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FOOD, FUEL AND THE DOMESDAY ECONOMY

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ABSTRACT

This paper develops a theory where access to food and fuel energy is critical to the location, number, and size of human settlements. By combining our theory with a simple Malthusian mechanism, we generate predictions for the distribution of economic activity and population across geographic space. We evaluate the model using data drawn from the very first census undertaken in the English language - the Domesday census - commissioned by William the Conqueror in 1086 A.D. Using G.I.S. data and techniques we find strong evidence that Malthusian forces determined the population size and the number of settlements in Domesday England.

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1 Introduction

This paper is an attempt to bring formal theory to bear in explaining the number, population size, and distribution of settlements across a spatially explicit geographic landscape. Our attempt is unusual because we study the economic landscape of Medieval England using data drawn from the very first census recorded in the English language. This data is summarized in the so-called - *Domesday book* - commissioned by William the Conqueror in 1086 A.D..

Any attempt to understand the location of production must decide which geographic features will take center stage, and which will play no role at all. We have chosen to focus on a location's access to abundant, high density, energy that is embodied in our agrarian economy's production of food and fuel. Agents reap energy from the surrounding environment and transport it to the economy's core, or settlement, for use. Food and fuel production determines a settlement's income, and via a Malthusian mechanism governing births and deaths, its steady state population size.[1] We then aggregate settlements across larger geographic units, called *landscapes*, and show how their specific geographies determine transport costs, settlement density, and overall population levels.

To evaluate our theory we need data from a time and place where local energy production was critical to both economic activity and human survival. This necessitates a move backwards in time. Economies in the distant past were simpler, far less integrated into larger regions, and therefore more reliant on single factors of production such as energy. As a result, the local abundance and productivity of land determined, to a large extent, incomes. Incomes in turn affected both birth and death processes, and hence populations. This Domesday England of 1086.

We proceed in three steps. First, we develop a theory of a single isolated settlement. Our theory provides an explicit link between food and fuel productivities and transport costs, to

[1] There is an ongoing debate over when the Malthusian period ended, how it ended, and how sharply England transitioned to a new demographic model (See for example, Nicolini (2007) for a cogent discussion). Clark (2008b) provides a robust defense of his well known Malthusian view of population history contained in Clark (2008a).

predictions for settlement population sizes, the share of land devoted to food production, and the overall area of land exploited by a settlement.

Second, we embed our model of a single settlement into a larger geographic space containing many such settlements. We refer to this space as a landscape. It is a geographic area populated by agents who share a set of common model primitives (tastes, technologies) and face a common physical environment defined by its geographic features (pre-existing Roman roads, rivers, impassible mountains and coastlines) which determine the costs of energy collection and transport. We define four types of landscapes: simple, connected, coastal and edge. Surprisingly, our theory's predictions vary in an entirely intuitive manner across them.

Finally, we move to empirical work. We treat each manor recorded in the Domesday book as a settlement.[2] We locate this manor within its parish, which in turn is contained within an ancient administrative unit called a *Hundred*. We then aggregate across settlement income and population data using parish area weights to obtain the average income and population of settlements in a given *Hundred*.[3] The data we employ provides observations on 875 hundreds contained in 34 of England's 39 ancient counties.

Domesday records provide us with measures of settlement income, the abundance of arable land, and populations. None of this data is perfect: our measure of arable land relies on an assumed constancy between arable land and livestock kept to plough fields; incomes are assumed to be proportional to the value of assets; and populations are estimates provided by the researchers who digitized the Domesday book. We use present day G.I.S. data and methods to generate a proxy for transport costs, to develop environmental controls, and to place *Hundreds* within landscapes based on G.I.S. obtained geographic descriptors. A

[2] J. McDonald and G.D. Snooks were the first to examine the statistical properties of entries in the Domesday book arguing, against conventional wisdom, that they contained much useful information about the organization of production, efficiency, and tax incidence. See for example, McDonald and Snooks (1985a), McDonald (2005), and McDonald and Snooks (1985b). None of this earlier work considers the same issues as those pursued here.

[3] The Domesday book contains data on several measures that, in theory, we could use to infer the geographic size of a settlement. This proved impossible because the units were inconsistent, ancient, and often unknown. Our attempts often produced counterfactual conclusions (for example, calculated land in a hundred was greater than actual land). Since the majority of parishes contain only a very few settlements, we employ parish area weights to capture the relative size of settlements, rather than rely on simple averages.

further challenge is that our data is a single cross-section recorded in 1086. This requires an interpretation of the data as observations at or near the Malthusian steady state.

Despite these challenges we find very strong evidence of Malthus at work in Domesday England. We divide Malthusian forces into their implications on two different margins.

On the intensive margin, they are reflected in the response of settlement populations to income gains. Empirically, we find a doubling of settlement income raises settlement population by over 80%. Alternatively, holding aggregate income constant, but doubling the abundance of arable land, raises settlement populations by over 25%. This is strong evidence of Malthus operating on the intensive margin.

On the extensive margin Malthusian forces are reflected in the response of settlement numbers and overall populations to increases in the useful land of a Hundred. We find a doubling of Hundred area raises settlement numbers by about 80%, while doubling Hundred populations. This is strong evidence of Malthus operating on the extensive margin. More land creates more settlements, greater population, but leaves constant population density.

Our model also has several, quite specific, predictions for the organization of economic production across space. For example, it predicts settlement density falls with some forms of income gains and rises with others. Surprisingly, we find just that. A doubling of income that leaves the composition of output constant, expands the geographic size of settlements, and settlement density falls. Empirically, we find it falls, via this channel, by 30%. Conversely, an increase in the abundance of arable land, shifts specialization patterns towards food production. Settlements are smaller and hence density rises. We find a doubling of the abundance of arable land raises settlement density by approximately 80%.

Our results add to the growing body of evidence supporting a Malthusian view of world history.[4] See for example the book length treatment of Gregory Clark (Clark (2008b)) and the many contributions by Oded Galor and co-authors (Galor and Weil (2000), Galor and

[4] There are of course Neo-Malthusians who contend that Malthusian forces are still at play today. Brander and Dowrick (1994) for example, find evidence that high fertility leads to investment dilution effects and lowers subsequent economic growth in contemporary data.

Moav (2002) and Ashraf and Galor (2011) for example). There are two common approaches to the empirical study of Malthusian forces. One approach focuses on the steady state relationships. The goal is, for example, to show a strong relationship between technological progress and populations, but none between progress and individual incomes (See Ashraf and Galor (2011) for a excellent example). Another approach is to study the underlying mechanisms at play in moving an economy towards its Malthusian steady state. In this approach, the goal is to estimate the strength of the preventative or positive checks put forward by Malthus. This is, for example, commonly used with time-series, (Nicolini (2007) and Møller and Sharp (2014)), or panel data, (Lagerlöf (2015)) methods.

Other related work comes from authors who have drawn a connection between the availability of energy resources and resulting populations. For food energy we have recent work by Nunn and Qian (2011), Chen and Kung (2016) and Cherniwchan and Moreno-Cruz (2019). For fuel energy there is a longer tradition. Recent important contributions are Allen (2009), Fouquet (2008), and Wrigley (2010) . In Moreno-Cruz and Taylor (2017) we developed the "Only Energy Model" and constructed a market economy where energy transforming intermediate goods created a motive for agglomeration leading to income and population growth. Here we extend the "Only Energy Model" to multiple energy sources, expand our predictions from single cores to landscapes, and develop an empirical method for evaluation.[5]

The rest of the paper proceeds as follows. In the section 2 we develop our simple model of the Food and Fuel economy, and prove four propositions linking variation in food and fuel productivities to variation in settlement populations, their geographic size, and the division of land across activities. Section 3 shows how we aggregate across individual settlements to obtain predictions at the landscape level. We also present the three equations guiding our empirical work. In section 4 we present, describe and interpret our empirical results. A short conclusion ends the paper. A lengthy appendix contains intermediate calculations, some proofs, and a full description of our data and empirical methods.

[5]We thank Oded Galor for suggesting we develop a food and fuel extension to the Only Energy Model.

2 Food and Fuel

There are two renewable energy resources producing harvests we call Food and Fuel. We abstract from optimal cropping decisions and assume storage is not possible. This allows us to focus on the relationship between energy availability and populations in steady state. This seems appropriate given our dataset is a single cross-section drawn from the 11th century. We assume consumption and production activities are located at a point in two dimensional space which we call the core, while resources supplying the core are distributed in the surrounding space. We treat cores and settlements as synonymous, because every core will be represented by a settlement drawn from the Domesday Book.

2.1 The Demand for Energy

Agents have a conventional quasi-concave and linearly homogeneous utility function defined over the service flow provided by food and fuel energy. By choosing service units appropriately we represent utility as:

$$u = u(W_o, W_e) \tag{1}$$

where W_o is food energy and W_e is fuel energy. Agents maximize (1) subject to their income. Given linear homogeneity, the distribution of income is irrelevant to aggregate demands; hence the (aggregate) relative demand for food vs. fuel, can be written as a simple function of their relative price. Choosing fuel as the numeraire, we have:

$$(W_o^D / W_e^D) = Q(p) \qquad Q' \leqslant 0 \tag{2}$$

where $p \equiv p_0/p_e$, and D indicates a quantity demanded at those prices.

2.2 The Supply of Energy

The supply of energy depends on two choices potential suppliers make. First, they must determine whether they can profitably deliver the harvest from either energy resource to the core. Second, if they can make a profitable delivery of either food or fuel, which energy resource should they cultivate and hence supply?

Consider the profitability question first. For either energy resource it is simple to calculate the distance at which transport to the core becomes prohibitive. We distinguish energy sources by their (power) density or spatial productivity, Δ, and let c be the unit energy cost of transport. Power density measures productivity per unit area, measured in energy provided, over a given unit of time.[6]

Then the net supply obtained from an energy resource with density Δ, delivered to the core at distance R, is simply:

$$d(\Delta, R) \equiv \Delta - cR \tag{3}$$

Marginal energy resources provide no supply: $d(\Delta, R) = 0$ and are located at distance $R = \Delta/c$. The more productive (dense) the energy resource (think dung, then wood, then coal) the further we are willing to go for it; likewise, the lower are transport costs (think overland, over road, and then on water) the lengthier the distance we willingly transport energy. If our two energy resources - food and fuel - have productivities denoted by Δ_o and Δ_e then their corresponding marginal energy resources would be located at distances $R_o \equiv \Delta_o/c$ and $R_e \equiv \Delta_e/c$ from our core.

[6]Power density is measured in Watts per meter squared [W/m^2]. An example might be helpful to fix ideas. Suppose a forest covering 100 m^2 generates a sustainable harvest of 10 kg of firewood per year. Firewood contains 15 MJ per kg; and there are 31,536 x 10^3 seconds in a year. Then this forest provides 4.75 W/m^2 on average for the year. This is its power density or productivity. A similar calculation for staple crops generates their power density. We assume the Watts produced by food and fuel are imperfect substitutes and both are essential for human survival.

2.3 The Composition of Output

To determine which resource to cultivate, agents compare their returns. The return to producing food is equal to its price times the quantity supplied to the core. This return varies with R and using (3), is $pd(\Delta_o, R)$. This is simply the value of its energy rents. The value of producing fuel is similarly $d(\Delta_e, R)$ if we recall that fuel is our numeraire. Without loss of generality we assume the power density of fuel exceeds that of food $\Delta_e > \Delta_o$. This immediately implies $R_e > R_o$.[7] We will adopt this assumption at present, but nothing important hinges on it. A comparison of energy rent schedules is shown in Figure 1 below.

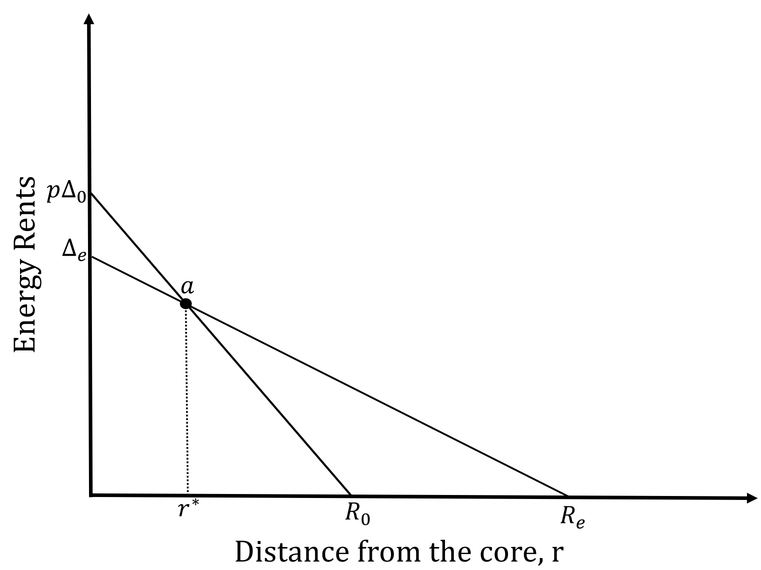


Figure 1: Energy Rent Schedules

Profit maximizing agents choose options from the upper envelope of the two rent schedules. At short distances, food provides a greater return. We can solve for the distance r^* where agents are indifferent between producing food or fuel. At point a, energy rents (per

[7]If transport costs differed across energy types, we could assume the ratio of fuel density to its transport costs exceed that of food and proceed. The key condition emanating from equal transport costs is $p(\Delta_o/\Delta_e) > 1$ and this will necessarily be true in equilibrium. With unequal transport costs a similar condition will obtain to ensure both goods are produced.

m^2 land) are identical, and this implies: $p\left[\Delta_o - cr^*\right] = \left[\Delta_e - cr^*\right]$. Solving we find:

$$r^* = \frac{R_o\left(p - \left(\frac{\Delta_e}{\Delta_o}\right)\right)}{(p-1)} \tag{4}$$

For any given relative price, food supply is found by adding up along a ray to r^*, and then sweeping this ray around the 2π radians of our exploitation zone. This produces:

$$W_o^S = \int_0^{2\pi}\int_0^{r^*} v\left(\Delta_o - cv\right) dv d\varphi = \frac{\pi\Delta_o^3}{c^2}\left(\frac{p - \frac{\Delta_e}{\Delta_o}}{p-1}\right)^2\left(1 - \frac{2}{3}\frac{(p - \frac{\Delta_e}{\Delta_o})}{(p-1)}\right) \tag{5}$$

Over $r^* < r < R_e$ fuel is supplied, and its supply can be written:

$$W_e^S = \int_0^{2\pi}\int_{r^*}^{R_e} v\left(\Delta_e - cv\right) dv d\varphi = \frac{\pi\Delta_e^3}{c^2}\left(\frac{1}{3} - \left(\frac{p\frac{\Delta_o}{\Delta_e} - 1}{p-1}\right)^2\left(1 - \frac{2}{3}\frac{(p\frac{\Delta_o}{\Delta_e} - 1)}{(p-1)}\right)\right) \tag{6}$$

It is useful to construct the relative supply of food energy to fuel energy as:

$$(W_o^S/W_e^S) = \left(\frac{\Delta_o}{\Delta_e}\right)^3 \frac{\left(\frac{p-\frac{\Delta_e}{\Delta_o}}{p-1}\right)^2\left(1 - \frac{2}{3}\frac{(p-\frac{\Delta_e}{\Delta_o})}{(p-1)}\right)}{\left(\frac{1}{3} - \left(\frac{p\frac{\Delta_o}{\Delta_e}-1}{p-1}\right)^2\left(1 - \frac{2}{3}\frac{(p\frac{\Delta_o}{\Delta_e}-1)}{(p-1)}\right)\right)} \tag{7}$$

Consider the properties of (7). For any relative price $p \leqslant \Delta_e/\Delta_o$ there is zero supply of food because it is not in any agent's interest to supply it. In terms of Figure 1 the fuel rent schedule would lie above the food schedule at all distances. For prices above $p = \Delta_e/\Delta_o$ food supply is positive and its relative supply is increasing in p. This is true because as p rises the food rent schedule pivots upwards and hence, r^* is an increasing function of p. As p rises and approaches plus infinity we can use (4) to show that r^* approaches R_o. Therefore as prices become very high, the relative supply curve becomes infinitely inelastic.

2.4 The General Equilibrium

It is apparent that as long as food and fuel are both essential in consumption there will be one, and only one, intersection of relative demand and supply. The equilibrium relative energy price p is therefore unique and can be found by equating relative demands and supplies; that is:

$$(W_o^D/W_e^D) = (W_o^S/W_e^S) \tag{8}$$

The general equilibrium generates a distribution of activity surrounding our core very similar to that of Von Thunen (See Thünen (1826)) - with one important distinction. Whereas Von Thunen assumed linear transport costs to limit city size, our linear transport cost c follows from the simple mechanics of friction, mass and work.[8] In this sense, we provide a theoretical and physics-based underpinning for Von Thunen's assumed linear costs.[9]

2.4.1 The National Income Function

Our Malthusian formulation requires us to study the determinants of real personal income quite closely. A useful step recognizes that using the equilibrium p from (8) we can compute aggregate income. This is the value of energy rents produced at the general equilibrium, or:

$$\begin{aligned} I(p, 1, \Delta_o, \Delta_e) &= pW_o + W_e \\ &= \frac{\pi \Delta_e^3}{3c^2}\left(1 + \frac{(p\frac{\Delta_o}{\Delta_e} - 1)^3}{(p-1)^2}\right) \end{aligned} \tag{9}$$

Since r^* reflects optimizing behaviour of price-taking agents, (9) represents a maximized GNP or national income function. It is homogeneous of degree one in all prices, and the partial derivatives with respect to prices equal optimal supplies. The partial derivative with

[8]See our appendix, section B.1 for a demonstration.

[9]It is a common misperception that Samuelson's iceberg transport costs are the same as those of Von Thunen. A very close read of Samuelson (1983) will reveal that settlement size is not determined by Samuelson's iceberg transport costs, but instead by an additional assumption imposed that limits the minimum density of labor to land employed. See our appendix, section B.2

respect to a productivity measure equals its positive marginal return. Consequently:

$$\frac{dI}{dp} = \frac{\partial I}{\partial p} = W_o^s \ , \ \frac{dI}{d\Delta_e} = \frac{\partial I}{\partial \Delta_e} > 0 \ \text{ and } \ \frac{dI}{d\Delta_o} = \frac{\partial I}{\partial \Delta_o} > 0$$

2.4.2 Malthus

In the simplest Malthusian set up, a population's birth rate is simply linear in a measure of average well being. Typically this measure of well being is taken to be average per capita real income. We follow that convention and write the birth rate (per unit time) as simply: $births \equiv b = b_0 + b_1[Y/L]$. Similarly, the death rate is: $deaths \equiv d = d_0 - d_1[Y/L]$ where real per capita income equals Y/L and L represents population size.

Population growth is equal to births minus deaths, but both forces reflect deeper determinants. First, there are the autonomous rates of births and deaths which determine whether population growth is positive or negative at the lower bound of well being (zero). These are the intercepts in the relations above. It is always assumed population growth is negative at very low levels of well being ($d_0 > b_0$). Second, there is a marginal response to changes in real income. These are the famous positive and preventative checks discussed by Malthus. These marginal responses arise from changes in fertility (preventative) and changes in mortality (positive) and they are captured by the slope coefficients in the relations above.

Setting births equal to deaths allows us to solve for the steady state relationship between real income per person and population size, finding:

$$L = M \cdot Y \quad \text{where} \quad M = \frac{d_1 + b_1}{d_0 - b_0} > 0 \tag{10}$$

M represents the Malthusian forces translating real income gains into resulting population sizes. Since $Y/L = 1/M$, for given Y, the stronger are the Malthusian forces the larger is the resulting steady state population and the lower is per capita income in the core.

Substituting for real income Y we can now obtain a solution linking characteristics of energy sources, Malthusian forces, and details of our general equilibrium economy to the resulting steady state population. This is given by:

$$L = M \cdot Y = M \cdot S \cdot V \cdot B \tag{11}$$

$$S = \frac{\pi \Delta_e^3}{3c^2}, \quad V = \left(1 + \frac{(p\frac{\Delta_o}{\Delta_e} - 1)^3}{(p-1)^2}\right), \quad \text{and} \quad B = 1/\beta(p) \tag{12}$$

S represents the scale of national income. It is equal to the value of fuel energy that would be available to the core if only fuel was produced. But of course more than fuel is produced, and V reflects how the value of national output is enhanced by the economy producing food as well. Therefore, V is a multiplier. It is greater than one because food is only produced when its value (in terms of fuel) exceeds that of fuel itself. Finally, B takes national income measured in terms of fuel and asks how many consumption baskets of food and fuel it could buy. B equals the number of baskets you can buy with income equal to one unit of fuel. As p rises, food becomes more expensive and B falls.

Combining our results, several Propositions now follow.

Proposition 1 *An increase in transport costs, c, leaves relative prices unchanged, but lowers the population size for any settlement. The exploitation zone for any settlement falls.*

An increase in transport costs hits each energy source equally and their relative supply is unaffected (see (7)). Relative demand is unaffected: hence prices do not change. Real income however falls (see (9)) and so too do population sizes. Every settlement's exploitation zone becomes geographically smaller (both horizontal intercepts in Figure 1 shift in). Conversely, settlements blessed with better transportation options (think roads, navigable rivers, or coastal locations) should be more populous. The mechanism is of course Malthusian: lower transport costs raise real income per capita, and these potential gains are then dissipated by population growth. In the end, settlements with better transport options are geographically larger but agents are not any richer.

A similar result follows when real income instead grows from a change in productivities.

Proposition 2 *An equiproportionate increase in food and fuel productivities* (Δ_o, Δ_e) *leaves relative prices unchanged, but raises the population size of any settlement. The exploitation zone for any settlement grows.*

This neutral change in productivities raises energy supplies equally. Real income per capita would rise, but is instead dissipated by population growth. In terms of Figure 1, the rent schedules shift out uniformly raising r^* in direct proportion to R_e. Settlements are bigger geographically, and in terms of population, but no richer on average.

It is less clear what happens to populations and exploitation zones when the productivity of only one energy source changes. This case requires further analysis because the composition of economic activities changes and this alters relative prices, real incomes etc. Nevertheless, there is a certain answer:

Proposition 3 *Settlement population sizes respond positively to increases in the productivity of fuel or food resources. An increase in the productivity of food leaves the size of exploitation zones unaffected; an increase in the productivity of fuel increases the size of exploitation zones.*

Consider the impact on a settlement's real income and hence its population. Recall real income Y is $I/\beta(p)$. We can differentiate $Y = I(p, 1, \Delta_o, \Delta_e)/\beta(p)$ with respect to Δ_o to find:

$$\frac{dY}{d\Delta_o} = \frac{\left(\beta[I_p \frac{dp}{d\Delta_o} + I_{\Delta_o}] - \beta'(p)\frac{dp}{d\Delta_o} I\right)}{\beta^2}$$

where subscripts on I refer to partial derivatives. The envelope theorem tells us that I_p equals the supply of food since I is a maximum value function; similarly, since Y is an indirect utility function, Roy's identity tells us that $\frac{\beta'(p)I}{\beta^2}$ equals the demand for food energy. Therefore the two terms multiplied by the price response cancel leaving us with a simple expression given by $dY/d\Delta_o = I_{\Delta_o}/\beta > 0$. Similarly, $dY/d\Delta_e = I_{\Delta_e}/\beta > 0$.

Real income again rises. In terms of Figure 1, the food rent schedule shifts out with the productivity improvement and then inwards as food's relative price falls. r^* may rise or fall depending on the elasticity of demand, but since r^* is set optimally, and ours is a competitive economy, real income must rise. Our Malthusian mechanism then translates these aggregate settlement wide real income gains into more populous settlements. For marginal changes, fuel will continue to determine the size of the exploitation zones and hence they are unaffected. A similar change in the productivity of fuel, raises real incomes, populations, but in this case increases the size of exploitation zones.[10] Finally, one last result we find useful is that:

Proposition 4 *The fraction of the exploitation zone taken up by food production is solely determined by the relative productivity of food to fuel.*

This is easy to prove by dividing the definition of r^* by R_e to find this ratio is only a function of relative productivities and relative prices. One implication is that the neutral changes in productivities discussed in Proposition 2, not only raise incomes and exploitation zones but leave the fraction of land employed in food unchanged. It appears to suggest, from Proposition 2, that an increase in the productivity of food will raise incomes, while increasing the share of land dedicated to food. Similarly, an increase in the productivity of fuel should lower the fraction of land dedicated to food. These last two statements however are only necessarily true when demands are sufficiently elastic. When the productivity of food rises, its supply rises and its relative price must fall to clear the market. With elastic demand, the needed change in relative prices is small and $r*$ rises. Land dedicated to food production rises. While individual agricultural commodities (and individual fuel types) often have inelastic demands, we have aggregated across all possible commodity and fuel types to obtain our aggregates. Therefore, an elastic demand for our aggregates seems appropriate, and we take this as given for the remainder of the paper.

[10] These results extend naturally to the addition of any new food or fuel type that competes for land with existing energy resources. If this new resource provides fuel or food energy more cheaply, a new r^* will emerge, real income rises, and so too will the settlement population. If the new resources are not perfect substitutes for the existing fuel or food resources, then the equilibrium will have several r^* switching points, but the argument remains the same.

3 From Core to Landscape Predictions

Thus far we have modelled only isolated settlements. The world however is composed of many concentrations of population and economic activity, and almost all statistical reporting units - provinces, prefectures, or states - include multiple settlements of various sizes and shapes. In order to facilitate empirical work we extend our theory to larger geographic units we call *landscapes*. We think of political units such as countries, provinces, counties, or shires as composed of landscapes that differ in terms of their geography and productivity; and the number and size of these landscapes would, inter alia, determine the overall spatial structure of the aggregate economy.

Landscapes are defined by two attributes: 1) a set of common model primitives; and 2), a description of its geography. We assume any settlement located within landscape j, is populated by agents whose actions are governed by the set of common primitives $\{c_j, M_j, \Delta_o^j, \Delta_e^j\}$. This ensures that all settlements within a given landscape are identical in terms of geographic size, population numbers, and of course, real income.

A landscape is also characterized by its physical geography: its physical size A_j and those features of its geography that determine transport costs through A_j. These features are access to the network of (pre-existing Roman) roads, rivers, mountain ranges, and coastlines. We define four *geographies* and refer to them as the simple, connected, coastal and edge geographies. The spatial organization of settlements within each geography is shown in Figure 2. This spatial organization reflects two additional assumptions we have made. First, we have assumed the area of a landscape is "full", in the sense that no free area large enough to support a settlement is left empty. This assumption is akin to ignoring an integer constraint, since free entry of settlements is assumed to perfectly exhaust useful land. Since A_j is useful productive land, this assumption does not rule out locations where very low productivity land supports few, if any, people.

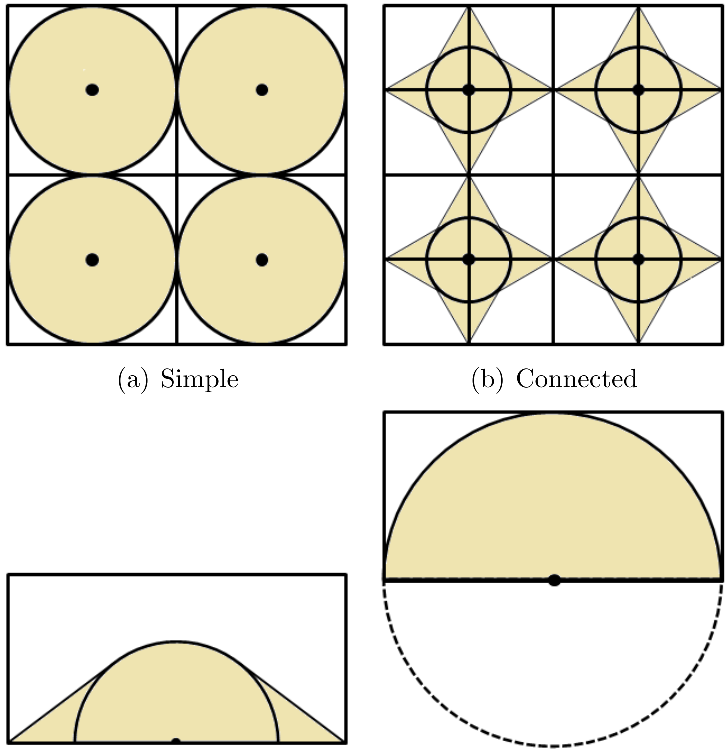
Second, we assume the exploitation zones of settlements cannot intersect. This reflects a deeper assumption we make regarding settlement size. Our theory assumes settlement size is the maximum possible limited only by energy constraints; specifically, the zero rent margin for fuel. As such, it rules out other possible limiting factors. For example, the exploitation zone for any settlement may be limited by the ability of its residents to defend its resources; it may be limited by the ability of manor managers to monitor serfs working on demense lands; or it may have been limited by political considerations and power sharing arrangements within the feudal system. Choosing the zero rent margin as the determinant of size, also implicitly assumes smaller settlements are inferior to larger ones.

In Moreno-Cruz and Taylor (2017), we addressed these settlement size issues by developing a similar model where energy products were slightly differentiated. In that setting, agents could remain isolated or join a settlement where there was a greater variety of lower cost products. A "love for variety" across products ensured agents wanted to live in the largest settlement possible, but in low productivity environments agents remained dispersed. Our setting here is, in many ways, representative of a special case of this model, where productivities in useful land are high enough to induce agglomeration into settlements, but differentiation within energy products approaches zero. Introducing differentiation across types of food and fuel harvests is possible, but would complicate and lengthen our analysis considerably.

With these provisos in mind, consider the top left panel of Figure 2, where we depict a simple landscape. In a simple landscape, transport in all directions is possible and equally costly. The uniform two dimensional space we employed in the theory fits this definition precisely.

A connected landscape is one where transport in all directions is possible but transport is less costly along an existing (North-South, East-West grid) road network cutting through the settlements. As a result of these low cost transport corridors, the exploitation zones appear as those shown in the right uppermost panel.

The third landscape is a coastal landscape where there is a low cost transportation option along one border perhaps provided by an ocean or lake. The coast provides cheap



(a) Simple (b) Connected

(c) Coastal (d) Edge

Figure 2: Geographies

transportation for resources further up or downstream from the core as shown. Finally an edge landscape is shown in the last panel. An edge landscape is one where expansion of the exploitation zone in at least one direction (the edge) is not possible. Edge landscapes are ones where a mountain range, a desert, or a political boundary limits potentially profitable expansion along one edge of the landscape boundary.

It is natural to think that settlements within a landscape featuring good transport options (say roads, rivers or a coastline) may engage in local (within landscape) or regional (across landscape) trade. Settlements on coastlines may even engage in international trade. These trading opportunities, would, in turn, provide real income gains affecting population numbers. It is beyond the scope of our theory to model all of these possibilities since they rely on the joint distribution of geographic features and potential differences in primitives across landscapes.[11] Nevertheless, in our empirical work we can allow for these complications

[11]This might be possible in a quantitative setting, but the relevant data remain very scarce. For an

quite readily. Our first step in doing so is to extend our theory's predictions to the landscape level. We provide this extension for simple landscapes in the text, and leave the remaining lengthier extensions for other landscapes to our appendix.

3.1 Simple Landscapes

Consider a single core at location i placed within a simple landscape j that has useful area A_j. Within this simple landscape consider what our theory says about the number of settlements, their average size and the landscape's population in a Malthusian steady state. We start with settlement numbers. The extensive margin for any settlement in landscape j is: $R_{ej} = \Delta_e^j/c_j$ because fuel represents the extensive margin of exploitation.

Since exploitation zones are circular they have an area proportional to the square of R_{ej}, and therefore a simple landscape that has useful land of size A_j can support at most N_j (non-intersecting) exploitation zones where N_j is given by:

$$N_j = \frac{A_j}{\pi[\Delta_e^j/c_j]^2} \tag{13}$$

When the number of cores or settlements reaches N_j the landscape is full. While this prediction for core numbers is interesting, its empirical verification is made difficult by the presence of fuel's spatial productivity in equation (13). Our data however includes information about both settlement population size and income. To exploit this information we note income at any core location i in landscape j can be written as:

$$I_{ij}(p, 1, \Delta_o, \Delta_e) = \frac{\pi[\Delta_e^j]^3}{3c_j^2}V_j \tag{14}$$

where we have purposely written out the determinants of scale S. Note V_j is solely a function of relative productivities; i.e., the comparative advantage of landscape j in producing food versus fuel. In contrast, the productivity of fuel scales income for a given composition of

excellent review of quantitative economic geography see Redding and Rossi-Hansberg (2017) settlement output. We can now easily isolate the productivity of fuel to find:

$$\Delta_e^j = \left[\frac{I_{ij}}{V_j} \frac{3c_j^2}{\pi} \right]^{1/3} \tag{15}$$

Eliminating the productivity of fuel is very useful step towards our empirics, because a measure of income is observable in our data, and we can develop controls for the determinants of V_j (comparative advantage) and transport costs, c_j. If we now substitute for Δ_e^j in (13) we obtain our first prediction at the landscape level:

$$N_j = \frac{A_j V_j^{2/3} c_j^{2/3}}{(9\pi)^{1/3} I_{ij}^{2/3}} \tag{16}$$

Or more simply in log form:

$$\log N_j = \gamma_0 + \gamma_1 \log A_j + \gamma_2 \log V_j - \gamma_3 \log I_{ij} + \gamma_4 \log c_j \tag{17}$$
$$\gamma_0 = -(1/3) \log 9\pi, \gamma_1 = 1, \gamma_{(2,3,4)} = 2/3$$

The (log) number of settlements in landscape j is equal to a location independent constant plus log measures of its area, a measure of its local comparative advantage, the income of a typical settlement, and transport costs. All gamma coefficients are positive, except the constant γ_0. Looking more closely, it is easy to see why the number of cores is proportional to useful area if the landscape is truly full. It is also easy to see why settlement numbers rise if transport costs are larger because exploitation zones are then smaller. It is a little harder to understand how I_{ij} and V_j affect settlement numbers. Consider two landscapes, and assume one is uniformly more productive than the other. Uniform differences in productivity means they share the same $V's$. But in terms of Figure 1, the rent schedules of the more productive landscape are shifted outwards and the geographic size of its exploitation zone is greater. For a given area, fewer settlements should be observed and this is why settlement income appears with a negative sign. Conversely, suppose settlement income was the same across two landscapes, but one landscape was a more productive location for food. All else equal, V_j is higher for this landscape, and to ensure average income across landscapes remained the same, its productivity of fuel must be correspondingly lower. A lower productivity for fuel in one landscape implies its settlements have smaller exploitation zones. For a given area, this landscape would have more settlements. This is why V_j enters with a positive sign.

Now consider how settlement population size varies across landscapes. We can easily write the steady state population in any given core i, located in any given landscape j as:

$$L_{ij} = M_j B_j I_{ij} \tag{18}$$

Taking logs we obtain a prediction for settlement population i within landscape j:

$$\log L_{ij} = \eta_1 \log M_j + \eta_2 \log B_j + \eta_3 \log I_{ij} \tag{19}$$
$$\eta_1 = \eta_2 = \eta_3 = 1$$

The (log) population in any settlement is determined by the strength of Malthusian forces, the local cost of a consumption basket, and average income of settlements in j. Holding income constant, as the cost of a consumption basket falls, B rises and so too does the population. Therefore, we would expect measures of productivity in food production to raise settlement population. Holding relative prices constant, increases in income raise population levels one for one. Combining these two we see Malthus at work: any (incipient) increase in settlement real income per person, is dissipated by a corresponding proportionate increase in settlement population size.

A different role for Malthus appears via M_j. Variation in M_j could arise from variation across landscapes in the behavioral response of birth and deaths to changes in income. These are Malthus's famous preventative and positive checks captured in the numerator of M in (10). Since our landscapes will be relatively small geographic units, these differences may be small or non-existent. The other source would be variation in the autonomous birth and death rates across landscapes. Any increase in the harshness of the natural environment might be expected to raise the gap between these death and birth rates. This raises the denominator of M in (10) lowering a settlement's population.

Finally we can use our solution for settlement size and numbers to obtain a prediction for aggregate landscape population. Combining, we find:

$$L_j = N_j L_{ij} = \frac{A_j M_j B_j V_j^{2/3} c_j^{2/3} I_{ij}^{1/3}}{(9\pi)^{1/3}} \tag{20}$$

Taking logs and introducing parameter coefficients, yields something more readable: :

$$\ln L_j = \mu_0 + \mu_1 \log A_j + \mu_2 \log M_j + \mu_3 \log B_j + \mu_4 \log V_j + \mu_5 \log c_j + \mu_6 \log I_{ij} \tag{21}$$
$$\mu_0 = -(1/3)\log(9\pi), \mu_{1,2,3} = 1, \mu_{4,5} = (2/3), \mu_6 = (1/3)$$

A landscape's (log) population is determined by (log) measures of the landscape's area, the strength of Malthusian forces, two terms that reflect the landscape's comparative advantage in food production, local transport costs and average income.

The roles of A_j, M_j and B_j in determining landscape populations are identical to the impacts they had on either settlement numbers or settlement population sizes. Similarly, variation in V_j and c_j only affect settlement numbers and their impacts follow from our earlier discussion.

One surprising finding is that while an increase in the (average) income of settlements in a landscape raises landscape population, a doubling of income does not double population sizes. This seems puzzling. To understand why, recall that to double income, holding both B_j and V_j constant, requires this increase come from a equiproportionate increase in both food and fuel productivities. This expands city size, and for given landscape area, it reduces settlement numbers. Each settlement is doubly as populous, but there are fewer of them. The net effect is a smaller increase in landscape population.

4 Empirics

4.1 The Domesday Book

The Domesday census is the first recorded census in the English language and it contains some of the most valuable information we have concerning the organization of medieval economies. The census was ordered by William the Conqueror in the winter of 1085 and was completed in a little under twenty months. The purpose was to obtain information on the resources and the financial wherewithal of the tenants he had conquered. The census was a major undertaking. To conduct it, the ancient counties were organized into seven circuits and each circuit was assigned a commission charged with collecting and verifying the information requested.[12] Each team of commissioners sent a list of questions to land holders. This information was then verified by personal testimony in the shire court in front of the commissioners and local leaders. This quite detailed information was then sent to a central clearing house believed to be the Exchequer at Winchester where it was transcribed, edited, and summarized to make up the final volumes.

While the census includes detail on many aspects of life at this time, some entries are more important than others for our purposes. The book contains a description of various manor resources such as fisheries, mills and pasture land, etc.; a measure of plough teams is available; and estimates of the value of the manor at three points in time. In addition the entries contain measures of the population at each location although this is incomplete. The book does not enumerate individual persons, but does list heads of households divided by class from which historians have produced population estimates.[13] While we do not have the census questions posed, most researchers accept the text of the Inquisitio Eliensis, an account of the estates of the Abbey of Ely in the counties of Cambridge, Hertford, Essex, Norfolk, Suffolk, and Huntingdon, presents the set of questions that fit the answers recorded in the Domesday records. In particular it asks the name of the manor; who held it in the

[12] Domesday contains entries from only 34 of the 39 ancient counties.

[13] See McDonald and Snooks (1985b), page 363 for a full account of the resources listed.

time of King Edward, and who holds it now, how many hides (approx 120 acres) are there, how many ploughs in demesne (how many oxen plough teams are there on the local lands of the manor) and how many belonging to the men (extra teams for other land), how many villeins, cottars, slaves, freemen and sokemen; how much woodland, meadow and pasture, how many mills and fisheries; how much has been added to or taken from the estate, how much the whole used to be worth, and how much it is worth now; and how much each freeman or sokeman had or has there; if more can be got out of it than is obtained now; all this three times over, with reference to the time of King Edward, and to the time when King William gave the land, and to the present time. As is apparent, this is a fairly intrusive and detailed accounting of the financial records of manors at the time. Since the records were given verbally and sworn to in the shire-court with local nobility and the sherriff present it is believed that the Domesday records are, to the best of our knowledge, reasonably accurate.

The specific data used in this project was obtained from the History Data Service and is the Electronic Edition of Domesday Book: Translation, Databases and Scholarly Commentary, located at https://www.ukdataservice.ac.uk. The database is the latest version of a long standing project to improve on the accuracy of both the Great and Little Domesday Books. The translation is based on the printed edition of Domesday Book by Phillimore and Co Ltd (39 volumes, 1975-92), as supplemented or amended by Domesday Explorer (2000), also published by Phillimore (www.phillimore.co.uk).[14]

4.2 Matching Theory to Domesday records

4.2.1 The Unit of Analysis

Landscapes are a useful device for generating theoretical predictions, but most data is collected over large politically defined geographic areas containing many or several landscapes. Since heterogeneity is a problem for aggregation, we adopt the smallest possible political

[14] For further information see the guide for the electronic resource also available at the same location under SN:5694 - Electronic Edition of Domesday Book: Translation, Databases and Scholarly Commentary, 1086.

aggregate we can - English hundreds (or wapentakes in former Danelaw regions) which are much smaller than traditional counties. There are for example only 39 ancient counties in England, but almost 900 hundreds. But some hundreds are large geographic units (larger than some counties) and they contain many manors and settlements that are quite heterogeneous. To partially remedy this, we exploit smaller sub-units of hundreds - parishes - in calculating hundred average characteristics. We first assign any Domesday entry to a parish from its location, and then use parish geographic size as a fraction of hundred size to create weighted averages over parishes within the hundred. Specifically, for any variable x_j tied to hundred j, we calculate: $x_j = \sum_{i=1}^{N_j} x_{ij} * [A_{ij}/Aj]$ where x_{ij} is the corresponding variable j drawn from a location in parish i, N_j is the number of parishes in hundred j, and A_{ij}/A_j is the area of parish i divided by the area of hundred j.[15] When x_j is a continuous variable, it is simply a parish-area weighted average. When x_j is a categorical variable (i.e. a parish has river access or not), then it represents the density of this characteristic within the hundred.

While the Domesday book contains information on 894 hundreds, in moving to estimation we make two adjustments to this potential sample. Since it is impossible to know whether the lack of a Domesday record for a hundred reflects a true zero for population or a value that is missing, we drop all hundreds for which there is no paired Domesday record. Similarly, we drop all hundreds that report a zero value for resources in 1086. With these two exclusions we are left with 875 observations at the hundred level. These 875 hundreds are in turn comprised of $8,103$ parishes containing $18,410$ settlements.

[15] We believe weighting by geographic size gives us a more accurate picture of hundred features, but there are some drawbacks to this procedure created by geographic spillovers. For example, manors will undoubtedly have lands and resources spread out over more than just the parish they are located within and parishes without a located resource will appear poorer than in reality. These spillovers will however be accounted for in neighboring parishes, which, in most cases, are also within the same hundred. Our choice of hundred as the unit of analysis was guided by the availability of parish boundary data, a concern that moving to parishes as the unit of analysis would create very large spillovers, while moving to counties would be aggregating over areas that are far too heterogeneous.

4.2.2 Economic Determinants

Our model links settlement numbers, settlement population sizes, and overall hundred populations to a relatively small number of economic forces determining transport costs, the scale and composition of incomes, and a Malthusian birth/death process. Key to our empirical work is our method for separating income into its scale and composition determinants. Recall from Propositions 2 and 3 that income gains coming from neutral increases in productivity have different impacts than income gains coming from an increase in the productivity of food alone. Both raise incomes, but one expands exploitation zones and one does not. Proposition 4 also tells us that the share of land dedicated to food production is unaffected in the first case, and should rise in the second (assuming demand is elastic).

With these results in mind, we start by assuming income earned on a manor is proportional to the value of its resources as recorded in the Domesday census. We use the most-often-reported 1086 value as our measure of income, although we also exploit the earlier 1066 value for some purposes (see below). This measure of income should be directly connected to the productivities of both food and fuel production, as it is in our theory (9). Average income, measured as described above, becomes our empirical measure of I_{ij}.

Also included in the Domesday survey is a measure of plough teams. Plough teams are exactly that, teams of oxen (thought to be eight) used to plough lands for intensive agriculture. Plough teams are a useful indicator of the composition of output, under two assumptions: the area of agricultural land (devoted to food) is proportional to the number of plough teams held to cultivate this land; and two, that our model's description of the division of land into that dedicated to food and fuel is correct. Under these assumptions we can use Proposition 4 to conclude that the number of plough teams per acre of land employed is tied directly to the relative productivities of food versus fuel. It is also an accurate measure of the fraction of land dedicated to food production (when demand is elastic). We exploit this connection to create a variable we call the abundance of arable land. It is of course a parish weighted average aggregated to the hundred level, and it captures, in theory, the fraction of land under the plough.[16] In theory, this abundance measure would affect both the composition of output V_j and the cost of the consumption basket B_j. We cannot separately identify these effects, and arable land, measured as described above, becomes our empirical measure of either or both V_j and B_j.

Finally, since the population shares many cultural and religious practices we treat the demographic portion of the model as common across all of English hundreds. While this doesn't rule out the possibility that hundreds differ in fertility and mortality because the local cost of a consumption basket differs, in addition we allow for the possibility that hundreds may differ in fertility and mortality, if they differ significantly in the harshness of the local climate. Variation in local climate is measured by average temperature and rainfall.

4.2.3 Transport costs, Geographic Descriptors and Interactions

To capture local differences in transport costs separate from those introduced by landscape geographic descriptors we employ a measure of the land's ruggedness. Greater ruggedness implies greater short term elevation changes over space, and hence higher transport costs. To classify hundreds into different landscapes we proceed in two steps. First, we create a set of categorical variables indicating the presence of roads, rivers, coastal or edge geographic features. Specifically, we identify all parishes within 5 km of a coastline and treat them as coastal; we find all parishes which are crossed by a major or minor Roman road and treat them as road connected; parishes on a political border are edge; and similarly, all parishes crossed by a major river are river connected. We then aggregate these categorical variables over the number of parishes in a hundred, weighting by their geographic size, to obtain a measure of the density of roads, rivers, or coastal access in that hundred. Since many parishes may be coastal and have river access, and this interconnection may matter for trade or commerce, we include a full set of interactions to allow for any non-linear network

[16] An alternative would be to use Domesday entries for plough lands. Unfortunately, this is recorded in disparate units and attempts at conversion to a common unit proved impossible. Plough teams in contrast are thought to be a fairly standard reference to a team of 8 oxen, whose productivity should not vary greatly geographically.

effects. Hundreds along the Welsh border are treated as edge, and we take simple landscapes as the excluded category in our empirical work. County wide differences are also captured via a set of county fixed effects. In doing so, our analysis is focused on the within county but across hundred variation in populations, settlements and incomes. Our hope is that by limiting our data's variation in this way we have retained sufficient variation to identify key forces at play, while eliminating problems arising from what we expect are sometimes large across county differences in unobservables. Finally, since the data was collected by common methods within each circuit, and circuits are contiguous, we cluster errors at the circuit level.

4.2.4 Endogeneity

The predictions we derived for population sizes, settlement numbers, etc. are reduced form expressions relating exogenous right hand side drivers to endogenous variables on the left. Settlement income is for example a predetermined variable setting population sizes in (19). This may be surprising, but in our theory, labour, and hence populations do not appear as a factor of production. Energy rents are collected, they are not generated by production. This assumption let us concentrate on transport costs, relative productivities, and our aggregation to landscape predictions. It also let us side-step, by assumption, a major issue in the empirical literature - the endogeneity of populations and incomes.

In similar, but more complicated, formulations, labor would appear explicitly in the national income function, and settlement density may affect individual settlement incomes. In these cases, settlement income and populations would be determined simultaneously. For the most part we will ignore this possibility and proceed with OLS estimation as if our theory was literally true, but in our appendix we investigate further by developing an instrument for income. Our instrument is provided in the Domesday survey - the previously determined settlement values in the year 1066. These values are strongly related to the subsequent 1086 values we employ, but are not be determined by the labor force employed twenty years hence.[17] These earlier values are not available for every settlement, so our sample size shrinks slightly but we retain over 700 hundreds in our dataset. In addition, Domesday contains records for several "resources" that are clearly in elastic supply and therefore potentially contaminated by population sizes.[18] Arable land, in contrast, is largely determined by geography. As a result, we ignore information on mills, fisheries, meadows etc. Doing so will strengthen the case that our results are truly causal.

To preempt slightly, instrumenting for income does not alter our OLS results in any significant way. Coefficient estimates are slightly different, but significance levels are not. Nothing of substance changes. It is for this reason that we feel comfortable with presenting and discussing the OLS results that follow.

4.3 Malthus at the Intensive Margin: Settlement Size

In Table 1 we examine the determinants of settlement size. Settlement size is, in theory, determined by a very small number of economic determinants as shown by (19): the average income of a settlement; the cost of a consumption basket; and Malthusian forces. In other landscapes, geographic descriptors also come into play.[19] Therefore, we divide the explanatory variables into three groups: economic determinants; landscape descriptors; and interaction effects. We start in column (1) with variables capturing the direct economic forces, and then add landscape descriptors and their interactions in columns two and three.

Recall that the abundance of arable land shifts a settlement's composition of output towards food and lowers its relative price. This lowers the price index and real income rises. Similarly, holding the composition of output constant, an increase in settlement income raises real income. Across all columns we find a strong positive relationship between these

[17]The rationale for the instrument is that the cross-sectional distribution of incomes in 1066 fully reveals underlying technological differences across hundreds, if 1066 is itself a Malthusian steady state. See our appendix for further details, the first stage results, and test for a weak instrument.

[18]We would like to thank an anonymous referee for this observation.

[19]We calculated equation (19) using the simple landscape. With different landscapes, the equation is identical up to a constant function $g(\rho)$ which depends on geographic descriptors. The full derivation of settlement size for alternative landscapes is in our Appendix A.3.2

determinants of real income and settlement population. In particular, a 100% increase in settlement income raises populations by over 80%. This is strong evidence for Malthusian forces at work on the intensive margin.

Table 1: Settlement Size

	(1)	(2)	(3)
Income	0.817^a	0.817^a	0.820^a
	(0.043)	(0.039)	(0.037)
Abund. Arable Land	0.263^b	0.269^b	0.264^b
	(0.092)	(0.086)	(0.083)
Precipitation	-1.205	-1.241^c	-1.252^c
	(0.647)	(0.628)	(0.621)
Temperature	0.110	-0.187	-0.231
	(0.577)	(0.667)	(0.631)
Coastal		0.031	0.002
		(0.036)	(0.043)
Rivers		0.223	0.312^b
		(0.143)	(0.118)
Minor Roads		0.027	0.028
		(0.161)	(0.167)
Major Roads		-0.093	-0.119
		(0.088)	(0.111)
Border Wales		0.291^a	0.289^a
		(0.069)	(0.070)
Coastal and Rivers			-0.727^a
			(0.163)
Coastal and Minor Roads			0.670^c
			(0.320)
Coastal and Major Roads			0.682^a
			(0.155)
Rivers and Minor Roads			-0.522^c
			(0.250)
Rivers and Major Roads			-0.072
			(0.157)
Constant	8.444	9.374	9.548
	(5.345)	(5.236)	(5.171)
County	X	X	X
Observations	875	875	875
Adjusted R^2	0.79	0.79	0.79

Notes: All variables are log transformed using $\tilde{x} = ln(1 + x)$. Errors clustered at the circuit level are reported in round parentheses. ^{a}, ^{b}, and ^{c} denote significance at the 1 , 5 and 10

Similarly, a doubling of the abundance of arable land raises populations a little less than 30%. Since we do not have information on the exact price index relevant at this time, nor the price adjustment created by an abundance of arable land, it is not possible to relate this magnitude directly to its impact on real income. Nevertheless, it indicates a very strong role for the abundance of arable land in determining real income and hence populations in this highly agrarian society.

To account for potential differences in the strength of Malthusian forces tied to the harshness of the climate, we have included both the average temperature and precipitation of the hundred. It seems reasonable to assume that the behavioral responses captured in the preventative and positive checks do not vary within counties. However, the harshness of the climate could adversely affect the very young and very old. Given our specification, our environmental variables capture only the within county and across hundred variation. Although some counties are very large, many are relatively small and hence this variation is undoubtedly small. Perhaps not surprisingly, of the environmental variables only precipitation is significantly related to populations. We find, across all columns that settlement size falls with rainfall even controlling for the composition and scale of income, temperature and potential coastal location.

In the last two columns we add landscape descriptors and their interactions. Column two offers little in the way of evidence for a positive link between additional transport options and populations. It does however show a strong influence of being on the border of Wales. This may indicate settlement size also reflects trade or security motivations. Column three is more useful, as it appears that the interaction of transport options is important albeit in confusing ways. Coastal locations appear to raise settlement sizes, but this is mediated by the joining interior transport option (roads or rivers).

Overall the results are highly encouraging. Consonant with Propositions 2 and 3, we find that real income gains, however created, drive large and highly significant increases in population. For example, a uniform increase in productivities that doubled income, would be almost completely dissipated by subsequent growth. This very strong intensive margin effect tells us that Malthusian forces are alive and well in Domesday England. Adding in controls for the harshness of the climate, and transport options has little if any effect on these results suggesting their robustness. Finally, we find strong evidence that transport options have large impacts on settlement size although exactly how remains unclear.

4.4 Malthus at the Extensive Margin

We now examine the strength of Malthusian forces at the extensive margin. Recall that settlements within landscapes have common productivity, abundance of arable land, and are therefore of equal size. This implies any expansion of hundred geographic size should produce more settlements, a greater population, but equal population density. This is, in essence, our model's Malthusian prediction at the extensive margin. We start our investigation of these extensive margin effects by examining the determinants of settlement density.

4.4.1 The Number of Settlements

In Table 2 we examine the determinants of settlement density by estimating different versions of (17) over our 875 hundreds.[20] We start in column (1) with variables capturing the direct economic forces, and then add landscape descriptors and their interactions in columns two and three respectively. The four key economic regressors are: the income of settlements in the hundred (I_{ij} averaged over i); the abundance of arable land which is our determinant of V_j; a direct measure of hundred area A_j; and ruggedness which measures variation in transport costs across hundreds.

In column one, we find strong evidence that our two determinants of income affect settlement size differently. For example, increases in settlement income coming from a larger reliance on arable land, holding overall settlement income constant, produces a landscape populated by geographically smaller but more numerous settlements. Conversely, increases in income coming from uniform differences in productivity, holding the abundance of arable land constant, produces larger and less numerous settlements (for given area). The impacts of these changes are also economically significant. An increase of 20% in the abundance of

[20]We calculated equation (17) using the simple landscape. With different landscapes, the equation is identical up to a constant function $g(\rho)$ which captures the impact of geographic features lowering transport costs. The full derivation of the number of settlements for alternative landscapes is in our Appendix A.3.3

Table 2: Number of Settlements

	(1)	(2)	(3)
Income	-0.315[a]	-0.311[a]	-0.309[a]
	(0.047)	(0.045)	(0.042)
Abund. Arable Land	0.811[a]	0.803[a]	0.802[a]
	(0.110)	(0.104)	(0.102)
Area	0.772[a]	0.769[a]	0.769[a]
	(0.021)	(0.018)	(0.018)
Ruggedness	0.015	0.009	0.008
	(0.033)	(0.035)	(0.037)
Coastal		-0.107	-0.151
		(0.076)	(0.088)
Rivers		-0.317[c]	-0.319[b]
		(0.144)	(0.105)
Minor Roads		-0.095	-0.132
		(0.068)	(0.072)
Major Roads		0.031	0.044
		(0.066)	(0.082)
Border Wales		0.342[a]	0.339[a]
		(0.039)	(0.036)
Coastal and Rivers			0.511[c]
			(0.234)
Coastal and Minor Roads			1.120[a]
			(0.112)
Coastal and Major Roads			0.145
			(0.393)
Rivers and Minor Roads			0.730[c]
			(0.310)
Rivers and Major Roads			-0.204
			(0.217)
Constant	-0.832[b]	-0.760[b]	-0.753[b]
	(0.255)	(0.274)	(0.296)
County	X	X	X
Observations	875	875	875
Adjusted R^2	0.91	0.91	0.91

Notes: All variables are log transformed using $\tilde{x} = ln(1 + x)$. Errors clustered at the circuit level are reported in round parentheses. [a], [b], and [c] denote significance at the 1 , 5 and 10

arable land, raises the density of settlements by 15%; An increase in overall productivity of the landscape by 20%, lowers the density of settlements by 7%.

Not surprisingly, area is a strong indicator of settlement numbers. A doubling of hundred area leads to an almost 80% increase. Since this point estimate falls short of unity, it implies the density of settlements falls with overall hundred size. This result remains true even as we move rightwards in the table to columns two and three. Since we are taking hundred area as equivalent to our theory's useful land, our finding that larger hundreds have less full landscapes is perhaps not surprising. Less satisfying is that ruggedness (our measure of within hundred variation in transport costs) has the predicted sign but fails to be significant. It is possible that too little variation in ruggedness within counties is left, leading to imprecision in this estimate. Adding in other determinants in columns two and three does nothing to remedy the situation, but neither does it worsen it.

In column two we introduce our landscape descriptors. Each of the regressors is measured as a density: they represent the weighted average proportion of parishes within a hundred that are crossed by (rivers, roads) or touch (coast) the named geographic feature. In theory, an increase in the density of these features should lower transport costs and produce fewer but geographically larger settlements for given hundred area. While three of our four descriptors do enter negatively, only river density seems to matter. Proximity to the Welsh border also seems to matter, although why this is true is a mystery.

In column three we include interaction terms to allow transport options to magnify the impact of others. Surprisingly, these interactions seem to matter greatly, although in the opposite direction our theory suggests. In almost all cases, these interactions enter positively suggesting smaller settlements and greater density. One possibility is that within hundred, across county or even across country, trade is being facilitated (a possibility not in our theory), by a more robust transportation network. If this trade brings income gains, akin to those raising V_j, then settlements maybe become richer, but not necessarily larger. This is, however, only one of many potential explanations and future work could explore more fully the potential role of trade in affecting Domesday geography.[21]

Overall, Table 1 presents strong support for our approach. Despite the task of explaining the variation in settlement density across much of Norman England over 1000 years ago, our simple model determinants and landscape descriptors do quite well.

[21] There is very little if any information on even regional trade at this time. Transport costs within country were thought to be very high, which may explain why transport networks loom so large here. It is difficult to see a meaningful way forward to identifying the source of these effects, other than mechanically introducing regional or river system effects or running gravity type specifications. See however Masschaele (1993) for an ingenious method of measuring transport costs in Medieval England. We leave this task to future researchers.

4.4.2 Hundred Populations

In Table 3 we examine the link between hundred population levels and our theory's set of determinants. The equation we estimate is a version of equation (21).[22] Consider first the role of income as measured in column one. We find strong evidence that differences in income across hundreds matters to populations. For example, a doubling of income raises hundred population by approximately 42%. This estimate is far from unity because our hundreds are of fixed size and this limits their expansion. Recall from Tables 1 and 2, that increases in income, raise settlement population sizes but lower settlement numbers given our fixed hundred size. Consequently, its total impact on hundred population levels is uncertain. What our estimates in Table 3 indicate, is that overall population does rise, but less than one for one with income gains.

In fact, we could have arrived at this result in a somewhat different way. If we add the partial impact of income on settlement numbers (from Table 2, column 1) to the partial impact of income on settlement size (from column 1 in Table 1) we find a total impact of .503 which is only slightly larger than our estimate in Table 3 column one. This tells us that our theory's very specific prediction for how income gains are dissipated by population gains as evidenced by Tables 1 and 2, are now confirmed by the aggregate results in Table 3.[23]

A similar result is true for changes in the abundance of arable land. From Table 3 we find a 100% increase in the abundance of arable land, produces an 140% increase in hundred populations. From Table 1 and 2, an increase in the abundance of arable land produces more and larger settlements. Since both effects work in the same direction, we find a greatly magnified impact of arable land at the aggregate level. We could arrive at this conclusion

[22]It differs from (21) only in terms of its constant which now appears as $\mu_0 = g(\rho)$ where $g(\rho)$ is zero in a simple landscape, but not equal to zero in a coastal, connected, or edge landscape. See our appendix section A.3 which contains the complete derivation of $g(\rho)$.

[23]Why do the estimates not add up exactly? What we are doing here is relating an aggregate z to its components x and y, where $z = xy$. Taking logs and differentiating shows we should be able to add up the partial effects estimated in the regressions. Apart from estimation and approximation error, they shouldn't add up exactly because average settlement population is a parish-area weighted-average, and this average, multiplied by the number of settlements does not equal the simple sum of population in that hundred.

Table 3: Overall Population Size Hundreds

	(1)	(2)	(3)
Income	0.419^a	0.429^a	0.435^a
	(0.087)	(0.085)	(0.082)
Abund. Arable Land	1.391^a	1.381^a	1.375^a
	(0.157)	(0.149)	(0.139)
Area	0.940^a	0.938^a	0.939^a
	(0.038)	(0.036)	(0.035)
Precipitation	-4.049^b	-4.038^b	-4.044^b
	(1.178)	(1.151)	(1.141)
Temperature	0.938	1.561	1.547
	(1.362)	(1.353)	(1.420)
Ruggedness	0.090	0.092	0.088
	(0.060)	(0.059)	(0.063)
Coastal		-0.228^b	-0.352^b
		(0.086)	(0.102)
Rivers		-0.120	-0.035
		(0.142)	(0.181)
Minor Roads		-0.026	-0.068
		(0.143)	(0.147)
Major Roads		-0.156	-0.173
		(0.166)	(0.204)
Border Wales		1.292^a	1.287^a
		(0.153)	(0.151)
Coastal and Rivers			0.255
			(0.312)
Coastal and Minor Roads			2.603^a
			(0.482)
Coastal and Major Roads			1.113
			(0.681)
Rivers and Minor Roads			-0.035
			(0.602)
Rivers and Major Roads			-0.338
			(0.295)
Constant	21.935^c	20.393^c	20.492^c
	(9.928)	(9.643)	(9.738)
County	X	X	X
Observations	875	875	875
Adjusted R^2	0.80	0.81	0.81

Notes: All variables are log transformed using $\tilde{x} = ln(1 + x)$. Errors clustered at the circuit level are reported in round parentheses. ^{a}, ^{b}, and ^{c} denote significance at the 1 , 5 and 10

by adding up the partial effects across tables. The sum of partial effects across tables, is 1.1 versus an estimated total effect in Table 3 of 1.4. Our theory's very specific prediction for how income gains from more abundant arable land are dissipated is confirmed by the aggregate results.

In Table 3 we find, across all columns, that the coefficient on area is positive, significant, and close to one in magnitude at .94. Given the standard errors shown, it is apparent we cannot reject the hypothesis of this coefficient being exactly one. Therefore, a doubling of hundred size doubles the overall population. This is strong evidence of Malthusian forces at work on the extensive margin.

We also find some evidence that climate may matter for populations. We again find variation in temperate has little effect on populations, but precipitation has a strong negative impact. This is suggestive evidence that cold harsh rainy locations may have higher death rates or lower birth rates, independent of their incomes. Turning to the costs of transport, a hundred's ruggedness per se has no significant impact on its population, although some of our geographic descriptors do have an impact. For example, location on a coast seems important although its unclear how or why. Coastal location appears to lower populations, but coastal locations tied to interior transport networks raise hundred populations. We find that our one descriptor of an edge landscape - an indicator for hundreds that border Wales - appears to raise population levels. Again, we are left with evidence that the transportation network matters, but does so in somewhat mysterious ways.

5 Conclusions

This paper developed a simple, spatially explicit, economic model that generates predictions for the size, location, and number of human settlements across geographic space. We started by examining a single core whose size was constrained by its productivity in food and fuel production. A simple general equilibrium determined relative prices, land use, and incomes. A Malthusian process, governing births and deaths, ensured population numbers kept real income per capita at subsistence levels. By placing this core into a larger geographic unit, we refer to as a landscape, we obtained additional predictions for the density of settlements and aggregate landscape populations.

We evaluated our theory's predictions with data drawn from the very first census in the

English language - the Domesday census of 1086 ordered by William the Conqueror. This census is a very rich source of geo-located data drawn from a time and place where energy constraints were of first-order importance. Using the Domesday data, together with other geo-spatial information on Roman roads, navigable rivers and coastlines, we evaluated our theory's precise, and sometime surprising, hypotheses. We have three major findings.

First, we find strong evidence of Malthusian population adjustment on two different margins. On the intensive margin, we find individual settlement population sizes rise more than 80% when settlement incomes double. Settlements within hundreds grow larger, but there are correspondingly fewer of them. When we expand hundred size, we find even stronger results on the extensive margin. Populations within a hundred would for example double, if hundred area doubled. Malthusian forces populate the new area with equal density. This is Malthus at work on the extensive margin.

Second, we find a surprising difference between the impacts of income gains created by an increase in the abundance (or productivity) of arable land, and the impact of income gains created by uniform productivity gains. The former raises populations, and generates more numerous but geographically smaller settlements. The latter raises populations, but generates fewer and geographically larger settlements.

Third, we find strong evidence that transport costs and physical geography have large effects on both settlement size and settlement numbers. While the estimated impacts of road, rivers and coastlines are sometimes in line with our theory; they are often not, and a key task for future research is to investigate how trade and transportation networks may have affected even 11th century economic geography.

Despite the obvious limitations to our cross-sectional data, and the challenges faced in modelling a Medieval economy, we have made significant progress in shedding light on the role Malthusian forces played in shaping the economic geography of Domesday England.

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Appendix:
Food, Fuel and the Domesday Economy

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A Lengthy Calculations

A.1 Net power supplied

A.1.1 One crop

Energy rents are given by $\Delta - cr$, where r is the distance to the core. Marginal energy rents are given by $\Delta - cR = 0$ so that the maximum radius defining the exploitation zone is $R = \Delta/c$. The net power supplied to the core is:

$$W^S = \int_0^{2\pi}\int_0^R v\Delta[1-\frac{c}{\Delta}v]dvd\varphi = 2\pi\int_0^R v\Delta[1-\frac{c}{\Delta}v]dv$$
$$= 2\pi\left[\frac{v^2}{2}\Delta - c\frac{v^3}{3}\right]\Bigg|_0^R = \frac{\pi\Delta^3}{3c^2} \tag{A.1}$$

A.1.2 Two Crops

The indifference point is calculated from:

$$p\left[\Delta_o - cr^*\right] = \left[\Delta_e - cr^*\right] \tag{A.2}$$

so that

$$r^* = \frac{R_o\left(p - \left(\frac{\Delta_e}{\Delta_o}\right)\right)}{(p-1)} \text{ where } R_o \equiv \Delta_o/c \tag{A.3}$$

The flow of (net) food energy they supply to the core is given by:

$$W_o^S = \int_0^{2\pi}\int_0^{r^*} v\left(\Delta_o - cv\right)dvd\varphi = \frac{\pi\Delta_o^3}{c^2}\left(\frac{p-\frac{\Delta_e}{\Delta_o}}{p-1}\right)^2\left(1-\frac{2}{3}\frac{(p-\frac{\Delta_e}{\Delta_o})}{(p-1)}\right) \tag{A.4}$$

The flow of (net) fuel energy supplied over $r^* < r < R_e$ becomes:

$$W_e^S = \int_0^{2\pi}\int_{r^*}^{R_e} v\left(\Delta_e - cv\right)dvd\varphi = \frac{\pi\Delta_e^3}{c^2}\left(\frac{1}{3} - \left(\frac{p\frac{\Delta_o}{\Delta_e}-1}{p-1}\right)^2\left(1-\frac{2}{3}\frac{(p\frac{\Delta_o}{\Delta_e}-1)}{(p-1)}\right)\right) \tag{A.5}$$

For the area of exploitation, we are only interested in the external margin, which is simply the area of a circle with radius $\bar{R}_e$. Here we use the double integral notation, because it is useful for future calculations as we deviate from the simplest case.

$$EX = \int_0^{2\pi} \int_0^{\bar{R}_e} v dv d\phi = \pi \left(\frac{\Delta_e}{c} \right)^2 \tag{A.6}$$

A.2 Connected, Coastal and Edge Landscapes

We have thus far only considered simple landscapes, and it is tempting to think that many of our results are reliant on this assumption. Surprisingly, very similar and often exactly the same results hold for very different landscapes. To understand why, we construct a specific example to help build intuition. We show that a river through any core at location i, in landscape j effectively magnifies by a factor $(1 + g(\rho)) > 1$, the power densities of both energy sources. That is, we can write:

$$\Delta_e^j = (1 + g(\rho))^{1/3} \Delta_e^{j0} \ and \ \Delta_o^j = (1 + g(\rho))^{1/3} \Delta_o^{j0} \tag{A.7}$$

$$\begin{aligned} g(\rho) &= \frac{1}{\pi} \frac{\sqrt{1-\rho^2}}{\rho} - \frac{\bar{\theta}}{\pi} \geqslant 0 \\ c(\theta) &= \begin{cases} c\Gamma[\theta, \rho] & \text{if } \theta \leqslant \bar{\theta} \\ c & \text{if } \theta \geqslant \bar{\theta} \end{cases} \\ \Gamma[\theta, \rho] &= \left((1-\rho^2)^{1/2} \sin\theta + \rho \cos\theta \right) \end{aligned} \tag{A.8}$$

where the superscript $j0$ represents the landscape's original productivities without the river. Note $g(\rho)$ is increasing in the cost advantage of the river option $\rho \leqslant 1$. More efficient river transport implies $\rho \to 0$ which drives $g(\rho)$ towards infinity. $\bar{\theta} = \cos^{-1} \rho$ is independent of relative prices and uniquely determined by the cost advantage of the river option, ρ. This result is just a generalization of our finding of a transport multiplier, but now extended to a market economy with two energy sources.

Given the multiplicative role of $g(\rho)$, it is apparent the relative supply of food to fuel energy will be unaffected by the existence of the river and hence so too will be equilibrium relative prices. But since core income is homogeneous of degree three in power densities, we conclude that the existence of a river through the core raises real income by a factor $g(\rho) > 0$. It is then immediate that the resulting steady state population in a core with river transport is greater by a factor $g(\rho)$.

To calculate the number of such cores supported in a given landscape, we need to amend our earlier calculations for the area of exploitation coming from the extensive margin. In the case of a river, the extensive margin is given by

$$R(\theta) = \begin{cases} \frac{\Delta_e}{c\Gamma[\theta,\rho]} & \text{if } \theta \leqslant \bar{\theta} \\ \frac{\Delta_e}{c} & \text{if } \theta > \bar{\theta} \end{cases} \tag{A.9}$$

Therefore, the size of the exploitation zone for a river located core is given by:

$$EX^{river} = (1 + g(\rho)) \frac{\Delta_e^2}{c^2} \tag{A.10}$$

and this implies the number of cores supported in a landscape of size A is given by:

$$N = \frac{A}{EX^{river}} = \frac{Ac^2}{\Delta_e^2(1+g(\rho))} \tag{A.11}$$

Putting these results together we have found our previous predictions need only small amendments. The river works like a lowering of transport costs albeit of a specific type. It lowers transport costs, expands exploitation zones, and lowers settlement numbers. Its strength in doing so depends on the cost advantage as captured by ρ. The addition of the river enters simply and drives up the population within each settlement. Finally, since the total landscape population is found by multiplying settlement numbers by their average size, quite surprisingly we find the overall population in the landscape is independent of $g(\rho)$. This is a surprising result. Access to a river makes any core larger in terms of its population and lowers the number of settlements in any given area, but leaves the overall population size of the landscape unaffected. Rivers - just like the costs of transport we already studied - affect the organization of production but not its overall efficiency. They support larger centers since they lower transport costs, but if the efficiency of the underlying environment is unaffected by their presence then so too are population levels.

Although it is not immediately apparent, these results generalize quite nicely. For example, consider a landscape where a road intersected the core rather than a river. In this case our magnification effect would be $(1 + 2g(\rho))$ or almost twice as large since transport is made less costly in both directions. Settlement numbers fall, their size rises and our log linear equations need only the most obvious amendment. Similarly, consider a landscape where along one side there was an ocean and the other was landscape with a given power density. This is a coastal landscape. Assuming transport in both directions along an coast is possible (like our road case) then it should be apparent the exploitation zone for a core along the coast is just equal to $(1/2 + g_j(\rho_j))\frac{\Delta_e^2}{c^2}$. A seaside located core would have its population magnified by a factor $(1/2 + g(\rho))$ and the number of such locations in a given area has to fall as before. Next, consider a landscape completely filled with N cores all connected by a rectangular road network with two roads (North-South, and East-West) running through the cores. This is our connected landscape. Each of the cores would then be twice as connected as those connected with a single road and hence more populous in proportion to $(1 + 4g(\rho))$. This implies there would be fewer and larger cores, and again all adjustment in our predictions are straightforward.

Finally, consider a situation where the expansion in one (or more) directions from the core is blocked by either a geographical or political barrier. This is our edge landscape. In this situation, the landscape would be just half the population size of the simple landscape and it would have the same number of places.

The derivation details are in the subsections below.

A.2.1 Rivers

Energy rents in the case of a river are given by $w = \Delta - c(\theta)r$ where

$$c(\theta) = \begin{cases} c\Gamma[\theta, \rho] & \text{if } \theta \leqslant \bar{\theta} \\ c & \text{if } \theta \geqslant \bar{\theta} \end{cases} \tag{A.12}$$

and $\Gamma[\theta,\rho] = \left((1-\rho^2)^{1/2}\sin\theta + \rho\cos\theta\right)$. Farmers located at an angle $\theta < \bar{\theta}$ will deviate to the river. The cut-off radius for farmers located at an angle $\theta > \bar{\theta}$ is given by:

$$r_a = \frac{p\Delta_0 - \Delta_e}{(p-1)c} \tag{A.13}$$

The cut-off radius for farmers located at an angle $\theta < \bar{\theta}$ is given by:

$$r_b(\theta) = \frac{p\Delta_0 - \Delta_e}{(p-1)c\Gamma[\theta,\rho]} \tag{A.14}$$

The integrals of energy supplied for food and energy are given respectively by:

$$\begin{aligned} W_o^{River} &= 2 \times \left[\int_0^{\bar{\theta}} \int_0^{r_b(\theta)} (\Delta_o - c\Gamma[\theta,\rho]v) v dv d\theta + \int_{\bar{\theta}}^{\pi} \int_0^{r_a} (\Delta_o - cv) v dv d\theta \right] \\ &= \frac{\Delta_o^3}{c^2} \left(\frac{p - \frac{\Delta_e}{\Delta_o}}{p-1} \right)^2 \left(1 - \frac{2}{3} \frac{p - \frac{\Delta_e}{\Delta_o}}{p-1} \right) \left(\pi - \bar{\theta} + \int_0^{\bar{\theta}} \Gamma[\theta,\rho]^{-2} d\theta \right) \\ &= \frac{\Delta_o^3}{c^2} \left(\frac{p - \frac{\Delta_e}{\Delta_o}}{p-1} \right)^2 \left(1 - \frac{2}{3} \frac{p - \frac{\Delta_e}{\Delta_o}}{p-1} \right) \left(\pi - \bar{\theta} + \frac{\sqrt{1-\rho^2}}{\rho} \right) \\ &= (1+g(\rho)) W_o^S \end{aligned} \tag{A.15}$$

$$\begin{aligned} W_e^{River} &= 2 \times \left[\int_0^{\bar{\theta}} \int_{r_b(\theta)}^{R_e(\theta)} (\Delta_e - c\Gamma[\theta,\rho]v) v dv d\theta + \int_{\bar{\theta}}^{\pi} \int_{r_a}^{R_e} (\Delta_e - cv) v dv d\theta \right] \\ &= \frac{\Delta_e^3}{c^2} \left(\frac{1}{3} - \left(\frac{p\frac{\Delta_o}{\Delta_e} - 1}{p-1} \right)^2 \left(1 - \frac{2}{3} \frac{p\frac{\Delta_o}{\Delta_e} - 1}{p-1} \right) \right) \left(\pi - \bar{\theta} + \int_0^{\bar{\theta}} \Gamma[\theta,\rho]^{-2} d\theta \right) \\ &= \frac{\Delta_e^3}{c^2} \left(\frac{1}{3} - \left(\frac{p\frac{\Delta_o}{\Delta_e} - 1}{p-1} \right)^2 \left(1 - \frac{2}{3} \frac{p\frac{\Delta_o}{\Delta_e} - 1}{p-1} \right) \right) \left(\pi - \bar{\theta} + \frac{\sqrt{1-\rho^2}}{\rho} \right) \\ &= (1+g(\rho)) W_e^S \end{aligned} \tag{A.16}$$

Now, we can write energy delivered to the core in the presence of a river as

$$W_o^{River} = (1+g(\rho)) W_o^S \tag{A.17}$$

$$W_e^{River} = (1+g(\rho)) W_e^S \tag{A.18}$$

where W_o^S and W_e^S are defined above, and $g(\rho)$ is given by the following expression:

$$g(\rho) = \frac{1}{\pi} \frac{\sqrt{1-\rho^2}}{\rho} - \frac{\bar{\theta}}{\pi}. \tag{A.19}$$

The area of the exploitation zone for a core with a river is given by:

$$EX^{River} = 2 \times \left[\int_0^{\bar{\theta}} \int_0^{R_e(\theta)} v dv d\theta + \int_{\bar{\theta}}^{\pi} \int_0^{R_e} v dv d\theta \right] \tag{A.20}$$

$$= \frac{\Delta_e^2}{c^2} \left[\pi - \bar{\theta} + \int_0^{\bar{\theta}} \frac{1}{\Gamma(\theta)^2} d\theta \right] \tag{A.21}$$

$$= (1 + g(\rho))EX \tag{A.22}$$

A.2.2 Roads

Next consider a core with a road instead of a river. A road is a river that allows for lower costs of transportation in both directions. This means the energy supplied is now given by:

$$W_e^{Road} = 4 \times \left[\int_0^{\bar{\theta}} \int_{r_b(\theta)}^{R_e(\theta)} (\Delta_e - c\Gamma[\theta, \rho]v) v dv d\theta + \int_{\bar{\theta}}^{\pi/2} \int_{r_a}^{R_e} (\Delta_e - cv) v dv d\theta \right]$$

$$W_e^{Road} = (1 + 2g(\rho))W_e^S \tag{A.23}$$

$$W_o^{Road} = 4 \times \left[\int_0^{\bar{\theta}} \int_0^{r_b(\theta)} (\Delta_o - c\Gamma[\theta, \rho]v) v dv d\theta + \int_{\bar{\theta}}^{\pi/2} \int_0^{r_a} (\Delta_o - cv) v dv d\theta \right]$$

$$= (1 + 2g(\rho))W_o^S \tag{A.24}$$

The area of the exploitation zone for a core with a road is given by:

$$EX^{Road} = (1 + 2g(\rho))EX \tag{A.25}$$

A.2.3 Connected Landscape

Consider two roads crossing the core perpendicular to each other. Under the simplifying assumption that $\bar{\theta} < \pi/4$ we get:

$$W_e^{Connected} = (4g(\rho) - 3)W_e^S \tag{A.26}$$

$$W_o^{Connected} = (4g(\rho) - 3)W_o^S \tag{A.27}$$

If $\bar{\theta} > \pi/4$ then we have to modify the $g(\rho)$ function to account for a small change. Define $\tilde{g}(\rho)$ as

$$\tilde{g}(\rho) = \frac{1}{\pi} \frac{\sqrt{1 - \rho^2}}{\rho} \tag{A.28}$$

and in this case we find

$$W_e^{Connected} = (1 + 4\tilde{g}(\rho))W_e^S \tag{A.29}$$

$$W_o^{Connected} = (1 + 4\tilde{g}(\rho))W_o^S \tag{A.30}$$

The area of the exploitation zone of a city in a connected landscape with $\bar{\theta} < \pi/4$ is given by

$$EX^{Connected} = (1 + 4g(\rho))EX \tag{A.31}$$

and for $\bar{\theta} > \pi/4$, it is equal to

$$EX^{Connected} = (1 + 4\tilde{g}(\rho))EX \tag{A.32}$$

A.2.4 Coastal

The energy provided to the core of a coastal city is given by

$$W_e^{Coastal} = (1/2 + g(\rho))W_e^S \tag{A.33}$$

$$W_o^{Coastal} = (1/2 + g(\rho))W_o^S \tag{A.34}$$

The area of the exploitation zone for a city in a coastal landscape is given by

$$EX^{Coastal} = (1/2 + g(\rho))EX \tag{A.35}$$

A.2.5 Edge

The energy provided to the core of a coastal city is given by

$$W_e^{Edge} = \frac{1}{2}W_e^S \tag{A.36}$$

$$W_o^{Edge} = \frac{1}{2}W_o^S \tag{A.37}$$

The area of the exploitation zone of a city in an Edge landscape is given by

$$EX^{Edge} = \frac{1}{2}EX \tag{A.38}$$

A.3 Political Aggregates

A.3.1 Aggregate income

Aggregate income is the value sum of all energy rents. Using the general equilibrium price p, we have for the simple landscape:

$$\begin{aligned} I(p, \Delta_o, \Delta_e) &= pW_o + W_e \\ &= \frac{\pi\Delta_e^3}{3c^2}\left(1 + \frac{(p\frac{\Delta_o}{\Delta_e} - 1)^3}{(p-1)^2}\right) \end{aligned} \tag{A.39}$$

Using this result, we can calculate aggregate income for all other landscapes as:

$$I(p, \Delta_o, \Delta_e) = pW_o^\ell + W_e^\ell \tag{A.40}$$

where $\ell \in \{Connected, Coastal, Edge\}$. Using the results from above, we obtain

$$\begin{aligned} I^{Connected}(p,\Delta_o,\Delta_e) &= (1+4g(\rho))I(p,\Delta_o,\Delta_e) \\ I^{Coastal}(p,\Delta_o,\Delta_e) &= (1/2+g(\rho))I(p,\Delta_o,\Delta_e) \\ I^{Edge}(p,\Delta_o,\Delta_e) &= \frac{1}{2}I(p,\Delta_o,\Delta_e) \end{aligned} \tag{A.41}$$

A.3.2 Average population size

The cities belonging to different landscapes will be characterized by a population size that is proportional to the cube of the productivity of the landscape. In particular, for the simple landscape, the size of a city is given by:

$$L_{ij} = MI(p,\Delta_o,\Delta_e)/\beta(p) = M\frac{\pi\Delta_e^3}{3c^2}\left(1+\frac{(p\frac{\Delta_o}{\Delta_e}-1)^3}{(p-1)^2}\right)/\beta(p) \tag{A.42}$$

where $\beta(p)$ is the appropriate price index. From here it follows directly from the results above that

$$\begin{aligned} L_{ij}^{Connected} &= (1+4g(\rho))L_{ij} \\ L_{ij}^{Coastal} &= (1/2+g(\rho))L_{ij} \\ L_{ij}^{Edge} &= \frac{1}{2}L_{ij} \end{aligned} \tag{A.43}$$

A.3.3 Number of places

The number of places in a landscape is calculated by dividing the area of the landscape, A_j, but the area of the exploitation zone. In particular, for the simple landscape, the number of places is given by:

$$N = \frac{A_j}{\pi\left(\frac{\Delta_e}{c_j}\right)^2} = \frac{A_j c_j^2}{\pi}\Delta_e^{-2} \tag{A.44}$$

Using this result we, we can write

$$N^\ell = \frac{A_j}{EX^\ell} \tag{A.45}$$

where $\ell \in \{River, Connected, Coastal\}$ to find

$$\begin{aligned} N^{Connected} &= (1+4g(\rho))^{-1}N \\ N^{Coastal} &= (1/2+g(\rho))^{-1}N \\ N^{Edge} &= 2N \end{aligned}$$

A.3.4 Total population landscape

Total population for the landscape is given by the multiplication of the number of places and the size of each place. For the simple landscape this is equivalent to:

$$L_j = NL_{ij} = \frac{1}{3}A_j M \Delta_e \left(1 + \frac{(p\frac{\Delta_o}{\Delta_e} - 1)^3}{(p-1)^2}\right) / \beta(p) \qquad \text{(A.46)}$$

which is independent of the geography of the landscape.

B von Thünen and Samuelson

B.1 Linear transportation costs

Work is equal to force, F, times distance, x, or work is $W_k = F \cdot x$. Force is in turn equal to mass, M, times acceleration g; as any mass moved horizontally must overcome the force of gravity as mediated by friction in transport, where μ is the coefficient of friction.[1] This work is done per unit time since power is a flow (as is for example the flow of labor and capital services that creates the flow of useful output in standard analyses). Choosing units is inconsequential and if we measure time in seconds, then the flow of work, W_k, measured in Joules per second is now power requirements measured in Watts.[2]

Now consider the costs of moving energy resources providing one Watt of power just one meter. Consider an energy source with power density Δ [Watts/m^2] with a concentration measure d[kg/m^2], this in turn implies the energy resources it represents must weigh d/Δ kilograms. Moving this mass one meter, and overcoming friction, requires a flow of power of $\mu gd/\Delta$. Therefore, μgd is the number of Watts needed to transport Δ Watts worth of an energy source with power density Δ, one meter. When energy sources are transported by land we have $c = \mu gd$. In this case, the zero energy margin distance is $R^* = \frac{\Delta}{\mu gd}$ and total energy collected is given by $W^* = \frac{\pi \Delta^3}{(\mu gd)^2}$.

B.2 Iceberg costs

Our model generates results much like those in von Thünen's Isolated State (1826). Our costs are constant per unit mass and thus generate a limit to the exploitation zone. We derive a primitive per meter transport cost similar to that assumed by von Thünen and but now explicitly linked to fundamentals such as the energy density of resources, the difficulty of terrain and the physical amount of work required to transport objects (Moreno-Cruz and Taylor, 2018). Just like von Thünen, we solve for a circular area of exploitation whose margins are determined by a zero rent condition. While von Thünen determined the zero

[1]We are ignoring static friction encountered when the object first moves. The force that needs to be overcome to keep an object in motion is equal to the normal force times the coefficient of friction. Since the object is moving horizontally, the normal force is just gravity times the mass of the object . The coefficient of friction is a pure number greater than zero; and force is measured in Newtons.

[2]Expending 1 Joule of energy in 1 second means you are delivering 1 Watt of power.

rent condition based on transportation cost only, we find that limit is a function of both productivity and transportation costs.

von Thünen motivates his constant per unit mass costs by assuming transportation costs are measured in "natural units," using the analogy that the horse eats the grain it is transporting to the city (Clark 1967). In our case, we use energy to move energy. Samuleson (1983) takes this analogy to justify his assumption about iceberg transportation costs. While the assumption of iceberg costs simplifies some of the calculations, Samuelson gets in trouble when trying to identify a limit to the exploitation. Under the iceberg assumption, the exploitation zone of the outer ring would extent infinitely.[3]

In Samuelson (1983)'s model, labor is required in situ to produce agricultural output and he shows that in equilibrium population density is declining away from the city core. Samuelson's limit on the exploitation zone comes from the assumption that labor is too scarce at long distances from the core, and thus at some point, more resources will not increase total energy delivered to the core.

Reading further von Thünen, Clark (1967) argues the idea of "natural units" captures all costs required to transport good, measured in terms of the good being transported, including paying for the means of transportation (the wagon) or the fact that waste of burning energy for transportation (incomplete combustion) leaves mass that needs to be transported. Introducing fixed costs the naturally generates a limit in the exploitation zone.[4]

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[3]To see how our model generates Samuleson's result, assume there is a farmer located at a distance r away from the city center. This farmer spends some of the energy he collects in transportation. Energy used in transportation per unit of distance is

$$W^T(x) = \frac{c}{\Delta} W(x) dx \tag{B.1}$$

where $W(x)$ is the amount of energy that is left after transporting the original amount of energy a distance x. That is, energy at distance $W(x + dx) = W(x) - \frac{c}{\Delta} W(x) dx$. We can rewrite this as

$$\frac{W(x + dx) - W(x)}{dx} = -\frac{c}{\Delta} W(x) \tag{B.2}$$

In the limit where dx approaches zero, the lefthand side in the previous equation becomes, by definition, dW/dx. The following differential equation determines the energy surplus at distance x:

$$\frac{dW(x)}{dx} = -TC(W(x)) = -\frac{c}{\Delta} W(x) \tag{B.3}$$

Assume the farmer is sitting in 1m^2 of land with power density Δ so that $W(0) = \Delta$. The solution to this differential equation is:

$$W(x) = \Delta e^{-\frac{c}{\Delta} x} \tag{B.4}$$

If we evaluate this expression at distance r, then we obtain the energy delivered to the city by a farmer located a distance r away from the core. In this case, due to the exponential nature of the energy supplied, there is not a limit to how far farmer can be located away from the city as the amount of energy brought into the city is always positive.

[4]Assume transportation costs are given by:

$$W^T(x) = \left(C(W_0) + \frac{c}{\Delta} W(x)\right) dx \tag{B.5}$$

where $C(W_0)$ are the fixed costs incurred to move energy W_0. Total energy at distance $W(x + dx) =$

C Data Appendix

Our data come from one of the most interesting records in history. The Domesday book is a historical artifact, but also an economic and cultural one. In our paper, we use it for its value as an accounting document. In this appendix, we describe how we handle the data and the assumptions we made to be able to use it as an input in our paper.

C.1 Domesday Book

The data used in this project was obtained from the History Data Service and is the Electronic Edition of Domesday Book: Translation, Databases and Scholarly Commentary, located at https://www.ukdataservice.ac.uk. The data come in many tables and observations are organized and traced throughout using the identifier "structidx." In the file "ByPlaces.csv" we have information on the "4-figures OS coordinates of Domesday vill" of the places, or settlements, referenced in the Domesday book. We use these coordinates to add environmental and landscape information, as we discuss below. We also have a shapefile of the parishes in England that match very closely to the location of places. We can then use this shapefile to calculate the approximate area of the place at the time. We then aggregate from Parishes to Hundreds and add circuit and county identifiers.

Most of the census information is in the file "Manors.csv." We use the following information:

Population data: We obtain the population data at the place as the sum of the population entries in the Domesday book "Villager + Smallholders." We aggregate them at the parish level and the hundred level.

Income data: We obtain income data at the place from the variables "Value 86" and "Value 66" which are the "value of the holding to its lord in 1086" and "value of the holding to its lord in 1066" respectively.

Ploughteams: We obtain income data from the variable "TotalPloughs" which captures "total number of ploughteams attributed to the holding, the teams each assumed to comprise 8 oxen." An oxgang captures how much land was tillable by one ox in a ploughing season. One ploughteam, or carucate, was equivalent to 120 acres, but there was substantial variance across villages. We use ploughteams to calculate the abundance of arable land in a hundred.

$W(x) - \left(C(W_0) + \frac{c}{\Delta}W(x)\right)dx$. Rearranging terms we can rewrite this expression as

$$\frac{W(x+dx) - W(x)}{dx} \equiv \frac{dW(x)}{dx} = -\left(C(W_0) + \frac{c}{\Delta}W(x)\right) \tag{B.6}$$

The solution to the differential equation is:

$$W(x) = \left(W_0 + \frac{\Delta}{c}C(W_0)\right)e^{-\frac{c}{\Delta}x} - \frac{\Delta}{c}C(W_0) \tag{B.7}$$

Define R as the radius for which $W(R) = 0$; that is, energy supplied to the city by sources farther than R is zero. The solution for R is:

$$R = \frac{\Delta}{c}\ln\left(\frac{c}{\Delta}\frac{W_0}{C(W_0)} + 1\right) \tag{B.8}$$

C.2 Environmental and Landscape Data

Ruggedness: We obtain terrain ruggedness from Nathan Nunn and Diego Puga article 'Ruggedness: The blessing of bad geography in Africa', published in the Review of Economics and Statistics 94(1), February 2012: 20-36. They provide the Terrain Ruggedness Index (in milimetres) at the level of individual cells on a 30 arc-seconds grid across the surface of the Earth.
Temperature: We use data from FAO-GAEZ (http://gaez.fao.org/Main.html). Our data is baseline mean annual temperature data for the years 1960-1990 measured in ^{o}C.
Precipitation: We use data from FAO-GAEZ (http://gaez.fao.org/Main.html). Our data is baseline mean annual precipitation data for the years 1960-1990 measured in mm.
Landscapes: We obtain data on navigable rivers and ancient (major and minor) roads from Satchell, M., Shaw-Taylor, L., Wrigley, E. (2018) [data collection]. UK Data Service. SN: 852999, http://doi.org/10.5255/UKDA-SN-852999. We use ArcGIS to identify coastal counties and counties bordering Wales. The approximate location of Norman castles is also in our database. All these variables are creating using a buffer of 2km around the feature. For example, the variable Rivers counts the number of parishes that are less than 2 km away from a navigable river. The same procedure applies to the other landscape characteristics such a road landscapes, coastal landscapes, and edge (Wales) landscapes.

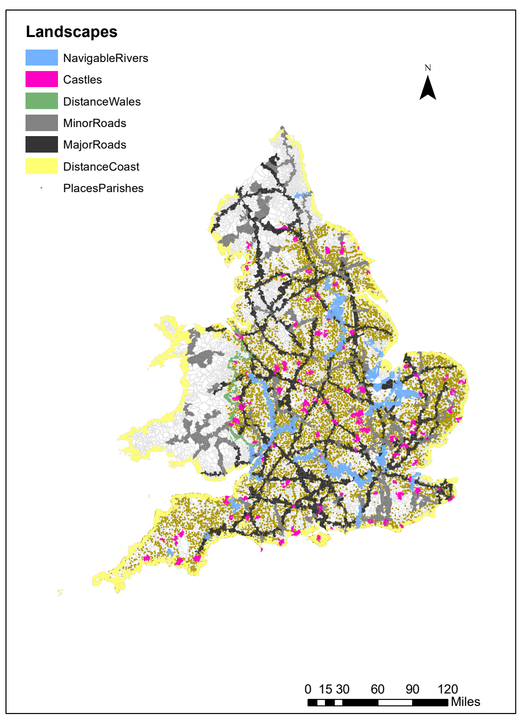

Figure C.1: Landscapes: This map summarizes the distribution of landscapes across England and Wales.

C.3 Variables construction and summary statistics

The summary statistics of the variables used in our analysis are presented in Table C.1. Below, we show how we constructed each variable. There are 875 hundreds in our sample.
No. Settlements is the count of settlements withing a Hundred.
Population Settlement is calculated as the area-weighted average of the settlement population. That is,

$$\text{Pop. Sett.} = \sum_{i=1}^{N_j} \text{Population}_{ij} * \frac{\text{Area}_{ij}}{Area_j} \tag{C.1}$$

Total Population at the hundred level is the sum of the populations in all settlements within a hundred.
Income is calculated via an area-weighted average of the income of the place as in equation (C.1).
Abundance of arable land is calculated as the total number of ploughteams, divided by the area of the hundred.

The environmental and terrain variables *ruggedness, temperature and precipitation* are represented as weighted averages and calculated the same way as in equation (C.1). Aggregate landscape characteristics are calculated as the count of parishes that belong to a particular landscape in a hundred. If two parishes have rivers, then the River variables at the hundred level is 2. We then divide by the total number of parishes in the hundred to get at a measure of intensity.

Table C.1: Summary Statistics

	Mean	Std. Dev.	Min	Max
No. Settl.	21.04	21.76	1.00	151.00
Pop. Settl.	21.69	26.66	0.00	344.15
Total Population	288.98	408.45	0.00	6801.00
Income 1086	8.89	12.45	0.00	142.77
Abund. Arable Land	0.96	1.99	0.00	34.27
Area	225.17	244.45	0.55	1553.64
Ruggedness	20756.88	19143.81	138.40	159844.53
		Environmental Variables		
Temperature	9.59	0.48	7.10	10.67
Precipitation	726.40	146.38	560.34	1285.02
		Landscapes		
Coastal	0.10	0.25	0.00	1.00
Rivers	0.07	0.20	0.00	1.00
Minor Roads	0.07	0.19	0.00	1.00
Major Roads	0.19	0.28	0.00	1.00
Border Wales	0.01	0.06	0.00	1.00
Castles	0.07	0.20	0.00	1.00

Notes: Summary statistics for the dependent and independent variables used in our analysis.

Figure C.2: Spatial distribution of dependent and independent variables

D Instrumental Variables Approach

We are concerned with the potential endogeneity of income and our outcomes of interest. In our model income is determined independently of labor, and is not affected by the number of neighboring settlements via trade or migration. In other settings it would or could be determined by these factors, contaminating the errors in our OLS specification. To address this issue we need an instrumental variable with across hundred variation that is both correlated with incomes in 1086, and otherwise excluded from the regressions. We instrument contemporaneous income levels in 1086 using incomes reported in 1066. The basic idea is that the cross-sectional distribution of incomes in 1066 contains information about the cross-sectional distribution of hundred productivities that is, in turn, responsible for an exogenous component of variation in the 1086 values. The logic behind this instrument comes from considering an alternative model where labor enters the national income function. For example, consider a neoclassical model where there are many hundreds that differed only in terms of their Hicks-neutral technological productivity. Then labor demands would differ across the hundreds since they differ in productivities, but the Malthusian steady state supply of labor is perfectly elastic at the subsistence wage. The hundreds would differ in terms of population sizes, and incomes as a result. If 1066 is an existing steady state, the variation we see across hundreds in terms of their average settlement incomes is perfectly correlated with their cross-sectional differences in productivity. Our underlying assumption is that the cross-sectional distribution of income in 1066 affects outcomes in 1086 only through the information it contains in terms of hundred productivities that is captured in 1086 average hundred incomes. Further complications arise if the observations in 1066 were not from an existing steady state; if our model is not true so labor supply is not elastic at the subsistence wage; or if transitory shocks from 1066 reverberated through to other variables in 1086 as well. To deal with any of these issues, a panel data estimation would be required, and of course we have no ability to generate such a panel as the 1066 entries in the Domesday book are very incomplete. With these caveats in mind consider Table D.1.

Table D.1 shows the strength and quality of our instruments. We restrict the sample the hundreds that report income in 1066. The number of observations is reduced from 875 to 712 hundreds. In Panels A through C, the first column shows the regression results for the Number of Settlements, the second column for Settlement Size and the third column for Total Population. To save space, we indicate but don't report when we are using Landscape controls (Coastal, Rivers, Minor Roads, Major Roads, Border Wales, Castles and their interactions) and Environmental Controls (Temperature and Precipitation).

Panel A replicates our results for the OLS from the main paper but with the restricted sample. Restricting the sample changes the point estimates, but their remain statistically significant, of equal magnitude and sign.

Panel B shows a statistically significant relation between income 1066 and the outcome variable. Higher income in 1066 is related with a lower number of settlements, higher settlement populations and higher overall population. These results are all statistically significant at the 5% level.

In Panel D the dependent variable is Income in 1086 and shows the first stage results. A positive relation between income in 1066 and income in 1086 exists across all specifications. this relations is statistically significant at the 1% level. The first stage Kleibergen-Paap

F-statistic for the excluded instrument is 12.5 or higher across different regressions. This implies it is unlikely that our estimates are biased by weak instruments.

Panel C shows the 2SLS results. In all cases, our earlier results are strengthened by instrumenting. The overall take away from our analysis remains the same.

Table D.1: Instrumental Variables (Value 86=Value 66)

	No. Settlements	Settlement Size	Total Population
		Panel A: OLS	
Income	-0.282[a]	0.812[a]	0.448[a]
	(0.039)	(0.042)	(0.081)
Abund. Arable Land	0.745[a]	0.268[b]	1.276[a]
	(0.115)	(0.085)	(0.142)
Area	0.769[a]		0.923[a]
	(0.017)		(0.050)
Ruggedness	0.010		0.106
	(0.037)		(0.069)
Constant	-0.784[b]	5.499	8.362[c]
	(0.317)	(2.870)	(3.851)
		Panel C: 2SLS	
Income	-0.340[a]	0.801[a]	0.347[a]
	(0.040)	(0.071)	(0.113)
Abund. Arable Land	0.813[a]	0.279[a]	1.396[a]
	(0.087)	(0.104)	(0.149)
Area	0.775[a]		0.933[a]
	(0.015)		(0.046)
Ruggedness	0.012		0.109[c]
	(0.035)		(0.064)
Constant	-0.780[b]	5.646[b]	9.480[a]
	(0.323)	(2.753)	(3.636)
		Panel D: First Stage — Dependent Variable: Income 1086	
Income 1066	0.507[a]	0.516[a]	0.504[a]
	(0.149)	(0.149)	(0.144)
Abund. Arable Land	0.740[a]	0.656[a]	0.741[a]
	(0.137)	(0.124)	(0.128)
Area	0.054[a]		0.052[a]
	(0.016)		(0.016)
Ruggedness	0.002		0.006
	(0.042)		(0.040)
Constant	0.066	4.003	3.005
	(0.534)	(5.501)	(4.889)
Landscapes	X	X	X
Environment		X	X
County	X	X	X
Observations	712	712	712

Notes: All variables are log transformed using $\tilde{x} = ln(1+x)$. Errors clustered at the circuit level are reported in round parentheses. [a], [b], and [c] denote significance at the 1 , 5 and 10. All regression include landscapes and environmental variables when required.