographic network the following set of matrices should be linearly independent: $\mathbf{I}, \mathbf{F}, \mathbf{G}, \mathbf{F}^2, \mathbf{G}^2, \mathbf{FG}, \mathbf{GF}, \mathbf{F}^3, \mathbf{G}^3, \mathbf{F}^2\mathbf{G}, \mathbf{FG}^2, \mathbf{GF}^2, \mathbf{G}^2\mathbf{F}, \mathbf{FGF}, \mathbf{GFG}, \mathbf{F}^4, \mathbf{G}^4, \mathbf{F}^3\mathbf{G}, \mathbf{GF}^3, \mathbf{FG}^3, \mathbf{G}^3\mathbf{F}, \mathbf{F}^2\mathbf{G}^2, \mathbf{G}^2\mathbf{F}^2, \mathbf{F}^2\mathbf{GF}, \mathbf{G}^2\mathbf{FG}, \mathbf{GF}^2\mathbf{G}, \mathbf{FG}^2\mathbf{F}, \mathbf{FGF}^2, \mathbf{GFG}^2, \mathbf{FGFG}$, and \mathbf{GFGE} .

D Robustness checks

D.1 Estimates excluding ploughlands variable

Table A3: Estimates baseline econometric model (GS2SLS)

Parameter	(1)	(2)	(3)	(4)	(5)	(6)
Labor: non-slaves	0.19*** (0.01)	0.17*** (0.01)	0.17*** (0.01)	0.18*** (0.01)	0.17*** (0.01)	0.17*** (0.01)
Labor: slaves	0.14*** (0.01)	0.11*** (0.01)	0.11*** (0.01)	0.13*** (0.01)	0.11*** (0.01)	0.12*** (0.01)
Capital: ploughs	0.64*** (0.01)	0.69*** (0.01)	0.67*** (0.01)	0.65*** (0.01)	0.68*** (0.01)	0.67*** (0.01)
Constant	-0.22*** (0.02)	-0.20*** (0.03)	-0.15*** (0.02)	-0.14*** (0.03)	-0.14*** (0.04)	-0.11* (0.06)
λ_F	0.80*** (0.01)		0.48*** (0.07)	0.56*** (0.02)		0.49*** (0.02)
λ_G		0.92*** (0.01)	0.70*** (0.01)		0.75*** (0.02)	0.63*** (0.02)
County FE				YES	YES	YES
Soil FE				YES	YES	YES
Observations	12,222	12,222	12,222	12,222	12,222	12,222

Note: Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

Table A4: Estimates extended econometric model (GS2SLS)

Parameter	(1)	(2)	(3)	(4)	(5)	(6)
Labor: non-slaves	0.19*** (0.01)	0.17*** (0.01)	0.17*** (0.01)	0.18*** (0.01)	0.17*** (0.01)	0.17*** (0.01)
Labor: slaves	0.14*** (0.01)	0.11*** (0.01)	0.11*** (0.01)	0.13*** (0.01)	0.11*** (0.01)	0.12*** (0.01)
Capital: ploughs	0.64*** (0.01)	0.69*** (0.01)	0.67*** (0.01)	0.65*** (0.01)	0.68*** (0.01)	0.66*** (0.01)
Constant	-0.34*** (0.02)	-0.52*** (0.05)	-0.83*** (0.04)	-0.25*** (0.03)	-0.50*** (0.05)	-0.64*** (0.06)
λ_F	0.76*** (0.02)		0.41*** (0.03)	0.46*** (0.02)		0.40*** (0.02)
λ_G		0.88*** (0.02)	0.64*** (0.02)		0.60*** (0.03)	0.50*** (0.03)
δ_F	0.10*** (0.02)		0.08*** (0.01)	0.09*** (0.01)		0.10*** (0.01)
δ_G		0.24*** (0.04)	0.42*** (0.02)		0.26*** (0.03)	0.30*** (0.03)
County FE				YES	YES	YES
Soil FE				YES	YES	YES
Observations	12,222	12,222	12,222	12,222	12,222	12,222

Note: Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

D.2 Estimates including manors with multiple locations

Table A5: Estimates baseline econometric model (GS2SLS)

Parameter	(1)	(2)	(3)	(4)	(5)	(6)
Labor: non-slaves	0.20*** (0.01)	0.15*** (0.01)	0.15*** (0.01)	0.17*** (0.01)	0.16*** (0.01)	0.16*** (0.01)
Labor: slaves	0.12*** (0.01)	0.09*** (0.01)	0.09*** (0.01)	0.10*** (0.01)	0.09*** (0.01)	0.10*** (0.01)
Capital: ploughs	0.53*** (0.01)	0.59*** (0.01)	0.56*** (0.01)	0.55*** (0.01)	0.59*** (0.01)	0.57*** (0.01)
Land: ploughlands	0.13*** (0.01)	0.16*** (0.01)	0.15*** (0.01)	0.14*** (0.01)	0.15*** (0.01)	0.15*** (0.01)
Constant	-0.26*** (0.02)	-0.22*** (0.03)	-0.18*** (0.02)	-0.18*** (0.03)	-0.20*** (0.04)	-0.17*** (0.06)
λ_F	0.82*** (0.01)		0.45*** (0.07)	0.57*** (0.02)		0.48*** (0.02)
λ_G		0.93*** (0.01)	0.71*** (0.01)		0.75*** (0.02)	0.63*** (0.03)
County FE				YES	YES	YES
Soil FE				YES	YES	YES
Observations	9,488	9,488	9,488	9,488	9,488	9,488

Note: Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

Table A6: Estimates extended econometric model (GS2SLS)

Parameter	(1)	(2)	(3)	(4)	(5)	(6)
Labor: non-slaves	0.20*** (0.01)	0.16*** (0.01)	0.16*** (0.01)	0.17*** (0.01)	0.16*** (0.01)	0.16*** (0.01)
Labor: slaves	0.12*** (0.01)	0.09*** (0.01)	0.09*** (0.01)	0.11*** (0.01)	0.09*** (0.01)	0.10*** (0.01)
Capital: ploughs	0.53*** (0.01)	0.59*** (0.01)	0.57*** (0.01)	0.55*** (0.01)	0.59*** (0.01)	0.57*** (0.01)
Land: ploughlands	0.13*** (0.01)	0.15*** (0.01)	0.15*** (0.01)	0.14*** (0.01)	0.15*** (0.01)	0.15*** (0.01)
Constant	-0.36*** (0.03)	-0.45*** (0.05)	-0.90*** (0.04)	-0.30*** (0.03)	-0.49*** (0.05)	-0.64*** (0.06)
λ_F	0.80*** (0.02)		0.40*** (0.04)	0.47*** (0.02)		0.38*** (0.03)
λ_G		0.93*** (0.03)	0.66*** (0.02)		0.63*** (0.03)	0.52*** (0.03)
δ_F	0.08*** (0.02)		0.10*** (0.01)	0.09*** (0.01)		0.10*** (0.01)
δ_G		0.15*** (0.04)	0.43*** (0.02)		0.21*** (0.03)	0.25*** (0.03)
County FE				YES	YES	YES
Soil FE				YES	YES	YES
Observations	9,488	9,488	9,488	9,488	9,488	9,488

Note: Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

D.3 Estimates excluding manors with outliers

Table A7: Estimates baseline econometric model (GS2SLS)

Parameter	(1)	(2)	(3)	(4)	(5)	(6)
Labor: non-slaves	0.21*** (0.01)	0.17*** (0.01)	0.17*** (0.01)	0.18*** (0.01)	0.17*** (0.01)	0.17*** (0.01)
Labor: slaves	0.13*** (0.01)	0.10*** (0.01)	0.10*** (0.01)	0.12*** (0.01)	0.10*** (0.01)	0.10*** (0.01)
Capital: ploughs	0.47*** (0.01)	0.51*** (0.01)	0.50*** (0.01)	0.48*** (0.01)	0.50*** (0.01)	0.49*** (0.01)
Land: ploughlands	0.14*** (0.01)	0.17*** (0.01)	0.17*** (0.01)	0.16*** (0.01)	0.17*** (0.01)	0.17*** (0.01)
Constant	-0.28*** (0.02)	-0.26*** (0.03)	-0.21*** (0.04)	-0.16*** (0.02)	-0.16*** (0.04)	-0.20*** (0.07)
λ_F	0.79*** (0.01)		0.34*** (0.04)	0.48*** (0.02)		0.36*** (0.02)
λ_G		0.93*** (0.01)	0.76*** (0.01)		0.77*** (0.02)	0.67*** (0.02)
County FE				YES	YES	YES
Soil FE				YES	YES	YES
Observations	8,287	8,287	8,287	8,287	8,287	8,287

Note: Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

Table A8: Estimates extended econometric model (GS2SLS)

Parameter	(1)	(2)	(3)	(4)	(5)	(6)
Labor: non-slaves	0.22*** (0.01)	0.17*** (0.01)	0.17*** (0.01)	0.18*** (0.01)	0.17*** (0.01)	0.17*** (0.01)
Labor: slaves	0.13*** (0.01)	0.10*** (0.01)	0.09*** (0.01)	0.12*** (0.01)	0.10*** (0.01)	0.10*** (0.01)
Capital: ploughs	0.47*** (0.01)	0.51*** (0.01)	0.50*** (0.01)	0.48*** (0.01)	0.50*** (0.01)	0.49*** (0.01)
Land: ploughlands	0.14*** (0.01)	0.17*** (0.01)	0.17*** (0.01)	0.16*** (0.01)	0.17*** (0.01)	0.17*** (0.01)
Constant	-0.34*** (0.02)	-0.68*** (0.05)	-0.96*** (0.03)	-0.23*** (0.03)	-0.54*** (0.05)	-0.64*** (0.05)
λ_F	0.79*** (0.02)		0.29*** (0.03)	0.42*** (0.02)		0.30*** (0.03)
λ_G		0.85*** (0.02)	0.66*** (0.02)		0.60*** (0.03)	0.53*** (0.03)
δ_F	0.05*** (0.02)		0.06*** (0.01)	0.06*** (0.01)		0.06*** (0.01)
δ_G		0.34*** (0.04)	0.54*** (0.03)		0.30*** (0.03)	0.32*** (0.03)
County FE				YES	YES	YES
Soil FE				YES	YES	YES
Observations	8,287	8,287	8,287	8,287	8,287	8,287

Note: Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

D.4 Estimates using other parameters for the spatial matrix

Table A9: Estimates baseline econometric model (GS2SLS)

Parameter	$d = 10\text{km}$	$d = 20\text{km}$	$d = 50\text{km}$	$d = 100\text{km}$
Labor: non-slaves	0.15*** (0.01)	0.15*** (0.01)	0.16*** (0.01)	0.16*** (0.01)
Labor: slaves	0.09*** (0.01)	0.10*** (0.01)	0.10*** (0.01)	0.10*** (0.01)
Capital: ploughs	0.58*** (0.01)	0.57*** (0.01)	0.57*** (0.01)	0.57*** (0.01)
Land: ploughlands	0.14*** (0.01)	0.14*** (0.01)	0.14*** (0.01)	0.14*** (0.01)
Constant	-0.18*** (0.04)	-0.17** (0.07)	-0.15*** (0.03)	-0.17*** (0.03)
λ_F	0.46*** (0.02)	0.46*** (0.02)	0.48*** (0.02)	0.51*** (0.02)
λ_G	0.44*** (0.02)	0.63*** (0.03)	1.24*** (0.09)	1.46*** (0.23)
County FE	YES	YES	YES	YES
Soil FE	YES	YES	YES	YES
Observations	"9,084"	"9,084"	"9,084"	"9,084"

Note: Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

Table A10: Estimates extended econometric model (GS2SLS)

Parameter	$d = 10\text{km}$	$d = 20\text{km}$	$d = 50\text{km}$	$d = 100\text{km}$
Labor: non-slaves	0.15*** (0.01)	0.15*** (0.01)	0.16*** (0.01)	0.16*** (0.01)
Labor: slaves	0.10*** (0.01)	0.10*** (0.01)	0.10*** (0.01)	0.10*** (0.01)
Capital: ploughs	0.57*** (0.01)	0.57*** (0.01)	0.57*** (0.01)	0.56*** (0.01)
Land: ploughlands	0.14*** (0.01)	0.14*** (0.01)	0.14*** (0.01)	0.14*** (0.01)
Constant	-0.43*** (0.05)	-0.63*** (0.06)	-1.07*** (0.09)	-1.09*** (0.08)
λ_F	0.36*** (0.03)	0.36*** (0.03)	0.36*** (0.03)	0.40*** (0.03)
λ_G	0.39*** (0.02)	0.51*** (0.03)	1.02*** (0.04)	1.81*** (0.32)
δ_F	0.10*** (0.01)	0.10*** (0.01)	0.11*** (0.01)	0.10*** (0.01)
δ_G	0.10*** (0.02)	0.25*** (0.03)	0.54*** (0.06)	0.56*** (0.05)
County FE	YES	YES	YES	YES
Soil FE	YES	YES	YES	YES
Observations	9084	"9,084"	"9,084"	"9,084"

Note: Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

D.5 Estimates imputing IDs unidentified lord

Table A11: Estimates baseline econometric model (GS2SLS)

Parameter	(1)	(2)	(3)	(4)	(5)	(6)
Labor: non-slaves	0.19*** (0.01)	0.15*** (0.01)	0.15*** (0.01)	0.17*** (0.01)	0.15*** (0.01)	0.15*** (0.01)
Labor: slaves	0.11*** (0.01)	0.09*** (0.01)	0.09*** (0.01)	0.10*** (0.01)	0.09*** (0.01)	0.10*** (0.01)
Capital: ploughs	0.54*** (0.01)	0.60*** (0.01)	0.57*** (0.01)	0.56*** (0.01)	0.59*** (0.01)	0.57*** (0.01)
Land: ploughlands	0.13*** (0.01)	0.15*** (0.01)	0.15*** (0.01)	0.13*** (0.01)	0.14*** (0.01)	0.14*** (0.01)
Constant	-0.24*** (0.02)	-0.21*** (0.03)	-0.18*** (0.02)	-0.17*** (0.03)	-0.20*** (0.04)	-0.16*** (0.07)
λ_F	0.84*** (0.01)		0.45*** (0.08)	0.57*** (0.02)		0.47*** (0.02)
λ_G		0.93*** (0.01)	0.71*** (0.01)		0.75*** (0.02)	0.62*** (0.03)
County FE				YES	YES	YES
Soil FE				YES	YES	YES
Observations	9,084	9,084	9,084	9,084	9,084	9,084

Note: Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

Table A12: Estimates extended econometric model (GS2SLS)

Parameter	(1)	(2)	(3)	(4)	(5)	(6)
Labor: non-slaves	0.19*** (0.01)	0.15*** (0.01)	0.15*** (0.01)	0.17*** (0.01)	0.15*** (0.01)	0.15*** (0.01)
Labor: slaves	0.12*** (0.01)	0.09*** (0.01)	0.09*** (0.01)	0.10*** (0.01)	0.09*** (0.01)	0.10*** (0.01)
Capital: ploughs	0.55*** (0.01)	0.60*** (0.01)	0.58*** (0.01)	0.56*** (0.01)	0.59*** (0.01)	0.57*** (0.01)
Land: ploughlands	0.12*** (0.01)	0.14*** (0.01)	0.14*** (0.01)	0.13*** (0.01)	0.14*** (0.01)	0.14*** (0.01)
Constant	-0.34*** (0.03)	-0.47*** (0.05)	-0.91*** (0.03)	-0.29*** (0.03)	-0.49*** (0.05)	-0.62*** (0.06)
λ_F	0.82*** (0.02)		0.39*** (0.04)	0.47*** (0.03)		0.38*** (0.03)
λ_G		0.92*** (0.03)	0.65*** (0.02)		0.62*** (0.03)	0.51*** (0.03)
δ_F	0.07*** (0.02)		0.10*** (0.01)	0.09*** (0.01)		0.10*** (0.01)
δ_G		0.17*** (0.03)	0.44*** (0.02)		0.21*** (0.03)	0.25*** (0.03)
County FE				YES	YES	YES
Soil FE				YES	YES	YES
Observations	9,084	9,084	9,084	9,084	9,084	9,084

Note: Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

D.6 Estimates excluding manors with unidentified lords

Table A13: Estimates baseline econometric model (GS2SLS)

Parameter	(1)	(2)	(3)	(4)	(5)	(6)
Labor: non-slaves	0.20*** (0.01)	0.16*** (0.01)	0.16*** (0.01)	0.18*** (0.01)	0.16*** (0.01)	0.16*** (0.01)
Labor: slaves	0.12*** (0.01)	0.09*** (0.01)	0.09*** (0.01)	0.10*** (0.01)	0.09*** (0.01)	0.10*** (0.01)
Capital: ploughs	0.55*** (0.02)	0.60*** (0.01)	0.57*** (0.01)	0.56*** (0.01)	0.59*** (0.01)	0.57*** (0.01)
Land: ploughlands	0.12*** (0.01)	0.15*** (0.01)	0.15*** (0.01)	0.13*** (0.01)	0.14*** (0.01)	0.14*** (0.01)
Constant	-0.27*** (0.02)	-0.23*** (0.03)	-0.17*** (0.04)	-0.19*** (0.03)	-0.20*** (0.04)	-0.25*** (0.08)
λ_F	0.79*** (0.01)		0.44*** (0.06)	0.52*** (0.02)		0.45*** (0.02)
λ_G		0.91*** (0.01)	0.70*** (0.02)		0.68*** (0.03)	0.58*** (0.03)
County FE				YES	YES	YES
Soil FE				YES	YES	YES
Observations	7,045	7,045	7,045	7,045	7,045	7,045

Note: Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

Table A14: Estimates extended econometric model (GS2SLS)

Parameter	(1)	(2)	(3)	(4)	(5)	(6)
Labor: non-slaves	0.21*** (0.01)	0.16*** (0.01)	0.16*** (0.01)	0.18*** (0.01)	0.16*** (0.01)	0.16*** (0.01)
Labor: slaves	0.12*** (0.01)	0.09*** (0.01)	0.09*** (0.01)	0.10*** (0.01)	0.09*** (0.01)	0.10*** (0.01)
Capital: ploughs	0.55*** (0.02)	0.60*** (0.01)	0.58*** (0.01)	0.56*** (0.01)	0.59*** (0.01)	0.58*** (0.01)
Land: ploughlands	0.12*** (0.01)	0.14*** (0.01)	0.14*** (0.01)	0.13*** (0.01)	0.14*** (0.01)	0.14*** (0.01)
Constant	-0.37*** (0.03)	-0.52*** (0.05)	-0.92*** (0.04)	-0.30*** (0.03)	-0.51*** (0.06)	-0.67*** (0.06)
λ_F	0.76*** (0.02)		0.38*** (0.04)	0.42*** (0.03)		0.35*** (0.03)
λ_G		0.89*** (0.03)	0.62*** (0.02)		0.54*** (0.04)	0.43*** (0.04)
δ_F	0.08*** (0.02)		0.09*** (0.01)	0.09*** (0.01)		0.09*** (0.01)
δ_G		0.19*** (0.04)	0.42*** (0.02)		0.22*** (0.03)	0.26*** (0.03)
County FE				YES	YES	YES
Soil FE				YES	YES	YES
Observations	7,045	7,045	7,045	7,045	7,045	7,045

Note: Standard errors are between parentheses.

*** : $p < 0.01$, ** : $p < 0.05$, * : $p < 0.1$

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