City seeds: geography and the origins of the European city system

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Abstract

This paper disentangles the different roles of geography in shaping the European city system, Using a new database covering actual and potential city locations over the period 800 – 1800, we find that physical, *first nature*, geography was the dominant determinant of city location during the early formative stages of Europe's city system. A location's relative position to already-existing cities (its *second nature geography*) only becomes important during the later centuries. Interestingly, it does so in a way corresponding closely to predictions from new economic geography theory. These findings hold up to a wide variety of robustness checks and extensions.

Keywords: city origins, economic geography, Europe

JEL codes: N93, O18, R10

"In a more advanced era, when better methods would permit man to conquer Nature […], it would doubtless have been possible to build towns anywhere the spirit of enterprise and the quest of gain might suggest a site. But it was quite another matter in a period when society had not yet acquired enough vigor to rise above the physical conditions in the midst of which it developed. […] the towns of the Middle Ages were a phenomenon determined as much by physical surroundings as the course of rivers is determined by the conformation of the mountains and the direction of the valleys." (Henri Pirenne, 1925 p.138/39).

1 Introduction

Today the European landscape is dotted with cities. Historically this was not always the case. In the early medieval period Europe only knew a handful of cities. Over the next millennium this changed dramatically, and cities started to appear on an unprecedented scale. These cities appeared virtually everywhere on the continent. Figure 1 shows that whereas in 800 we only find a few scattered cities in mainly Spain, France, Germany and Italy, in 1800 they can be found all over the continent[1].

Figure 1. The European city system in 800 and 1800

| a) 800 | b) 1800 |
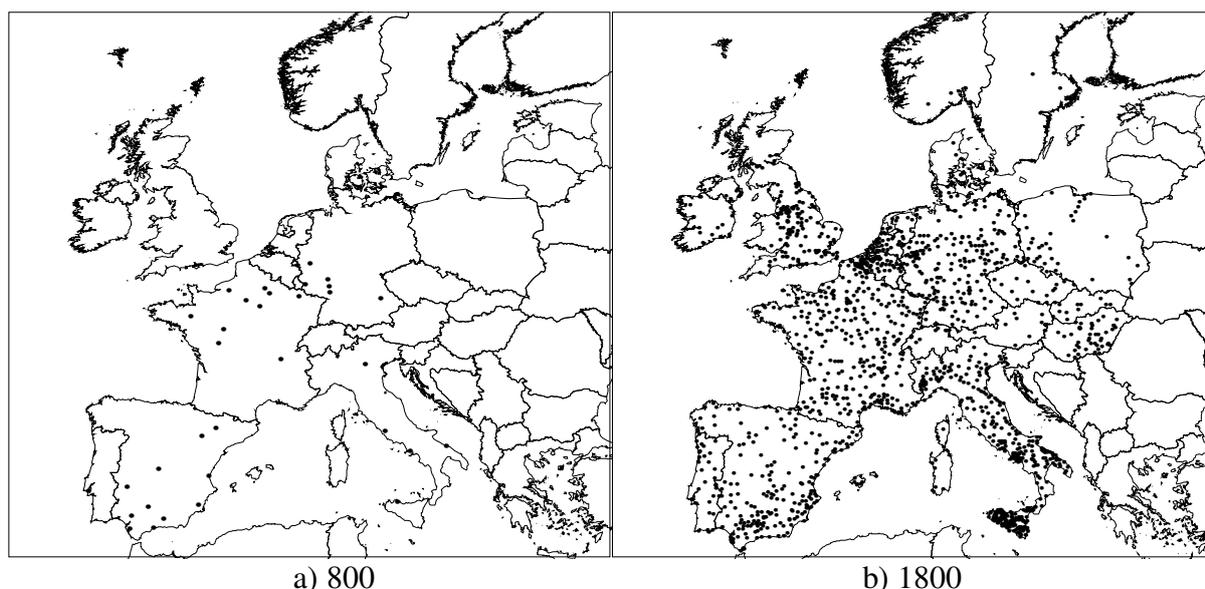
Notes: cities are denoted by black dots [see section 3.2 for more detail on the city definition used]. In 800 there are 34 cities, in 1800 this number has increased to over 1,450.

The rise of the city in the European landscape is important for several reasons. Throughout history, cities have been the important loci for technological innovation, institutional progress, (international) trade, political power, and culture (Bairoch, 1988; Pirenne, 1925; Hohenberg and Lees, 1995). Also, cities are generally more productive places. The concentration of many people e.g. allows for a greater degree of specialization, carries positive externalities such as

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[1] Figure A1 and Table A1 in Appendix A further illustrate the rise of the city in the European landscape. Over our sample period, Europe's urbanization rate increased from only 3% in 800 to 15% in 1800. Urban population increased 30-fold from 0.7 to 21 million, whereas total population increased 6-fold from 23 to 137 million. A full, century-by-century, visualization of the formation of the European city system is available upon request.

knowledge spillovers, and facilitates a more efficient provision of public goods (Lampard, 1955; Marshall, 1890). It may therefore not be surprising that cities are argued to have played a very important role in Europe's economic 'take-off' during the late Medieval and Early Modern period. Economic development and urbanisation often go hand in hand (Acemoglu et al., 2005; De Vries, 1984; Galor, 2005). Today, an estimated 75% of world production takes place in cities (World Bank, 2009).

The importance of cities in the development process makes understanding their origins of great interest. Cities do not develop everywhere. The question '*why they form in particular locations, and not, or only much later, in others that often appear equally viable city sites*' lies at the heart of this paper. In particular, we empirically uncover the role(s) of geography, widely viewed as the most important determinant of a location's urban chances, in 'sowing the seeds' of the European city system.

Many authors, in both the narrative urban (economic) history (e.g. Pirenne, 1925; De Vries, 1984; or Bairoch 1988), the economic geography (e.g. Christaller, 1935; Lösch, 1940; Ullman, 1941; Lampard, 1955; Duranton, 1999), or the more recent urban economic and geographical economics literature (Krugman, 1993a; Fujita and Mori, 1997; Behrens, 2007), stress two important, but very different, roles for geography in the origins of an urban system.

The first is in determining a location's physical, or *1st nature geography*, characteristics. These determine a location's agricultural potential, its transportation possibilities and its defensive advantages, that all have been noted as important city seeds. The second role for geography, although already stressed by e.g. Christaller (1935) and Lösch (1938; 1940)[2], has received renewed attention in the economics literature following Krugman (1991; 1993b). While not denying an important role of 1st nature geography, this line of literature stresses the importance of a location's position relative to the rest of the (potential) urban system, its *2nd nature geography*, for its urban prospects. As already acknowledged by Pirenne (1925, p.145), some locations may be well suited for urban development based on their own characteristics, but *"situated too far from the great highways of communication, […] they remained sterile, like seed fallen upon stony ground."*

The debate on the relevance of the two different roles of geography in determining cities' origins has up to now largely taken place without using any empirical evidence[3].

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[2] An even earlier contribution focussing on 2nd nature geography is von Thünen (1826). He however considered the evolution of only one isolated city in relation to its hinterland, instead of the evolution of a system of cities.

[3] Several papers do look at the relative importance of 1st and 2nd nature geography for the evolution of a city system after its initial establishment, e.g. looking for evidence of path-dependence in urban development (see Bleakley and Lin, 2010; Davis and Weinstein, 2002; Bosker et al., 2008, Redding and Sturm, 2008).

Instead, it relies on historical narratives, largely descriptive accounts of European urbanization, and detailed case studies looking at one particular city or region only. This paper fills this gap. Using a large, and for a substantial part newly collected, data set on (potential) city locations in Europe over the period 800 – 1800, we empirically uncover the (relative) importance of 1st and 2nd nature geography in determining city location.

The European case provides an ideal testing ground for the following two reasons. First, historical data availability on the size and characteristics of individual cities in Europe is the best in terms of both spatial and temporal coverage. This is largely due to the work of Bairoch et al. (1988) and De Vries (1984). They have constructed comprehensive data sets providing population estimates for many cities in Europe starting as early as the year 800^{4}. Our dataset builds on this data. We extend its coverage to also cover potential city locations, locations that in principle could have become a city but never did. Also, we complement the existing population data with, most important for the purposes of this paper, detailed information on each location's 1st and 2nd nature geography (it also contains information on several religious, educational and institutional characteristics).

Second, all this data is available for the period, 800 – 1800, during which one can forcefully argue that the seeds for the eventual European city system were sown. Following the eclipse of the Roman empire, cities in Europe withered (Pirenne, 1925; Greif, 1992). But, over the next millennium Europe witnessed an unprecedented revival of urban activity and the establishment of cities on a scale not seen before (see Davis, 1955 p.432, or Figure 1).

Using our data set, we quantify the role of 1st and 2nd nature geography in conditioning the spread of cities across the European continent. We explicitly base our empirical analysis on the main theoretical insights regarding the role of 1st and 2nd nature geography in sowing the seeds of cities. These insights come from the economic and urban history literature on the one hand, and from the more recent new economic geography literature on the other hand. They serve as the theoretical underpinnings of our empirical analysis, guiding the selection of 1st and 2nd nature geography variables, as well as our choice of potential city locations. In case of 2nd nature geography this results in developing a novel, more flexible, way to quantify the

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[4] This data has up to now been used either to provide descriptive accounts of urban expansion (Bairoch et al., 1988; De Vries, 1984), or to uncover the major drivers of a city's size *once a city is established* (Acemoglu, Johnson and Robinson, 2005; De Long and Shleifer, 1993; Bosker et al., 2008; Kim, 2000; or Bosker et al, 2010). By looking at city size *conditional* on a city's existence, although very interesting in itself, these papers effectively take cities' location as given and refrain from shedding empirical light on the question why these cities were formed at their particular locations in the first place. They do not answer the question why other, often a priori equally viable, locations never became a city or only did so at a much later stage.

effect that an already established city exerts on the urban chances of its surroundings.

We find that both 1st and 2nd nature geography played an important role in the origins of the European city system. However, the (relative) importance of 1st and 2nd nature geography shows substantial changes over time. 1st nature geography dominates in the early stages of the formation of the European city system. But, as trade costs fall, economies of scale increase, and the overall European population increases, 2nd nature geography gains in importance and starts to be an equally important determinant of city location from the seventeenth century onwards. Interestingly, the effect that an already existing city exerts on the urban chances of its surroundings corresponds closely to the predictions made by economic geography theory.

2   Theory

2.1   Economic and urban history

Traditionally, the debate on cities' origins was conducted within the realm of the, largely narrative, economic and urban history literature (Pirenne, 1925; Weber, 1922; Bairoch, 1988; De Vries, 1984). This literature stresses a priori differences between locations as the main reason for some locations to be more likely to become a city than others. Such spatial inhomogeneities between locations, what we call *1st nature geography*, arise most notably from economic motives related to either resource abundance or transportation possibilities. Attractive city locations were those close to natural resources (fertile plains, mineral deposits, thermal springs, etc.) and locations with good access to the main trade routes (see e.g. Pirenne, 1925 p.133; Ratzel, 1891). Given that the city relies on exchange with its hinterland (most notably for the feeding of its population), location on a navigable river, an overland transport route, or at sea offers substantial advantages in terms of transportation possibilities (a recent paper by Bleakley and Lin (2010) aptly illustrates this for portage sites in the US).

Besides these economically motivated spatial inhomogeneities, other 1st nature geography characteristics that have been stressed as important, mostly concern defensive and religious motives (see Hohenberg, 2004; Bairoch, 1988 p.121; Pirenne, 1925 pp.72/74; or Hohenberg and Lees, 1995 p.30). Cities were established near places with an important religious function (an abbey, monastery or local shrine) or at a strategic location (a river crossing, the foot of a mountain pass or a hill overlooking the countryside). However, the earlier-mentioned economic motives, and most notably a location's transportation possibilities, are often viewed to overshadow these religious and defensive motives. As put by

Bairoch (1988, p.143) *"The critical role played by transport in the location of cities does not rule out exceptions, but statistically speaking these are in the minority."*

2.2 Economic geography

Spatial inhomogeneities also feature prominently in the economic (geography) literature on city creation (Duranton, 1999; Anas, Arnott, Small, 1998; Fujita and Mori, 1996; Krugman, 1993a, Behrens, 2007). Although this literature does not deny endowments of minerals, soil or climate to be important determinants of city location (see Anas, Arnott and Small, 1998), the 1st nature geography characteristic that receives most attention in this literature is (again) preferential location on the main trade routes (Krugman, 1993a; Fujita and Mori, 1996; Behrens, 2007; Konishi, 2000). Transportation or, more generally, trade costs[5], together with scale economies, are viewed as the crucial elements in the process of city formation.

Trade costs are vital to a city given that it relies entirely on exchange with its hinterland to meet its own demand for agricultural produce. When the cost of transporting these agricultural goods (or the goods the city produces in exchange for these) are very high, this results in the so-called tyranny of distance and cities only form in locations offering good 1st nature geography conditions so that sufficient food can be imported from nearby (see e.g. Duranton, 1999, p.2173).

However, when trade costs diminish due to e.g. improvements in transportation technology or lower trade barriers (decreased tariffs, safer roads, improved freight insurance, etc), the tyranny of distance is alleviated and the (relative) importance of 1st nature geography diminishes. Since agricultural products can now be shipped over longer distances at lower costs, it becomes possible to establish cities at locations that, given their lack of 1st nature geography advantages, were previously unviable to host a city.

Still, even with a diminishing importance of 1st nature geography, not all locations become equally viable future city sites. This crucially depends on their *2nd nature geography characteristics*, i.e. their position relative to the rest of the (potential) urban system. Earlier contributions in the geography literature (e.g. Christaller, 1935; Lösch, 1938 or 1940; Pirenne, 1925; or Ullman, 1941) already stressed that *"no city is ever an island existing in and of itself"* (Lampard, 1955). Yet, it was only recently that several papers explicitly focus on the *where-do-cities-form* question in a theoretical framework of endogenous city location that

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[5] All costs associated with moving goods from one location to another, including not only transportation costs but also tolls, tariffs and less tangible costs associated with differences in e.g. language, institutions or culture.

formalizes the idea that already-existing cities influence the urban chances of their surroundings[6].

Started with contributions by Krugman (1993a,b), Fujita (1993), and Fujita and Krugman (1995), these papers (Fujita and Mori, 1996 and 1997; Fujita, Krugman and Mori, 1999 and Behrens, 2007) not only establish theoretically, using fully specified general equilibrium models, under what conditions a city (or subsequent cities) will form, they also make clear predictions about which locations are more likely to become a city than others.

Figure 2 (taken from Fujita and Mori, 1996) illustrates how an already existing city affects the urban chances of other locations[7].

Figure 2. The 2nd nature geography effect of an existing city
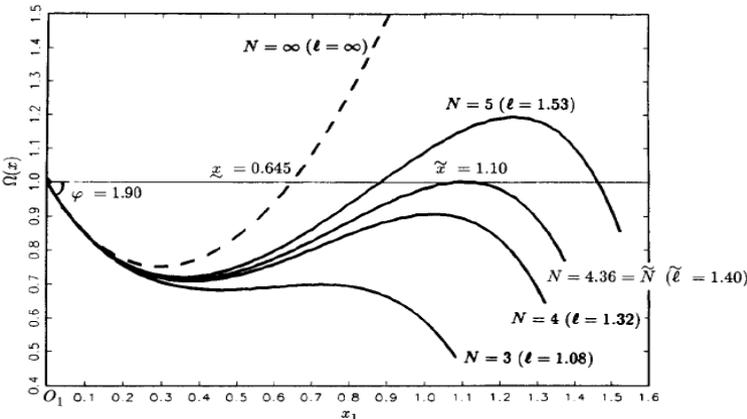
Notes: This figure is taken from Fujita and Mori (1996, p.108). The x-axis (x_1) indicates the distance from the already established city, which is located at the origin. The y-axis depicts the value of the so-called market potential function: locations where the value of the market potential curve exceeds 1 (the solid straight line in the figures) are locations where a new city is viable. *N* denotes overall population.

It depicts so-called market potential curves[8] that can be interpreted as indicating the likelihood of a location, located at a distance *x* from an already existing city at the origin, to become a city too. Whenever a location's market potential exceeds 1, it is in principle a viable new city

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[6] Earlier urban economic theories relying on scale economies and transport costs remain silent on the *where do cities from*-question. A city's relative location is either completely disregarded (e.g. Henderson, 1974 or Black and Henderson, 1999) and bears no consequences for its further development, or, often despite assuming no differences in 1st nature geography characteristics between locations (i.e. a continuous homogenous plain), the (relative) position of a discrete number of possible city locations is a priori assumed (see e.g. von Thünen, 1826; Christaller, 1935; Lösch, 1940). Moreover, a drawback of these latter models is that the final structure of the urban system does not follow endogenously from a set of assumptions concerning the behavior of firms and consumers (see Ottaviano and Thisse, 2005 for an extensive and very useful overview of the history of location analysis in urban economic and economic geography theory).

[7] Figure 2 depicts the case when no potential city location has an a priori advantage in terms of their 1st nature geography. Fujita and Mori (1996) and Behrens (2007) further generalize this and show that locations with a 1st nature geography advantage in terms of their transportation possibilities (hubs) produce sharp positive kinks in the market potential function, making them more likely future city candidates (see Figure A2 in the Appendix). However, 1st nature geography advantages are not the whole story: a location may have a 1st nature geography advantage, but, if located too far from or too close to existing cities, it will still fail to become a city.

location. Whether or not this is the case depends first and foremost on a location's distance to the already existing urban center (see Fujita et al., 1999 and Fujita and Mori, 1996).

Locations too close to an already-existing city face too strong competition with that city, both for agricultural produce and for inhabitants (or, not uncommon in medieval times, the existing city uses force to prevent a competitor city forming in its immediate backyard, or, less violently, it puts severe restrictions on any economic activity in its immediately vicinity[9]). On the other hand, locations too far from an already existing city can not take full advantage of (cheap) trading possibilities with the already existing city. This leaves locations at medium range from existing cities as preferred new city locations: they offer relatively cheap trading possibilities with the already existing cities compared to locations too far off, as well as only limited competition with these same existing cities compared to locations at too close range.

The strength, and spatial reach, of this 2nd nature geography effect depends on the important model parameters. Most importantly, when total population is too small, trade costs are too high, and/or the productivity advantages of co-locating in a city are too low (compared to the disadvantages of co-locating in a city), 2nd nature geography plays no role in determining the location of new cities. Also, when transportation costs are extremely low, overall population too small to sustain multiple cities, or productivity advantages of co-location very high, the models predict that only one city will emerge. Only at intermediate values of trade costs and scale economies, and given a sufficiently large overall population, does the above-described non-linear 2nd nature geography effect come into play[10].

By introducing an important role for the current state of the urban system in determining its future development, 2nd nature geography offers a substantially different and more dynamic answer to the *where-do-cities-form* question than the much more static[11] explanation offered by 1st nature geography hinging on a priori spatial differences between

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[8] See Appendix B and D in Fujita and Mori (1997) for the analytical details of these market potential functions. Also, see section 4.2 in their paper for a more thorough discussion of the market potential curve.

[9] The German 'Bannmeile' is a good example (see Ennen, 1972).

[10] Our exposition is admittedly a bit too stylized and does not do entire justice to the richness of the models, where the relevance of the discussed 2nd nature geography effect depends delicately on the interaction between trade costs (and the relative size of those for agricultural and non-agricultural goods respectively), (dis)economies of scale, the share of agricultural consumption in overall consumption, and overall population size (for particular configurations of these model parameters, it can even be the case that only one city, or even no city, emerges). However, the effect of an existing city is always negative at close and at large distances from an already existing city. It is the positive effect at medium range (and the extent of this range) that depends delicately on the model parameters. We take this non-linear effect exerted by an already existing city as the main insight from theory that we take to the data in our empirical sections.

[11] Not completely static however. The importance of particular spatial inhomogeneities, or the inhomogeneities themselves, may change over time. A good example is cities formed for defensive purposes only. Located at impregnable locations, these offer limited possibilities for expansion in more peaceful times. Another example is location near natural resources. These locations lose their attractiveness once the resource is depleted or becomes obsolete. In section 5.2 we explicitly allow the importance of 1st nature geography to change over the centuries.

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locations. This makes establishing their (relative) importance the more interesting. In the remainder of this paper we do just that. We construct a new dataset on the basis of which we can empirically identify the (relative) importance of both 1st and 2nd nature geography in 'sowing the seeds' of the European city system.

3   Data and descriptives

We focus in turn on our choice of potential city locations, the city-definition that we employ, the 1st and 2nd nature geography variables we are considering, and, briefly, some additional non-geography related control variables that we include in several robustness checks. We discuss in particular detail how we incorporate 2nd nature geography into the analysis. We propose a novel way to construct our 2nd nature geography variables that corresponds closely to the main theoretical insights presented in section 2.2.

3.1   Potential city locations

In order to empirically study the rise of cities in Europe[12], the first important choice to make is what locations to consider as potential city locations. Figure 3 shows all potential city locations that we consider in our baseline estimations.

Figure 3. Potential city locations
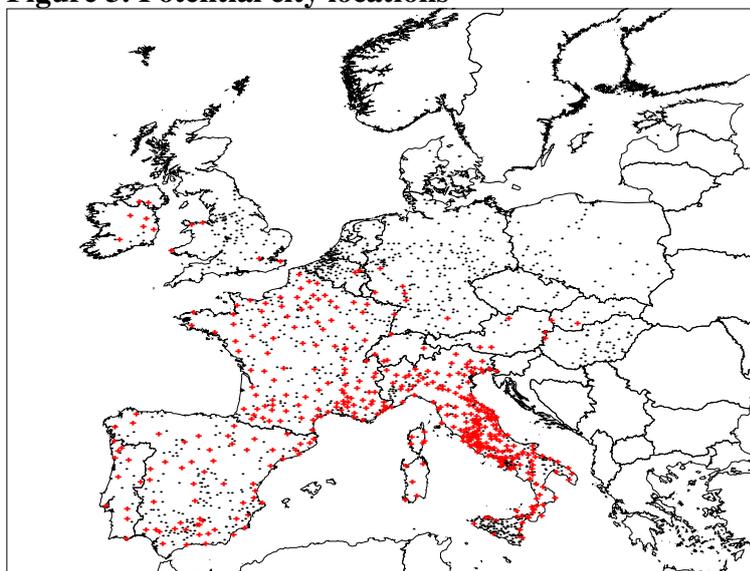
Notes: each black dot represents a potential city location. Those potential city locations that are included on the basis of being an (arch)bishoprics in 600 are further denoted by a red cross.

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[12] We define Europe as roughly everything west of the line Trieste – St. Petersburg. This line is well known from the literature on the European Marriage Pattern (see Hajnal, 1965) and is arguably the best approximation of the border of the Latin West: it coincides with the border of the Catholic Church during the Middle Ages. See also De Vries (1984) or Findlay and O'Rourke (2007). Europe thus defined comprises current-day Norway, Sweden, Finland, Poland, Germany, Czech Republic, Slovakia, Austria, Hungary, Belgium, Luxembourg, the Netherlands, France, Great Britain, Ireland, Switzerland, Italy, Spain and Portugal.

They are based on fulfilling one of the following two criteria: The first group of potential city locations comprises all locations documented in Bairoch et al. (1988). Bairoch et al. (1988) provide centennial population estimates for all cities in Europe that in some century have more than 5,000 inhabitants during the period 800 – 1800. This gives us a total of 1,588 potential city locations. Note however, that by using this criterion we effectively obtain a set of actual, and not potential, city locations because we know for certain that each of these locations will, in some century between 800 and 1800[13], become a city according to our definition (specified in section 3.2 below).

This is not true for our second group of potential city locations. Based on insights from the urban history literature (see section 2.1), these locations are selected on the basis of their religious importance. In particular, we consider all (arch)bishoprics in 600 as potential city locations[14]. The assumption is that these places were in principle perfect candidates to become future cities given that they were, in 600, important enough to the Catholic Church to turn them into the seats of one of its (arch)bishops. A defendable assumption in our view as the Church played an important role in maintaining some urban continuity following the collapse of the Roman urban system in Europe during the early Middle Ages (Hohenberg and Lees, 1995 p.58; Bairoch, 1998 p.121).

All known bishoprics in Europe are documented in Jedin et al. (1980)'s *Atlas zur Kirchengeschichte*. In total we found 456 (arch)bishoprics in 600. The red crosses in Figure 3 show that they are mostly concentrated in those parts of Europe that were once under Roman control, reflecting the fact that the Catholic Church initially built on the vestiges of the Roman empire. Of these 456 (arch)bishoprics, 260 (or 57%) are also present in the Bairoch et al. (1988) dataset. It is the other 196 (or 43%) that provide us with an interesting 'control group', i.e. locations that could have become a city but did not do so during our sample period.

On the basis of our two main selection criteria, we obtain a total number of 1,784 potential city locations (those depicted in Figure 3). They constitute the baseline sample we consider in most of our empirical analysis. Table A2 in the Appendix provides some additional detail on the geographical distribution of these potential city locations, documenting how many of them are found in each of the (current-day) European countries in our sample, as well as indicating the % of locations that had an (arch)bishop in 600 and the %

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[13] There are no population estimates for 1100. For this century we have linearly interpolated the reported 1000 and 1200 population estimates. All our results are fully robust to excluding these interpolated 1100 numbers from the analysis. Results available upon request.

[14] We choose the year 600 as it preceeds the muslim conquests of the Iberian peninsula and parts of Italy (Sicily), so that throughout the region of the former western Roman Empire Catholicism was the predominant religion.

of locations that eventually became a city according to our definition.

In various robustness checks aimed at addressing concerns regarding the possible endogeneity of our baseline sample, we also consider other samples of potential city locations (see sections 5.1.2 and 5.2.1 for more detail). For example, we extend our baseline sample with an additional 217 potential city locations that never had more than 5,000 inhabitants during our sample period, but did so in 1850[15]. Or alternatively, we consider all coordinate pairs to be potential city locations and do our estimations based on a random sample of over 2,000 coordinate pairs.

3.2 *City definition*

We define a city as an agglomeration of at least 5,000 inhabitants. In doing so, we basically adopt the definition proposed by Bairoch (1988). He gives the following two reasons for using this definition (see pp.137/138 of his book for a more extensive discussion):

A)   *"a population of 5,000 is […] a criterion that may be questionable in certain respects but which nevertheless remains for all that the most adequate and especially the most operational."* (p.494)

B)   *"One of the essential reasons for adopting the criterion of 5,000 is that the margin of error for the number of people living in cities 2,000 – 5,000 people is much greater than that for the number living in cities of more than 5,000 people."* (p.218)

Such an absolute size criterion of 5,000 inhabitants may in certain cases be too low and thus wrongly ascribe an urban role to a location (see e.g. Malanima (1998a,b) on Sicilian agrotowns). On the other hand, the opposite, i.e. the cutoff being too high, has also been argued, especially for the early medieval period (see e.g. Dyer, 1995). Both Bairoch (1988) and De Vries (1984, pp. 53/54) view the use of a population cutoff of 5,000 inhabitants as providing a 'best of both worlds'[16] [17].

The alternative to defining cities on the basis of a population cutoff would be to define

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[15] We do not consider this 1850 data in our baseline sample for two reasons. First, it adds the Industrial Revolution to our sample (see e.g. Ashton, 1948). The substantial changes during that period in terms of transportation (railroads, steamships), production (both industrial and agricultural), and the importance of different natural resources (coal), turned many locations that previously had little chance of becoming a city into potential city sites (e.g. many locations in the coal-rich areas of Germany, Sweden, north-east England, and the Limburg provinces of both Belgium and The Netherlands). Including the Industrial Revolution in our view requires a detailed account of its effects, something that lies beyond the scope of this paper. Second, the rest of our data is available on a centennial basis. Including the 1850 data would constitute a substantial shortening (halving) of the sampling period, with possibly unwanted consequences for the statistical analysis.
[16] *"So long as the only criterion* [to define a city] *systematically available to us is population size it is advisable to be prudent. […] Thus our examination of European urbanization will generally extend no further than cities of 5000."* (De Vries, 1984 pp.53/54).
[17] Also in archaeology, its is common practice to define cities as population centres with more than 5,000 inhabitants. See for example Fagan (1997, p.27) or Bahn (1996, p.57).

cities on the basis of more criteria than total population size only (e.g. having city rights or certain economic, religious or institutional features). This would however, in the words of Bairoch (1988, p.494) be 'much less operational' (see also De Vries, 1984 pp.21/22 or pp.52/53). Not only would it constitute a very time consuming exercise; to agree on what features a certain location would have to have in order to qualify as a city would be subject to much debate. Are city rights sufficient, or should it also have a fair, a market or a mint in order to qualify as a city? And, if so, should these fairs or markets be of a certain size, or of regional importance, before a location qualifies as being a city? Even if we were to agree on which features to include in this city definition (and data on all these features would be readily available), the substantial institutional, political and religious differences between the different societies in Europe further complicates the task of consistently applying this definition (e.g., city rights in one part of Europe are not necessarily directly comparable to those in other parts).

An absolute population cutoff to define a city avoids these issues of comparability, it makes the city definition less subjective, more transparent, and much more up to scrutiny as one can easily compare the results using different, even possibly time-varying, population cutoffs (in Appendix A.3 we do just that).

3.3 Explanatory variables determining city location[18]

3.3.1 1st nature geography

To capture a location's opportunities for water- and land-based transportation, we use a set of dummy variables that indicate whether or not it has direct access to the sea, to a navigable waterway, or to the former Roman road network. Besides documenting whether or not a location was located on a (former) Roman road, we also classify locations where two (or more) Roman roads crossed as hub locations.

The information concerning location at sea or on navigable waterways is from Dumont and Miermans (1959). Locations along a waterway that is presented on one of the maps in the Atlas with a scale of at least 1:2,000,000 are classified as located on a navigable waterway[19]. A location is classified as located at sea when there was a possibility to beach or harbor boats along the coast where it is situated.

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[18] Table A3 in Appendix A provides descriptive statistics on all variables discussed in this section.
[19] The use of this scale results in classifying many more (smaller) waterways than only the major European rivers as navigable. We think this is warranted given that *"navigation expanded wherever a rivulet of water offered even the slightest alternative to the beaten path or the ruined public highway"* (Lopez, 1956 p.21).

The information on the presence of a Roman road comes from Talbert (2000). We use location on a roman road instead of on an actual road for two reasons. First, the roman road network is argued to have played an important role in trade long after the withering of the empire itself[20]. Roman roads constructed using similar methods and adhering to uniform quality standards can be found throughout the formerly Roman parts of Europe. Second, using location on a roman road or a hub of roman road avoids some of the reverse causality issues that could arise when using actual roads (i.e. roads being built to future city locations, instead of a road increasing the urban chances of locations along this road).

Besides these transportation related 1st nature geography variables, we collected information on each potential city location's elevation [in meters] and on its ruggedness [calculated as the standard deviation of the elevation of the terrain within 10km of a potential city location]. Both serve as a proxy of a location's accessibility, although they can also be argued to be related to its agricultural possibilities.

A location's agricultural conditions are by many viewed as one of the crucial 1st nature geography determinants of its urban prospects (see Pirenne, 1925; Bairoch, 1988 or Duranton, 1999). To capture this, we use data from Ramankutty et al. (2002). That study combines information on climatic conditions (surface air temperature, precipitation and potential sunshine hours) and soil quality (total organic content [carbon density], availability of nutrients [pH] and water holding capacity) into one index that gives the probability that a certain location will be cultivated. This data is available in gridded form at a resolution of 0.5 degrees latitude-longitude (in case of our sample this corresponds to a grid of on average 56 km by 39 km). We match each potential city location to this data on the basis of its coordinates. Locations falling within the same grid cell have the same cultivation probability.

The Ramankutty et al. (2002) data provides a time-invariant indication of a location's agricultural possibilities. It it not unlikely that a location's agricultural conditions (and most notably its climatic conditions) vary over the centuries. To our knowledge however, historical climate data is not available at a sufficiently disaggregated scale to be useful for our purposes. To overcome this difficulty we capture the possibly time-varying agricultural conditions at a somewhat more aggregated spatial scale by including *country-century* fixed effects in all our baseline model specifications[21]. Besides controlling for time-varying agricultural conditions that possibly differ between European countries, these *country-century* fixed effects also

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[20] Glick (1979, p.23) gives several examples of policies by medieval Spanish states and cities to maintain the system of Roman roads. See also Bairoch (1988, p.110) or Lopez (1956). The latter offers a much more critical view on the importance of Roman roads in the centuries after the demise of the Roman Empire.

[21] We also include our agricultural potential variable interacted with a timetrend in most specifications.

capture any country-specific institutional, political, demographic or economic developments that may have left their mark on locations' urban chances[22].

In robustness checks we also use three other fixed effects specifications. The first involves adding *ecozone-century* fixed effects that are based on a division of Europe in terms of agricultural potential (see Buringh et al., 1975). Based on local soil classification and climate data (water, light, evaporation, etc.), Buringh et al. (1975) identify five different classes of agricultural potential in Europe, ranging from very high (e.g. the Po Valley) to very low (e.g the Pyrenees or northern Scandinavia) [see Figure A3 in the Appendix for a map of these ecozones]. Second, we provide results that allow for time-varying, geographically clustered, unobserved effects by including *block-century* fixed effects, with locations grouped in geographically clustered blocks on the basis of their coordinates. Finally, we also show results when controlling for unobserved time-*invariant* location-specific fixed effects.

3.3.2   2nd nature geography

We propose a novel way to uncover the effect(s) of 2nd nature geography. The most commonly used measure of a location's 2nd nature geography is its market or urban potential (see e.g. Stewart, 1947; De Vries, 1984; Black and Henderson, 2003; Dobkins and Ioannides, 2001; Ioannides and Overman 2004; Bosker et al., 2008). This measure is the distance weighted[23] sum of the population of all other already existing cities. In each century *t*, city *i*'s urban potential (*UP*) is calculated as follows:

$$UP_{it} = \sum_{j=1, j \neq i}^{N} \frac{pop_{jt}}{D_{ijt}} \tag{1}$$

We argue that such *UP*-type measures do not do justice to theory when looking at the establishment of new cities. The way *UP* is constructed allows the impact of 2nd nature geography to diminish with the size of, and distance to, other already existing cities. But, it implicitly assumes that the impact of the urban system already in place on a location's own urban chances is either always negative or always positive (depending on the sign of the estimated coefficient on *UP*).

This is clearly a too strong restriction when looking at Figure 2. An existing urban centre exerts an urban shadow at close range, prohibiting the formation of new cities in its

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[22] Countries are defined using current country boundaries. This arguably does not do full justice to the actual political, or institutional situation during our sample period. However, we think it serves as a good proxy (see also Acemoglu et al., 2005 (footnote 8); or De Long and Shleifer (1993).
[23] Sometimes additional weights are introduced in (1). For example cities with higher wages are given more weight than others (Ioannides and Overman, 2004) or, alternatively, the distance between cities that both share favourable conditions for transport, e.g. both are located at sea, is downweighted (Bosker et al, 2008).

immediate neighborhood. At the same time, potential locations that are too far removed from an already existing city also have little chance of becoming a city. It are the locations at medium distance from an already existing city that have the best urban chances. Theory thus predicts that an existing city exerts a *non-linear* effect on its surroundings. *UP*-type measures fail to adequately capture this.

To do more justice to theory, we adopt the following dummy variable approach that does not a-priori restrict the effect of existing cities to be positive or negative at all distances[24]. We first draw three concentric circles around each potential city location at ever further distance[25]. Next, we construct three dummy variables that indicate whether or not we find at least one already existing urban centre within each of the three constructed distance bands. Moroever, to capture possible competition effects between different potential city locations, we also create three dummy variables that indicate whether or not we find at least one other potential city location within each of the distance bands.

Figure 4. Constructing dummy variables to capture 2nd nature geography.
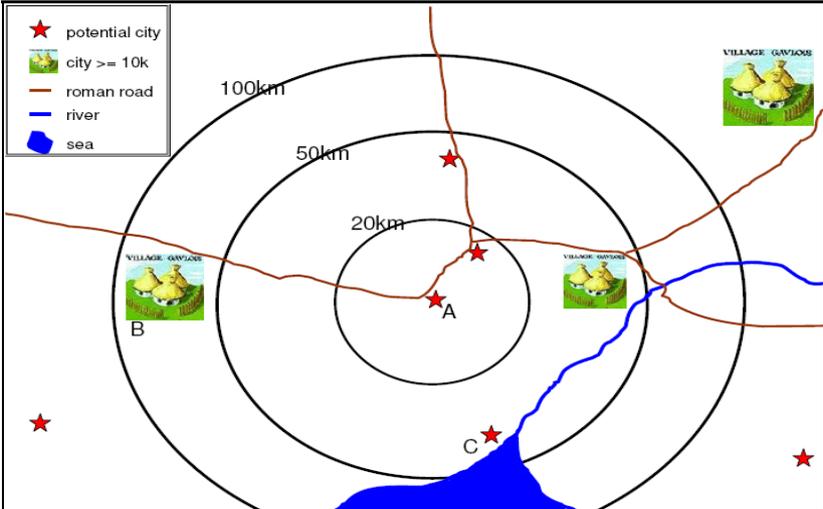
Figure 4 illustrates in more detail how we construct these dummy variables in case of a hypothetical potential city location A. For this location, the dummy variables indicating the presence of an established urban centre are only 1 in case of the 20-50km and the 50-100km distance band (there are no already existing urban centres within 20km of A). Instead, the dummy variables indicating the presence of a competitor potential city location are only 1 in case of the 0-20km and 20-50km distance band (there is no competitor potential city location within 50-100km from A).

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[24] It does constrain the effect to be the same within each distance band. But, one can experiment with different distance bands (see Table A7 in Appendix A).
[25] We calculate great circle distances between all locations in our data set on the basis of their coordinates.

In our baseline estimations we include six dummy variables, two for each of our three distance bands (defined as 0-20km, 20-50km and 50-100km from a potential city location[26]), indicating the presence of:

1) at least one already existing city with at least 10,000 inhabitants[27]
2) at least one competitor potential city location

In further extensions (see section 6) we also consider more elaborately specified dummy variables indicating e.g. the presence of more than one already-existing city, a competitor potential city location with certain 1st nature geography characteristics, or an already-existing city with more than 25,000 inhabitants, within each of our three specified distance bands. In case of location A in Figure 4, a dummy variable indicating the presence of a competitor potential city location located at sea would for example be 1 in case of the 20-50km distance band (location C). Similarly, the dummy variables indicating the presence of at least two existing cities within each respective distance band would always be 0 in case of location A (none of the distance bands contains two already-existing cities).

3.3.3 Non-geography related (control) variables

Finally, we include some other non-geography related variables in robustness checks to our baseline specification that concern the political, religious and educational characteristics of a location. We know for each location in each century whether it was an archbishopric, the capital of a large political entity, and whether it had a university or not. These data are taken from Bosker et al. (2010). Also, in one of our specifications we control for both the total population size and the growth in population size of the (current-day) country a location belongs to. This data comes from McEvedy and Jones (1979). In most specifications these two variables are however fully captured by the included country-century fixed effects.

4   Empirical framework

To empirically quantify the effect of a location's 1st and 2nd nature geography characteristics on its chances of developing into a city, we specify the following simple empirical model:

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[26] The first distance band is based on the idea that 20 kilometers roughly corresponds to a one day round-trip during most of our sample period (roughly because this depends on mode of transportation, travel on horseback or donkey was generally faster than travel by foot, cart or water).

[27] We construct the dummy variables on the basis of existing cities larger than 10,000 inhabitants instead of 5,000 inhabitants to limit possible reverse causality (simultaneity) issues from including a spatially lagged variable. We further limit these simultaneity issues by considering these dummy variables lagged one century (see section 4). In some robustness checks in section 6.1 we do show results when constructing these dummy variables on the basis of a larger and/or smaller population threshold for existing cities.

$$P\left(c_{ict}=1\mid c_{ict-1}=0,X_{ict-1},X_i,\alpha_{ict}\right)=F\left(X_{it-1}\beta_1+X_i\beta_2+X_{ct-1}\beta_3+\alpha_{ict}\right) \qquad (2)$$

, where c_{ict} is a dummy variable indicating whether or not location i in country c is a city at period t, $X_{it\text{-}1}$ are time-varying variables at the location level, X_i are time-invariant variables at the location level, and $X_{ct\text{-}1}$ are time-varying variables at the country level. We include all time-varying variables lagged one century to limit potential endogeneity issues resulting from reverse causality. The α_{ict} capture any unobserved effects at the city, country or century level. In our main specification we specify these unobserved effects to be *country-century-specific* fixed effects: $\alpha_{ict}=\alpha_{ct}$, but we also show results using various different specifications (e.g. using ecozone-century fixed effects, or assuming away any unobserved heterogeneity by taking $\alpha_{ict}=\alpha$). In most of the paper F denotes the CDF of the standard normal distribution, Φ (i.e. we estimate a probit model), but in robustness checks we also allow it to be the logistic function (a logit model) or simply the identity function (a linear probability model[28]).

Our main empirical specification is essentially a (restricted) dynamic probit model. Therefore, we need to assume that we have no serial correlation in the error term in order to obtain consistent estimates of our parameters of interest using standard probit techniques. Note that the need to make this assumption precludes us from basing our inference on clustered standard errors. Although these can be calculated, their use would be internally inconsistent with the necessary assumption of no serial correlation in the error term that underlies our estimations.

The β's are our parameters of interest. They reveal the sign, size (after calculating Average Partial Effects [see footnote 29] and, together with their estimated standard error, (in)significance of our included 1st and 2nd nature geography variables.

As our baseline 1st nature geography variables [the X_i in (2)] we include the dummy variables for location at sea, at a river, and on a (hub of) roman road(s). Besides these four transport related variables, we also include the log of a location's elevation and of its ruggedness as proxies for its ease of access, and a location's probability of cultivation as a measure of its agricultural possibilities. We also include a location's probability of cultivation interacted with a time trend in all (but one) of our specifications to allow for a possibly varying effect of this variable over the centuries.

Finally, as our baseline 2nd nature geography variables [the $X_{it\text{-}1}$ in (2)], we include the three 'already existing city'- and the three 'competitor potential city location'-dummy

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[28] Given that the identity function is not a distribution function, we need to add an error term to (2) in this case.

variables discussed below Figure 4 in section 3.3.2. Since we include these variable lagged one century, our assumption of no serial correlation in the error term also ensures that our inclusion of spatially lagged variables (i.e. all 2nd nature geography variables) does not result in inconsistent estimates (see also footnote 27).

5   Results

Table 1 builds up to our baseline results. Unless noted explicitly, all Tables in our paper do not show the estimated coefficients of (2), but report Average Partial Effects (APEs) instead. APEs reveal the significance, direction, and, contrary to the estimated coefficients in (2), the magnitude of each included variable's effect[29]. When interpreting our findings, it is useful to keep in mind that the unconditional probability of becoming a city is about 12%.

In column 1, we start by ignoring any potential unobserved heterogeneity and simply assume that $\alpha_{ict} = \alpha$. Under this (strong) assumption, location at a river and at sea both significantly positively affect a location's chances of becoming a city. Good location for land-based transportation instead has a surprising negative effect. Locations on the former roman road network have lower urban chances (even when located on a hub of two roman roads[30]). Also, we find that locations in more rugged areas have significantly lower urban chances. Perhaps most remarkably, these first results suggest that the better a location's agricultural possibilities or the lower its elevation, the worse its urban prospects.

Turning to our 2nd nature geography variables, we find that they are all significant. This suggests strong evidence that potential city locations, surrounded by other already existing cities at close or medium-large distance, have much higher chances of becoming a city than more isolated locations. On the contrary, fiercer competition from other potential city locations at close or medium-large range diminishes a location's own urban chances. Finally, and as expected, both the size and the growth rate of a country's total population have a significantly positive effect on the urban chances of all locations within that country.

The results in column 2 however show that the above conclusions are far too preliminary.

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[29] Average Partial Effects are an estimate of the derivative of the expected value of the independent variable with respect to the included variables of interest (see e.g. Wooldridge, 2005). In case of our model specified in (2), the APE of X_{it-1} is for example calculated as:

$$\hat{\beta}_1 \frac{1}{NT} \sum_{it} F'\left(X_{it-1}\hat{\beta}_1 + X_i\hat{\beta}_2 + X_{ct-1}\hat{\beta}_3 + \hat{\alpha}_{ict} \right) \qquad (3)$$

Using a linear probability model, with F the identity function, this would simply be $\hat{\beta}_1$. When F is a nonlinear function (Φ in our baseline probit case), this is no longer so.

[30] Note that the results on our hub-variable have to be interpreted as the *additional* effect of being a hub location over that of simply being located on a roman road.

Table 1. Baseline results

P(city t | no city t-1)	1	2 (BASELINE)	3 ecozone/ century FE	4 blocks/ century FE	5 ecozone- & blocks- & country- century FE	6 potential city location FE (CRE)
X_{ct-1}						
ln country population (t-1)	0.063***	-	-	-	-	-
	[0.000]	-	-	-	-	-
D country population (t-1 -> t)	0.420***	-	-	-	-	-
	[0.000]	-	-	-	-	-
X_i						
sea	0.017*	0.013	0.014*	0.008	0.013	0.012
	[0.054]	[0.134]	[0.082]	[0.397]	[0.206]	[0.149]
river	0.034***	0.061***	0.050***	0.061***	0.066***	0.057***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
hub	0.002	0.015*	0.011	0.015*	0.015	0.015**
	[0.828]	[0.070]	[0.151]	[0.088]	[0.106]	[0.049]
road	-0.016***	-0.010*	-0.009*	-0.003	-0.003	-0.009
	[0.006]	[0.074]	[0.071]	[0.608]	[0.627]	[0.129]
ln elevation	0.005**	0.002	0.004*	0.001	0.004	0.002
	[0.034]	[0.341]	[0.061]	[0.826]	[0.183]	[0.497]
ruggedness	-0.012***	-0.008***	-0.007***	-0.008***	-0.005*	-0.008***
	[0.000]	[0.001]	[0.001]	[0.003]	[0.090]	[0.001]
P(cultivation)	-0.044***	0.114***	0.050*	0.050	0.038	0.098***
	[0.000]	[0.002]	[0.095]	[0.192]	[0.404]	[0.004]
P(cultivation) * trend	-	-0.013***	-0.007*	-0.003	-0.001	-0.011***
	-	[0.004]	[0.052]	[0.543]	[0.814]	[0.006]
X_{it-1}						
city >= 10k? (t-1)						
0 – 20 km	0.037***	-0.003	0.001	-0.009	-0.007	-0.007
	[0.000]	[0.716]	[0.918]	[0.322]	[0.476]	[0.56]
20 – 50 km	0.049***	0.010*	0.013***	0.012**	0.013**	0.024***
	[0.000]	[0.051]	[0.006]	[0.039]	[0.045]	[0.001]
50 - 100 km	0.057***	0.009*	0.014***	0.011*	0.015**	0.005
	[0.000]	[0.084]	[0.003]	[0.085]	[0.031]	[0.432]
competitor potential city location? (t-1)						
0 - 20 km	-0.034***	-0.015***	-0.013***	-0.010*	-0.012**	-0.011
	[0.000]	[0.004]	[0.003]	[0.065]	[0.049]	[0.425]
20 - 50 km	-0.061***	-0.007	-0.008	-0.008	-0.008	-0.005
	[0.000]	[0.471]	[0.374]	[0.437]	[0.486]	[0.797]
50 - 100 km	-0.078***	-0.027	-0.019	-0.022	-0.046	0.060
	[0.001]	[0.250]	[0.370]	[0.341]	[0.114]	[0.229]
country/century FE	no	yes	no	no	yes	yes
nr observations	15156	13228	14771	11715	11034	15156
ln pseudo likelihood	-4500.5	-3193.4	-3412.5	-3112.4	-2927.2	-3173.2
LR – test statistic	-	2614.1	-	-	-	-
2.5% upper tail critical value χ²(n)	-	225.7 χ2(186)	-	-	-	-

Notes: p-values, based on robust standard errors, between square brackets. *, **, *** denotes significance at the 10%, 5%, 1% respectively. Instead of the estimated coefficients in (2), the table reports average partial effects. The p-values are based on the estimated coefficients and their standard errors since these do not depend on the particular calculation of the average partial (or marginal) effects. Result are the same when using the p-values based on the calculated standard errors of the average partial effects. If a likelihood ratio test statistic and a 5% critical value are reported in a column, they are used to test whether or not the specification in that column is statistically preferred over the preceding column (to the left). Only in this table we add X_{ct-1}, X_i and X_{it-1} to the left of our variable names to clarify the correspondence between equation (2) and our results. When interpreting the results, it is useful to keep in mind that the unconditional probability of becoming a city is about 12%.

They depend strongly on the assumption of no unobserved heterogeneity. In column 2 we include country-century-specific fixed effects (i.e., $\alpha_{ict} = \alpha_{ct}$) to control for any unobserved developments over the centuries, possibly specific to each country, that may have left their

mark on each location's urban chances. Moreover, we also allow the effect of a location's cultivation potential to change over time[31]. This specification is statistically strongly preferred over assuming away any unobserved heterogeneity (see the likelihood ratio test at the bottom of column 2). More importantly, it substantially changes our findings.

The results regarding the included 1st nature geography variables change in important ways. First, the surprising negative effect of a location's cultivation potential turns out to be driven by the later centuries. When allowing its effect to change over the centuries, it shows that initially, the better a location's cultivation potential, the higher its urban chances. However this effect becomes significantly smaller over the centuries (its overall marginal effect is insignificant from about the 15th century onwards). This is not only consistent with gradually improving agricultural methods that diminish the relative advantage of being located near highly productive lands, but also with the notion that in the later centuries food could be transported over greater distances at lower costs due to improvements in transportation technology. This diminished the advantage of location right next to fields of high agricultural productivity (Duranton, 1999, p.2173). In north-western Europe for example, the grain trade with eastern Europe became increasingly important (Hybel, 2002).

Second, we still find that a location's opportunities for water-based transportation are a very important determinant of its urban chances. However, location at sea looses its significance. Only locations on a navigable river have a significantly higher probability to become a city of about 6 percentage points. Also, we still find no evidence that location on the former roman road network bore any significant advantages. Non-hub locations on the former roman road system even have significantly lower urban chances. This finding corresponds to the account of Lopez (1956). He argues that the importance of the Roman road network diminished during the Middle Ages. On the one hand water-based transportation gained in importance (no need for maintenance, and easier to ship heavier loads), on the other hand the Roman road system was planned mostly for military purposes so that it did not always correspond to the most economical route[32].

It are the results on the 2nd nature geography variables however that change most dramatically. This is perhaps not that surprising. A location that is located in a country that is,

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[31] Invariably, a location's cultivation potential is never significant at the 10% level when not also including it interacted with a time-trend.

[32] As a result (Lopez, 1956 p.21): *"in the later Middle Ages […] little by little a new network of roads was put into effective operation, different totally in structure and methods from the ancient one […] The routing reflected the needs of commerce rather than the convenience of soldiers and civil servants."* The diminishing importance of the roman road network is further confirmed when allowing the effect of 'hub-location' to vary over the centuries (see section 5.2).

for unobserved reasons, a good seedbed for city development, will have a high probability of becoming a city. But, so do other locations in that country. As a result, this location is also more likely to be surrounded by some already existing cities. When not adequately controlling for geographically clustered unobserved heterogeneity, one can thus easily, and wrongly so, ascribe an important role to 2nd nature geography.

This is exactly what happened in column 1. In column 2 we find that our 2nd nature geography variables are much less significant. Strikingly however, the 2nd nature geography results correspond closely to the theoretical predictions following from the standard economic geography models discussed in section 2.2. We find evidence of the nonlinear effect that an already existing city is predicted to have on other locations' urban chances: the effect of another already existing city is only significantly positive at medium range (20-100km)[33]. Being located too close (0-20km) or too far (> 100km) from an already existing city does not significantly affect a location's probability to become a city.

We also no longer find a significantly negative competition effect with other potential city locations at all distances. The results in column 2 show that competition with other potential city locations is fiercest at close range: only having a rival potential city location within 0-20km significantly diminishes a location's urban chances[34].

Overall, we can summarize our preliminary baseline findings as follows:

1) *1st nature geography* is very important in determining a location's urban chances. Especially preferential location for river-based transportation substantially increases a location's probability to become a city. Location at (a hub of) overland transport routes does not carry such positive effects. Favorable location in terms of agricultural possibilities also contributes positively to a location's urban chances, but especially so at the beginning of our sample period (a reflection of both gradually improving agricultural production techniques as well as better possibilities to import food grown on farther fields). Finally, we find that better accessible places, located in less rugged terrain, do have better urban chances.

2) *2nd nature geography* is also important, but to a lesser extent. What is very interesting however, is that our flexible modelling strategy uncovers almost the exact prediction made by new economic geography theory. Locations at medium range (20-100km) from already existing cities have significantly better urban chances. They have about a 1 ppt higher

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[33] The p-value of a test of the joint significance of our 20-50km and 50-100km already-existing city dummies is [0.039]

[34] These results also come through when including only the already-existing-city or only the competitor-potential-city dummy variables. Results available upon request.

probability to become a city than locations located closer to or further away from other already existing urban centres. On the contrary, competition with other potential city locations is fiercest at close range. Only a competitor within the nearest 20km significantly diminishes a location's urban chances by about 1.5 ppt.

In the remainder of the paper, we show that these baseline results hold up to a wide variety of robustness checks. These checks result in one important refinement that shows the changing importance of 1st and of 2nd nature geography in determining city location over the centuries.

5.1 *Robustness*

Besides the robustness checks discussed in the main text, Tables A6 – A9 in Appendix A contain additional checks that verify the sensitivity of our baseline results to the estimation strategy used, to the particular distance bands used to construct our 2nd nature geography variables, or to the absolute population cutoff of 5,000 inhabitants that we use to define a city.

5.1.1 *Controlling for unobserved heterogeneity*

Our first four robustness checks are shown in columns 3 - 6 of Table 1. They concern the way we control for unobserved heterogeneity. In our baseline results we control for any unobserved *country-century-specific* variables that could leave their effect on a location's urban chances. Columns 3 – 5 verify whether or not our findings critically hinge upon this country-century specification.

In column 3 we instead include ecozone-century fixed effects constructed on the basis of a division of Europe in five different *ecozones* taken from Buringh et al., 1975 (see Figure A3 in the Appendix). Next in column 4, we use block-century fixed effects based on a division of Europe into 25 geographically clustered *blocks* using the 20th, 40th, 60th and 80th quantile of the distribution of all locations' latitude and longitude as boundaries. And, in column 5, we include country-, ecozone-, and block-century fixed effects at the same time. Our baseline results hold up to using any of these different specifications to control for time-varying unobserved heterogeneity. Location on a roman road and a location's agricultural potential are most sensitive to these additions. Both loose their significance when including block-century fixed effects[35].

Besides questioning the way we control for time-varying unobserverd heterogeneity in

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[35] Given that our agricultural potential variable is based on a grid of 0.5 by 0.5 degree longitude and latitude, it may not be so surprising that it is especially sensitive to controlling for these block-century fixed effects that are also based on a (be it somewhat larger) longitude and latitude defined, grid-wise division of our sample.

our baseline specification, one could also stress the need to control for unobserved time-*invariant* factors at the *potential city location level*. Despite the drawback that doing this makes it impossible to infer the relevance of our time-invariant 1st nature geography variables, it does serve as an additional robustness check on our 2nd nature geography results[36].

Allowing for such location-specific unobserved heterogeneity when employing non-linear panel data techniques is not as straightforward as in linear panel data models where one can simply include a dummy variable for each location and obtain consistent estimates of the parameters of interest (see e.g. Heckman, 1981; Wooldridge, 2005; Fernández-Val, 2009 or Carro, 2007). In our baseline probit case including such dummy variables results in inconsistent estimates of the parameters of interest (the incidental parameters problem)[37].

To get around this problem, we use the conditional random effects (CRE) strategy proposed by Wooldridge (2005) and specify the distribution of the unobserved *location-specific* effects conditional on the individual specific mean, $\overline{X}_{i\cdot}$, of the included time-varying X_{it-1} variables, the country-century specific fixed effects, α_{ct}, and a location's initial city status in 800[38], c_{i800}, i.e.: $\alpha_{ict} = \alpha_{ct} + c_{i800}\zeta + \overline{X}_{i\cdot}\xi + \eta_i$, with $\eta_i \mid \alpha_{ct}, c_{i800}, \overline{X}_{i\cdot} \sim N(0, \sigma_\eta^2)$. Under this assumption for the location-specific unobserved heterogeneity we can employ random effect probit techniques to get consistent estimates of the parameters of all our second nature geography variables[39].

Column 6 of Table 1 shows that the effect of 2nd nature geography is somewhat weakened when employing this CRE estimation strategy. In particular, we no longer find evidence of any significant competition effect among potential city locations. The nonlinear effect exerted by an already existing city is however robust to also controlling for unobserved time-invariant location-specific effects. Locations at medium distance (20-50km) from an

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[36] Our baseline results are only valid under the assumption of no time-invariant location-specific heterogeneity (even when this heterogeneity is uncorrelated with the variables of interest, i.e. random effects, we would get incorrect estimates of our parameters of interest given the implicit dynamic nature of our model).

[37] Table A6 in Appendix A shows that our results are the same when using a conditional logit or fixed-effects linear probability estimation strategy instead. It also reveals that we find the same results when employing a semi-parametric Cox proportional hazard model. Using this method arguably takes better account of any duration-dependence in the probability of becoming a city (i.e. this probability may not be the same depending on the time a location has already not become a city). However, the fact that we include country-century fixed effects in all our baseline specifications already go a long way in controlling for duration-dependence (they allow the baseline hazard to (arbitrarily) change over the centuries in a possibly different way across countries).

[38] Given the dynamic nature of the model, the presence of any (random or fixed) location-specific time-invariant unobserved heterogeneity requires the inclusion of this initial value to address the 'initial condition problem'.

[39] Note that although we still appear to obtain estimates of the effects of the 1st nature geography variables, these are misleading since we can not separately identify each 1st nature geography variable's effect on a location's urban chances from its partial correlation with the location-specific unobserved effects (see Wooldridge, 2005). If one is willing to assume that this partial correlation is zero, the coefficients on our 1st nature geography variables can be interpreted. In that case, all our baseline findings, come through.

already existing city have a significantly higher probability (2.4 ppt) to become a city than those located closer to, or farther away from, that city.

5.1.2 *Endogenous sample selection*

Our second set of robustness checks is aimed at addressing the important issue of endogenous sample selection. As already touched upon in section 3.1, one could question whether our baseline sample of potential city locations is an exogenous sample from the population of all potential city locations given that many of our potential city locations are included on the basis of actually becoming a city at some point during our sample period. If it is not, our estimations could be painting a distorted picture of the true effect of our variables of interest. We look at this inherently difficult issue from four different angles (see also section 5.2.1).

First, the CRE results in column 6 of Table 1 already address the issue of endogenous sample selection. In order to obtain consistent estimates of our parameters of interest, we only require exogeneity of our sample *conditional on all the included regressors* in our empirical specification. Consequently, the issue of endogenous sample selection effectively becomes irrelevant when using an estimation strategy that allows for location-specific fixed effects. These location-specific fixed effects perfectly predict the urban history of all locations that never develop into a city. Effectively, a CRE estimation strategy considers all possible city locations, but only uses the within-variation provided by locations that do become a city at some point to identify the effect of our variables of interest. As discussed above, the results on all our time-varying variables are robust to using such an estimation strategy.

The drawback of addressing the issue of endogenous sample selection by allowing for potential city location-specfic fixed effects is that it prohibits the identification of the effect of all our 1st nature geography variables that are time-invariant [see footnote 39]. This is not the case in our other three robustness checks aimed at addressing concerns about endogenous sample selection. They verify whether our results change substantially when considering a smaller, larger, or completely different set of potential city locations. Their results are shown in columns 8 – 10 in Table 2 below.

In column 8 we exclusively focus on our 456 'bishop 600' locations. The case that these 'bishop 600' locations are, conditional upon all the other included regressors in our model, randomly chosen with respect to their future city prospects may be easier to make compared to our Bairoch et al. (1988) locations. Column 4 shows that most of our baseline results hold up to restricting our analysis to this sample, despite the fact that it involves a substantial reduction in the number of observations (we lose more than 10,000 observations compared to

our baseline results)[40].

In column 9 we instead add 217 potential city locations to our baseline sample. We include the 217 cities that according to Bairoch et al. (1988) did have a population larger than 5,000 inhabitants in 1850, yet never passed this threshold during our sample period [see footnote 15 for the main reason(s) not to include these locations in our baseline specifications]. Table A4 and Figure A4a show further information on the distribution of these additional '1850 locations' over the European continent. They are mostly situated in the (future) industrial cores or coal-rich areas of Europe (e.g. Belgium, the UK, The Netherlands, Sweden and the German Ruhr-area). Besides adding these locations to the sample, we also consider them when constructing the three different 'competitor potential city location'-dummies. Importantly, most of our baseline results hold up to this extension of the number of potential city locations. The positive effect of having an existing city at medium distance does lose some of its significance[41] (it is only significant for the 50-100 km distance band).

Finally, in column 10 we completely change the set of potential city locations. In particular, we consider each possible coordinate pair as a potential city location and focus on a randomly drawn sample of 2,067 coordinate pairs, all located within one of the countries present in our baseline sample[42] (see Figure A4b). For each of these coordinate pairs we collect the same 1st and 2nd nature geography variables that we included in our baseline specification, with the exception of our 'competitor potential city location'-dummy variables. When considering each coordinate pair as a potential city location, each potential city location faces competition from another potential city location at any distance. This leaves us without any variation between locations to identify possible competition effects.

Next, we matched these randomly drawn coordinate pairs to the original city data from Bairoch et al. (1988) maintaining a margin of error of 5km[43].. That is, we replace a randomly selected coordinate pair with a Bairoch city if the random draw lies within a range of at most

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[40] We no longer find a significant effect of location on a roman road, of a location's cultivation potential nor of its ruggedness. The competitor potential city location dummy for the 50 – 100km distance band drops out because it is perfectly captured by the included country-century fixed effects.

[41] Note that our final time-varying results in Table 3 are even more robust to this change in sample.

[42] We actually drew 2,500 random coordinate pairs, but 433 of these turned out to be located in a sea or lake. One could argue that we should do our analysis using all possible coordinate pairs. This would however involve a tremendous data collection exercise that lies beyond our current capabilities (especially since part of our data comes from non-digital sources). Also, one would have to make an, in our view non-trivial, choice regarding the spacing between coordinate pairs to consider (i.e. does all coordinate pairs mean all locations within 1 cm, 1 inch, 1 km or 5 mile from one another?).

[43] Results are the same when using a 10km distance margin to match the random coordinate pairs to our Bairoch data (in that case 228 coordinate pairs ever become a city). When using a 1km matching margin instead, the number of (successfully matched) coordinate pairs that ever become a city reduces to 4 making the results quite sensitive to the particular matches that occur in case of our particular random sample.

5km to that city. This results in 64 matches, i.e. 64 of our total 2,067 coordinate pairs become a city at some point during our 800-1800 sample period.

Table 2. Robustness (variables included, sample composition, endogenous sample selection)

P(city t | no city t-1)	1 political and religious function	2 ever a city before?	3 'Bairoch' history < 5k?	4 only > 20% bishop 600 countries	5 no UK	6 < 1600	7 >= 1600	8 only bishop 600	9 extra '1850' potential city locations	10 random coordinates 5km match
sea	0.012	0.013	0.009	0.003	0.016	0.003	0.034	-0.005	0.011	-0.002
	[0.163]	[0.139]	[0.275]	[0.775]	[0.101]	[0.698]	[0.154]	[0.709]	[0.189]	[0.627]
river	0.058***	0.059***	0.057***	0.061***	0.061***	0.046***	0.096***	0.101***	0.047***	0.007**
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.035]
hub	0.006	0.014*	0.017**	0.009	0.011	0.027***	-0.044*	0.022**	0.015**	0.051***
	[0.463]	[0.087]	[0.033]	[0.280]	[0.213]	[0.000]	[0.051]	[0.049]	[0.047]	[0.001]
road	-0.010*	-0.010*	-0.009*	-0.008	-0.011*	0.010*	-0.056***	-0.017	0.001	0.034***
	[0.067]	[0.072]	[0.097]	[0.182]	[0.076]	[0.076]	[0.000]	[0.209]	[0.787]	[0.000]
ln elevation	0.003	0.002	0.001	0.001	0.002	-0.002	0.012**	-0.007*	0.003	-0.003**
	[0.268]	[0.389]	[0.683]	[0.552]	[0.32]	[0.285]	[0.045]	[0.064]	[0.146]	[0.033]
ruggedness	-0.008***	-0.008***	-0.008***	-0.009***	-0.007***	-0.009***	-0.004	-0.003	-0.010***	0.001
	[0.002]	[0.002]	[0.002]	[0.001]	[0.006]	[0.000]	[0.585]	[0.442]	[0.000]	[0.456]
P(cultivation)	0.113***	0.113***	0.104***	0.071*	0.104***	0.078**	-0.227	0.065	0.117***	-0.014
	[0.002]	[0.002]	[0.003]	[0.070]	[0.007]	[0.027]	[0.509]	[0.255]	[0.001]	[0.435]
P(cultivation) * trend	-0.013***	-0.013***	-0.011***	-0.01**	-0.012**	-0.009	0.021	-0.005	-0.014***	0.001
	[0.005]	[0.004]	[0.01]	[0.036]	[0.011]	[0.101]	[0.542]	[0.513]	[0.001]	[0.52]
city >= 10k? (t-1)										
0 - 20 km	-0.001	-0.002	-0.005	0.005	0.001	-0.026**	0.021	-0.049*	-0.001	0.005
	[0.879]	[0.759]	[0.541]	[0.545]	[0.925]	[0.015]	[0.255]	[0.051]	[0.851]	[0.298]
20 - 50 km	0.011**	0.011**	0.009*	0.018***	0.013**	-0.005	0.041***	0.018*	0.004	0.007*
	[0.039]	[0.041]	[0.088]	[0.002]	[0.019]	[0.345]	[0.002]	[0.097]	[0.369]	[0.058]
50 - 100 km	0.011**	0.009*	0.007	0.013**	0.009	-0.006	0.060***	0.019*	0.009*	0.004
	[0.044]	[0.083]	[0.210]	[0.038]	[0.110]	[0.200]	[0.000]	[0.074]	[0.079]	[0.223]
competitor potential city location? (t-1)										
0 - 20 km	-0.014***	-0.014***	-0.016***	-0.012**	-0.017***	-0.012**	-0.020	-0.017	-0.014***	-
	[0.008]	[0.005]	[0.002]	[0.043]	[0.002]	[0.014]	[0.154]	[0.117]	[0.004]	-
20 - 50 km	-0.011	-0.007	-0.006	-0.004	-0.008	-0.010	-0.009	-0.007	0.010	-
	[0.284]	[0.503]	[0.540]	[0.733]	[0.477]	[0.246]	[0.74]	[0.718]	[0.307]	-
50 - 100 km	-0.033	-0.027	-0.023	-0.002	-0.026	-0.022	-0.058	-	-0.035	-
	[0.160]	[0.263]	[0.334]	[0.963]	[0.302]	[0.362]	[0.315]	-	[0.145]	-
country/century FE	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
nr observations	13228	13228	13228	9567	12197	9610	3618	3242	14892	5182

	extra included variables			extra info on political and religious variables			
archbishop t-1	0.146***	-	-		archbishop t-1		
	[0.000]	-	-	city t-1	no (%)	yes (%)	
capital t-1	0.268***	-	-	no	15252 (99)	*118 (1)*	
	[0.000]	-	-	yes	2198 (89)	272 (11)	
university t-1	0.157***	-	-		capital t-1		
	[0.000]	-	-	city t-1	no (%)	yes (%)	
ever a city before?	-	0.030***	-	no	15335 (99.8)	*35 (0.2)*	
	-	[0.005]	-	yes	2306 (93)	164 (7)	
>= 1k t-1?	-	-	0.101***		university t-1		
	-	-	[0.000]	city t-1	no (%)	yes (%)	
				no	15327 (99.7)	*43 (0.3)*	
				yes	2204 (89)	266 (11)	

Notes: p-values, based on robust standard errors, between square brackets. *, **, *** denotes significance at the 10%, 5%, 1% respectively. Instead of the estimated coefficients in (2), the table reports average partial effects. The p-values are however based on the estimated coefficients and their standard errors. When interpreting the results, it is useful to keep in mind that the unconditional probability of becoming a city is about 12%.

Using this sample of random coordinate pairs, we estimate our baseline specification Reassuringly, our main baseline results regarding the importance of a location's transportation possibilities as well as the positive effect of being located at medium range from an existing city come through[44].

5.1.3 Additional variables and sample composition
The next set of robustness checks concerns the inclusion of additional non-geography related control variables to our baseline model, as well as several checks to establish whether or not our results are primarily driven by developments in a few centuries or in particular countries only. Again, table 2 shows the results.

Columns 1 – 3 add additional variables to our baseline specification. Reassuringly, and with only few exceptions, all our main baseline results come through. The results on the extra included variables are of interest by themselves however.

Column 1 controls for a potential city location's religious, political and educational status in period *t-1*. We find that having an important religious [archbishopric] or political [capital] function substantially increases a location's urban chances. Note however that the results on these non-geography related variables should be taken with some care. The extra information on the included political and religious variables in Table 2 shows that only 0.2% of all our potential city locations are a capital, 0.3% have a university, and only 1% are an archbishopric, before becoming a city. Although these characteristics significantly improve a location's urban chances, such locations are major exceptions.

Column 2 and 3 instead control for a location's (urban) population history. In column 2 we include a dummy variable indicating whether or not a location had ever been a city before. This is done to control for the presence of cities (13% of the sample) that at some point pass our 5,000 inhabitants criterion, subsequently fall back below this number, to pass it again in a later century. These cities would – so to speak – be counted double in our sample, which could leave an effect on the results. This is however not the case[45], but the results do

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[44] We now do find a significantly negative effect of a location's elevation as well as a significantly positive effect of location on a roman road, suggesting that we may underestimate the effect of these variables in our baseline due to lack of variation (i.e. we undersample locations at high altitudes that never become a city as well as locations not located on former roman roads that never become a city). Also note that our final time-varying results in Table 3 are 'even more robust' to using this random sample of coordinate pairs.

[45] The baseline results are also robust to simply removing those locations that had already qualified as a city before. We also note that the Black Death (the plague epidemic of 1342) is responsible for many of these 'city-disappearances'. 40% of the existing cities in 1300 'disappear', i.e. fall back below the 5,000 inhabitants threshold, during the fourteenth century. Our results are also robust to either excluding the plague years (1400 and possibly also 1500 to account for a possible 'recovery' effect), or excluding those cities that 'disappeared' in the fourteenth century. Results available upon request.

show that locations that once already qualified as a city, but subsequently lost their city status, have a 3 ppt higher probability to (again) gain city status.

Finally, in column 3 we make use of the fact that Bairoch et al. (1988) do report a few population estimates below 5,000 inhabitants. Although Bairoch et al. (1988, p.218) stress that these numbers are subject to much greater margins of error than their numbers larger or equal than 5,000 inhabitants, we include an additional dummy variable indicating whether or not a location was already reported to have a population between 1,000 and 4,000 inhabitants in period *t-1*. Again our baseline results come through, only the presence of an existing city within the 50-100km distance band looses its significance. The additional 'population history' dummy is significant and has the expected sign: already having a reported number of inhabitants increases a location's chances of becoming a city by about 10ppt.

The other four robustness checks verify whether our baseline results are driven by particular countries or centuries only. Column 4 verifies whether or not the results depend on a possible Roman empire bias resulting from our use of 'bishop 600' locations that are mainly found within the boundaries of the former Roman Empire. Only considering potential city locations in countries where at least 20% of all potential city locations were an (arch)bishopric in 600 (see Table A2) does however not affect our baseline results. Similarly, column 5 shows that our baseline results hold up to excluding the UK, the earliest industrializing country[46], from the sample.

By contrast, column 6 and 7 show that they do change when we consider only the period before or after 1600 respectively. Both the relevance of 1st and of 2nd nature geography differs markedly between the earlier and later centuries in our sample.[47]

Regarding 1st nature geography, the different pre- and post-1600 estimates show an increasing importance of location on a navigable river. The importance of the other 1st nature geography variables decreases over the centuries. Both favourable location for land-based transportation (hub location), as well as a location's accessibility (being located in less rugged terrain) have a significantly positive effect on a location's urban chances in the pre-1600 period but loose this positive influence in the later centuries. Also, the decreasing importance of favorable location for agriculture (earlier shown by the negative coefficient on cultivation

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[46] Ashton (1948) dates the start of the Industrial Revolution in Britain in the late eighteenth century. In continental Europe it only gathered steam in the first half of the nineteenth century. Excluding also Belgium, the earliest industrializer on the continent, also leaves our results unaffected. Results available upon request.

[47] In Table A5 in the Appendix we show results when using a finer decomposition of the sample along century lines. The patterns shown in these results are very similar to those using a pre- and post-1600 split of the sample. Only in case of our 'competitor potential city location'-dummy variable do these finer decompositions give less clear-cut results. For parsimony reasons we decided to show the pre- and post 1600 results in the main text.

potential interacted with a timetrend) is confirmed: we only find a positive effect of a location's cultivation potential during the earlier centuries in our sample.

Second, regarding 2nd nature geography, we do not find the significant positive effect of having an already existing city at medium distance in the pre-1600 period, but an already existing city at too close distance (within 20 km) does significantly lower a location's probability to become a city during this period (this echoes our 'Italy'-finding above). When instead considering the post-1600 period, the same pattern in the effect of an already existing city as in our baseline results turns up: only the presence of an existing city at medium distance increases a location's urban chances. Moreover, the negative effect of having a competitor potential city location at close range looses its significance in the later period.

5.2   *The changing importance of 1st and 2nd nature geography over time*

The above-described difference in results when considering the earlier or later centuries of our sample period is the most important refinement to our baseline results. In this section we further explore this finding. Instead of simply splitting the sample, we estimate (2) allowing all variables to have a pre- and post-1600 specific effect by interacting each variable with a pre- and a post-1600 dummy[48]. This has the advantage that it allows us to formally test the equivalence of the pre- and post-1600 effect of each of the included variables[49]. The p-values corresponding to tests for the equality of each respective variable's effect in the pre- and post-1600 period are found at the bottom of the Table 3.

Column 1 of Table 3 shows the results for our baseline specification, confirming the results we found when simply splitting the sample (see columns 6 and 7 in Table 2).

Regarding 1st nature geography, we find that the importance of land-based transport significantly diminishes, whereas that of water-based transport, and river-based transport in particular, significantly increases over the centuries. Location at a hub of roman roads is beneficial to a location's urban chances in the pre-1600 period only, turning negative (or insignificant) in the post-1600 period. It shows the gradually diminishing (economic) importance of the former Roman road network. Instead, the importance of location on a

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[48] For parsimony reasons we do not allow for a different effect in the pre- and post 1600 period for our roman road and elevation variables. Doing so does not yield any significant differences over time for these two variables, moreover it does not affect the results shown in Table 3. Results available upon request. It is also the reason why the results in column 1 of Table 3 are not exactly the same as those in columns 6 and 7 in Table 2.

[49] We stress at this point that we not claim in any way that 1600 is the exact year in which these changes occurred. What we do want to stress is that the (relative) importance of 1st and 2nd nature geography in determining city location changed significantly over the centuries. Since our data come at 100 year intervals, taking the year 1600 to be some kind of a crucial 'breakpoint' year would in our view be unwarranted.

Table 3. Pre- and post-1600 results

P(city t | no city t-1)	1 MAIN RESULTS	2 CRE	3 extra '1850' potential city locations	4 random coordinates 5km match	5 no UK	6 no 1800	7 'Bairoch' history < 5k?	8 measurement error ?
sea < 1600	0.013*	0.011*	0.012*	-0.004	0.016**	0.016**	0.011	11%
	[0.080]	[0.098]	[0.074]	[0.279]	[0.041]	[0.033]	[0.139]	< 57% >
sea >= 1600	0.007	0.014	-0.002	0.000	0.007	0.056**	-0.001	0%
	[0.741]	[0.548]	[0.932]	[0.962]	[0.772]	[0.024]	[0.941]	< 0% >
river < 1600	0.049***	0.041***	0.042***	0.000	0.049***	0.048***	0.047***	100%
	[0.000]	[0.000]	[0.000]	[0.923]	[0.000]	[0.000]	[0.000]	< 100% >
river >= 1600	0.088***	0.102***	0.054***	0.016**	0.087***	0.080***	0.080***	100%
	[0.000]	[0.000]	[0.000]	[0.015]	[0.000]	[0.000]	[0.000]	< 100% >
hub < 1600	0.039***	0.033***	0.034***	0.050***	0.036***	0.032***	0.040***	100%
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	< 100% >
hub >= 1600	-0.069***	-0.061***	-0.057***	0.032	-0.079***	-0.018	-0.061***	98%
	[0.001]	[0.003]	[0.005]	[0.169]	[0.000]	[0.410]	[0.002]	< 100% >
ruggedness < 1600	-0.009***	-0.008***	-0.009***	0.001	-0.009***	-0.011***	-0.009***	100%
	[0.000]	[0.000]	[0.000]	[0.529]	[0.000]	[0.000]	[0.000]	< 100% >
ruggedness >= 1600	-0.002	-0.006	-0.007	0.001	0.003	-0.012	0.000	0%
	[0.754]	[0.426]	[0.273]	[0.629]	[0.718]	[0.110]	[0.984]	< 0% >
roman road	-0.008	-0.007	0.003	0.036***	-0.009	0.005	-0.007	0%
	[0.168]	[0.227]	[0.538]	[0.000]	[0.169]	[0.368]	[0.209]	< 5% >
ln elevation	0.002	0.001	0.003	-0.003**	0.002	0.005**	0.000	0%
	[0.462]	[0.534]	[0.238]	[0.035]	[0.456]	[0.035]	[0.848]	< 0% >
P(cultivation)	0.111***	0.096***	0.114***	-0.002	0.102***	0.101***	0.100***	100%
	[0.003]	[0.006]	[0.002]	[0.940]	[0.008]	[0.006]	[0.006]	< 100% >
P(cultivation) * trend	-0.013***	-0.011***	-0.014***	0.000	-0.012**	-0.012**	-0.011**	99
	[0.006]	[0.009]	[0.001]	[0.946]	[0.013]	[0.014]	[0.016]	< 100% >
city >= 10k? (t-1)				**0 - 20 km**				
< 1600	-0.024**	-0.029**	-0.021**	0.002	-0.023**	-0.023**	-0.024**	89%
	[0.025]	[0.012]	[0.025]	[0.737]	[0.037]	[0.035]	[0.023]	< 100% >
>= 1600	0.019	-0.004	0.020	0.003	0.030	-0.007	0.014	3%
	[0.309]	[0.874]	[0.257]	[0.300]	[0.130]	[0.757]	[0.450]	< 9% >
city >= 10k? (t-1)				**20 - 50 km**				
< 1600	-0.004	0.005	-0.004	-0.002	-0.003	-0.004	-0.004	0%
	[0.436]	[0.336]	[0.387]	[0.527]	[0.613]	[0.474]	[0.394]	< 0% >
>= 1600	0.042***	0.066***	0.022*	0.017**	0.048***	0.034**	0.037***	97%
	[0.002]	[0.000]	[0.094]	[0.012]	[0.001]	[0.028]	[0.004]	< 100% >
city >= 10k? (t-1)				**50 - 100 km**				
< 1600	-0.005	-0.006	-0.004	0.003	-0.004	-0.006	-0.006	0%
	[0.254]	[0.197]	[0.279]	[0.693]	[0.399]	[0.229]	[0.170]	< 0% >
>= 1600	0.062***	0.060***	0.053***	0.010	0.060***	0.071***	0.054***	100%
	[0.000]	[0.002]	[0.001]	[0.106]	[0.001]	[0.000]	[0.001]	< 100% >
competitor potential city location? (t-1)				**0 - 20 km**				
< 1600	-0.011**	-0.010	-0.009**	-	-0.011**	-0.011**	-0.012**	92%
	[0.020]	[0.250]	[0.05]	-	[0.029]	[0.021]	[0.015]	< 100% >
>= 1600	-0.020	-0.024	-0.027**	-	-0.028*	-0.021	-0.022*	10%
	[0.146]	[0.408]	[0.043]	-	[0.057]	[0.183]	[0.097]	< 26% >
competitor potential city location? (t-1)				**20 - 50 km**				
< 1600	-0.010	-0.008	0.002	-	-0.013	-0.010	-0.010	0%
	[0.248]	[0.556]	[0.814]	-	[0.163]	[0.266]	[0.237]	< 0% >
>= 1600	-0.005	-0.013	0.023	-	0.002	-0.056**	0.000	0%
	[0.863]	[0.741]	[0.367]	-	[0.936]	[0.049]	[0.992]	< 0% >
competitor potential city location? (t-1)				**50 - 100 km**				
< 1600	-0.021	0.044	-0.061***	-	-0.012	-0.024	-0.022	0%
	[0.361]	[0.277]	[0.005]	-	[0.628]	[0.305]	[0.312]	< 0% >
>= 1600	-0.057	0.095	0.002	-	-0.077	-0.051	-0.043	2%
	[0.324]	[0.367]	[0.974]	-	[0.224]	[0.433]	[0.480]	< 8% >
country/century FE	yes	yes	yes	yes	yes	yes	yes	yes
nr observations	13228	15156	14892	5182	12197	12094	13228	-

TABLE 3 CONTINUED					p-value H0: pre 1600 = post 1600			
sea	[0.325]	[0.387]	[0.160]	[0.358]	[0.226]	[0.612]	[0.254]	-
river	[0.060]*	[0.110]	[0.000]***	[0.144]	[0.069]*	[0.065]*	[0.055]*	-
hub	[0.000]***	[0.000]***	[0.000]***	[0.203]	[0.000]***	[0.001]***	[0.000]***	-
ruggedness	[0.010]***	[0.014]**	[0.012]**	[0.837]	[0.003]***	[0.095]*	[0.004]***	-
city >= 10k? (t-1)								
0 - 20 km	[0.014]**	[0.011]**	[0.012]**	[0.866]	[0.010]***	[0.161]	[0.020]**	-
20 - 50 km	[0.007]***	[0.017]**	[0.078]*	[0.042]**	[0.007]***	[0.033]**	[0.010]***	-
50 - 100 km	[0.000]***	[0.000]***	[0.001]***	[0.488]	[0.002]***	[0.000]***	[0.001]*	-
competitor? (t-1)								
0 - 20 km	[0.582]	[0.545]	[0.981]	-	[0.913]	[0.716]	[0.654]	-
20 - 50 km	[0.523]	[0.672]	[0.672]	-	[0.323]	[0.387]	[0.430]	-
50 - 100 km	[0.995]	[0.609]	[0.036]**	-	[0.641]	[0.902]	[0.855]	-

Notes: p-values, based on robust standard errors, between square brackets. *, **, *** denotes significance at the 10%, 5%, 1% respectively. Instead of the estimated coefficients in (2), the table reports average partial effects. Whenever the effect of a variables is split in a pre- and post-1600 effect, the average partial effect is calculated using only the observation in the pre- or post-1600 period only. The p-values are however based on the estimated coefficients and their standard errors. In column 6 the results on the dummy variable indicating whether or not a location was already home to at least 1,000 inhabitants in century *t-1* are not shown, its APE is 0.099 and it is significant at the 1% level. In column 9 we show the percentage of simulations that each respective variable is significant at the 5% or < 10% > level. When interpreting the results, it is useful to keep in mind that the unconditional probability of becoming a city is about 12%.

navigable river increases substantially[50]. These findings correspond to many narrative accounts by (economic or urban) historians that document the increased dominance of water- over land-based transport in late Medieval and pre-modern Europe (Lopez, 1956; Bairoch, 1988; Hohenberg, 2004). Also, we again find that a location's agricultural possibilities as well as its accessibility (measured by its ruggedness) become less important over the centuries in determining city location.

The results on 2nd nature geography also confirm the results found in Table 2. Only in the later centuries of our sample do we find that locations at medium range (20 – 100km) from an already existing city have significantly higher urban chances than locations located too close to or too far away from existing urban centres. This significantly differs from the earlier centuries, when we do not find this effect. Instead we only find a significant negative effect on the urban chances of locations at very close range to an already existing city. Also, the negative competition effect with other potential city locations at close range is only significant in the pre-1600 period[51].

5.2.1 Robustness of our time-varying results

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[50] Location at sea does not play as significant a role in city location as location at a river, also not during the later centuries. Note that although its effect is insignificantly different from zero during the later centuries, we also reject that it is significantly different from the positive effect during the earlier centuries. Also, in some of the robustness checks we do find a significant role for location at sea in determining city location, but never does it play a more important role that location at a river.

[51] The post-1600 effect of competition at close range is not significant, but note that we also reject that it changed significantly compared to its pre-1600 effect.

Before discussing the implications of our findings, we first show that our main time-varying findings are very robust (even more than our baseline findings in Table 1). Besides the robustness checks we discuss in this section, Appendix A.3 and A.4 contain two additional robustness checks. Appendix A.3 shows the (in)sensitivity of our baseline findings to the particular absolute population cutoff used to define a city, and Appendix A.4 addresses possible concerns that our 2nd nature geography results may arise by construction due to the increased density of the European city system over the centuries.

Columns 2 – 4 are again aimed at addressing concerns regarding possible endogenous sample selection. See section 3.1 or 5.1.2 for a detailed discussion of this important issue. Column 2 shows that our main results, except for the competition effect at close range, hold up when also allowing for any time-invariant location-specific unobserved heterogeneity (in addition to any country-century specific unobserved heterogeneity). This effectively means that we (implicitly) include all possible potential city locations in our sample. We perfectly capture the (time-invariant) urban history of all locations that never developed into a city by allowing for location-specific fixed effects[52].

Column 3 and 4 instead address the issue of possible endogenous sample selection by extending, or completely changing the set of potential city locations considered in our estimations[53]. The results show that our main results hold up (even more than our baseline time-invariant results in Table 2) to either considering an additional 217 '1850 locations' as potential city locations throughout our 800-1800 sample period, or to considering a truly random sample from all possible coordinate pairs.

Next, column 5 (re-)confirms the insensitivity of our main results to excluding the UK, the earliest industrializing country, from the sample[54]. In column 6 we do not consider the eighteenth century. As shown in Figure A1 and Table A1 in Appendix A, the eighteenth century saw an unprecedented increase in the number of cities. Column 6 however shows that it is not only this episode that drives our results.

In column 7 we include an additional dummy variable indicating whether or not a

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[52] We only show results of estimating a conditional random effects probit model. Results when employing conditional logit or fixed effect linear probability models instead are very similar and available upon request. Also, using different specifications to capture possible time-varying unobserved heterogeneity (similar to column 3-5 in Table 1) does not change our main results.

[53] We do not show results when focussing on a sample of 'bishop 600' locations only (as in Table 2). The reason is that the severe reduction in sample size, resulting from focusing on this 'bishop 600' sample only, results in finding no significant differences between the pre- and post-1600 period for all our included variables, except for location on a navigable river. Results are available upon request.

[54] Our results are also fully robust to excluding either Italy, France or Spain (the countries with the most potential city locations) from the sample.

location was already reported in Bairoch et al. (1988) to have a population between 1,000 and 4,000. The inclusion of this variable most strongly affected the significance of our already-existing city dummy variables in Table 2 (see column 3). Column 7 shows that including this variable does not have such strong effects on our main time-varying results. We do however still find that locations with an already-reported number of inhabitants below 5,000 do have higher urban chances than other locations (about 10ppt higher, see the notes to Table 3).

Finally, the last robustness check reported in Table 3 deals with the important issue of measurement error. Bairoch et al. (1988) acknowledge that their population estimates are very likely to be imprecise, especially for the smaller cities and for the earlier centuries. As we are using a nonlinear transformation of the city population data (by estimating a probit model) such measurement error, even if it were random, could leave its effect on our results (see e.g. Hausman, 2001). To shed some light on this we adopt the following simulation strategy. We assume that each reported population estimate has a similar 40% probability of being misreported. Conditional upon being misreported, we subsequently assume that there is an equal, 25%, chance of being underestimated by 2,000 inhabitants, overestimated by 2,000 inhabitants, underestimated by 1,000 inhabitants, or overestimated by 1,000 inhabitants respectively. Assuming this structure for the measurement error implicitly assumes that Bairoch et al. (1988) made relatively bigger mistakes for smaller population numbers[55]. We generate 1,000 different population samples using this sampling strategy and do our baseline analysis for each of the 1,000 simulated samples. Column 9 reports the percentage of simulations that each variable is significant at a 5% and at a 10% level respectively. Under the assumption of measurement error, each of the 1,000 simulated samples is 'equally true'. If we find that a significant variable in our main results is less than 90% of the times significant at the 10% level, this would shed some doubts on the actual relevance of this variable.

The colum 9 results show that our main findings hold up to this measurement error check. The only exception is the positive effect of being located at sea that we found in the pre-1600 period. This is significant at the 10% level in our main results, yet it only comes up significant at the 10% level in 57% of the simulation runs. Also, both the effect of an already-existing city as well as of a competitor potential city location within a distance of 0-20km only reach their baseline significance level of 5% in the pre-1600 period in 89% and 92% of the simulations. Both variables are however significant at the 10% level in all simulation runs.

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[55] Bairoch (1988, p.525) explicitly remarks that the margin of error is larger for smaller cities. Overall, he expects a margin of error of about 10% for overall European city population around 1300 and 1500, increasing to 15% in 1000 and even 20% in 800.

5.3   The importance of our time-varying results

Overall, the time-varying impact of both 1st and 2nd nature geography is the most important refinement to our baseline results in Table 1. It reveals that the relevance of 1st and 2nd nature geography in determining city location changed substantially over the centuries.

The difference between the pre- and post-1600 1st nature geography results shows that, over our sample period, good access to water-based transport becomes much more important than being well situated for land-based transport. This corresponds nicely to earlier accounts by for example Lopez (1956) or Pirenne (1925). Also, it concurs with the notion that improvements in shipping technology [not only in the size and speed of the vessels used, but also in e.g. navigation (van Zanden and van Tielhof, 2009) and canal building (Bairoch, 1988)] were larger than those in land transportation despite the fact that e.g. horseshoes, rigid tandem horse collars, and the use of explosives to build tunnels, did all significantly improve land-based transportation (see Lopez, 1956). Also, the importance of a location's agricultural possibilites gradually diminishes over time. A finding that is not only consistent with improving agricultural methods, but also with the notion that in later centuries food could be transported over greater distances at lower costs due to improvements in transportation, hereby diminishing the 1st nature geography advantage of location right next to fields of high agricultural productivity.

The way the importance of 2nd nature geography changes over the centuries is consistent with predictions from theory (see e.g. Behrens, 2007; Fujita and Mori, 1997; or Duranton, 1999). In the early centuries we find that competition at close range, both with other cities and with other potential city locations, is the only significant 2nd nature geography determinant of a location's urban chances. As set out briefly in section 2.2, theory predicts that 2nd nature geography will become an important *positive* determinant of city location only when overall trade costs are sufficiently low, the advantages of co-locating in a city are sufficiently large compared to its disadvantages, and overall population is large enough to sustain multiple urban centres.

Each of these three developments occurred over our 1000 year sample period. Trade costs diminished substantially. Not only did transportation technology improve significantly (as discussed above), also the 'invention' of e.g. the bill of laden, insurance contracts (Greif, 2006 p.24), and other institutional and political changes that improved security and law[56] greatly reduced the costs of (long-distance) trade (Greif, 1992; Hohenberg, 2004 p.3025;

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[56] Lopez (1956, p.24): " *an English statute of 1285 ordered that along highways between market towns "there be no dyke, tree or bush whereby a man may lurk to do hurt within 200 feet of either side of the way"* "

Duranton, 1999 p.2177). Second, the advantage of co-locating in a city gradually increased due to improved non-agricultural production techniques (e.g. the blast furnace, finery forge, treadwheel crane, water- and windmills, and the printing press), while its disadvantages decreased (improved living conditions). And finally, overall European population increased markedly over our sample period, largely because of improvements in agricultural production (crop rotation, heavier plows, the introduction of new crops).

Our finding that 2nd nature geography only exerts a significant positive influence on a location's urban chances during the later centuries in our sample is consistent with these three developments. In earlier centuries trade costs were too high, and economies of scale and/or overall population (too) low, making 1st nature geography the dominant determinant of city location. Only with the gradual increase in economies of scale, a growing overall population and decreasing trade costs, do we start to find the positive effect of location at medium distance from existing cities that corresponds closely to the predictions from economic geography theory.

6. Refining 2nd nature geography

In this section we show that further refining the impact of already existing cities or competitor potential city locations respectively[57], provides some very useful additional insights into the role of 2nd nature geography in determining city location[58]. It also gives further confidence in our baseline 2nd nature geography results[59].

6.1 Refining the impact of already existing cities

Table 4 shows results of further refining the impact of already existing cities. In column 1 we replace our 'already existing city'-dummy variables with the standard urban potential measure specified in equation (1).

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[57] We could also further refine the impact of 1st nature geography by adding various interaction terms of our 1st nature geography dummy variables. Doing this generally gives the result that having a favourable location for both land- and water-transport (again river transport in particular) significantly increases a location's urban chances compared to favourable location for only one of the two transport modes. Adding these interaction terms leaves the baseline results regarding 2nd nature geography unchanged. They are available upon request.

[58] An even more elaborate way to refine our 2nd nature geography variables would be to take account of e.g. actual road or river systems, or the ruggedness of the terrain, and come up with more detailed indicators of travel distance between locations than our great circle distances. Aside from the additional data requirements, note that such extensions require making assumptions on the relative importance of each of the additionally considered characteristics in determining overall travel distances. We leave such extensions for future work.

[59] If we would for example find that the presence of an existing city larger than 25,000 inhabitants does exert a positive influence on potential city locations' urban chance within a 0 – 20 km range (whereas an existing city larger than 10,000 does not [i.e. our baseline result]), or that the presence of more than one competitor potential city location alleviates the negative influence of having only one such location within a 0 – 20 km range found in our baseline estimates, this would shed some doubts on our main findings.

Table 4. Extended 2nd nature geography – existing cities

P(city t | no city t-1)	1 (a) In UP cities >= 10k (b) - (c) -	2 (a) city >= 10k? (b) - (c) city >= 25k?	3 (a) city >= 10k? (b) city >= 5k? (c) city >= 25k?	4 (a) city >= 10k? (b) 2 cities >=10k? (c) -	5 (a) In dist near. city >= 10k (b) In pop near. city >= 10k (c) -
1st nature geography results are not reported. They correspond closely to those in column 2 of Table 1.					
(a) t-1					
0 - 20 km	-0.005	-0.001	-0.019	-0.003	0.001
	[0.624]	[0.960]	[0.142]	[0.735]	[0.779]
20 - 50 km	-	0.017***	0.014	0.010*	-
	-	[0.004]	[0.106]	[0.080]	-
50 - 100 km	-	0.005	0.008	0.004	-
	-	[0.426]	[0.394]	[0.516]	-
(b) t-1					
0 - 20 km	-	-	0.022**	-0.009	-0.002
	-	-	[0.024]	[0.696]	[0.457]
20 - 50 km	-	-	0.004	-0.002	-
	-	-	[0.612]	[0.797]	-
50 - 100 km	-	-	-0.005	0.012**	-
	-	-	[0.612]	[0.044]	-
(c) t-1					
0 - 20 km	-	-0.010	-0.010	-	-
	-	[0.489]	[0.475]	-	-
20 - 50 km	-	-0.019**	-0.019**	-	-
	-	[0.014]	[0.015]	-	-
50 - 100 km	-	0.009	0.009	-	-
	-	[0.146]	[0.134]	-	-

Results for the 'competitor potential city'-dummy variables are not reported. They correspond closely to those in column 2 of Table 1.

country/century FE	yes	yes	yes	yes	yes
nr observations	13228	13228	13228	13228	13228
p-values tests		H0: β_city>=10 >0?	H0: β_city >=10 >0?	H0: β_2 cities >=10 >0?	
0 - 20 km		-	[0.682]	[0.593]	
20 - 50 km		-	[0.005]***	[0.351]	
50 - 100 km		-	[0.793]	[0.011]**	
		H0: β_city >=25 >0?	H0: β_city >=25 >0?		
0 - 20 km		[0.375]	[0.517]		
20 - 50 km		[0.785]	[0.870]		
50 - 100 km		[0.031]**	[0.089]*		

Notes: p-values, based on robust standard errors, between square brackets. *, **, *** denotes significance at the 10%, 5%, 1% respectively. Instead of the estimated coefficients in (2), the table reports average partial effects. The p-values are however based on the estimated coefficients and their standard errors. All regressions contain the same 1st nature geography variables and the same 'competitor potential city'-dummy variables as in column 2 of Table 1. The estimated parameters on these variable correspond closely to those reported in column 2 of Table 1. They are available upon request. When interpreting the results, it is useful to keep in mind that the unconditional probability of becoming a city is about 12%.

The estimated effect of this measure is insignificant, corroborating our claim (see section 3.3.2) that such a measure is too restrictive to do justice to the patterns in the data. By assuming an always positive or always negative effect of other already existing cities, it is unable to uncover the nonlinear effect that already existing cities exert on the urban chances of their surroundings.

Second, columns 2 – 4 further specify the dummy variables included in our baseline estimations. Column 2 includes three additional dummy variables indicating the presence of *at least one already existing city larger than 25,000 inhabitants* in each of the three distance bands, and column 3 adds a further dummy variable per distance band indicating the presence of *at least one already existing city larger than 5,000 inhabitants.*

The results show an interesting pattern: the larger the distance between an existing city and a potential city location, the larger the existing city has to be to exert a positive influence on that potential city location's urban chances. Put differently, the larger an already existing city the larger its urban shadow (a finding that corresponds nicely with both earlier observations by e.g. Lösch (1940, p.126) or Ullman (1941, p.856), and with predictions from economic geography theory [see e.g. the discussion around figure 6 in Fujita et al., 1999]). This effect shows up in column 2 and 3 where the existence of a city larger than 5,000, 10,000 or 25,000 inhabitants only significantly positively affects the urban chances of potential city locations within 0 – 20km, 20 – 50km or 50 – 100km respectively (see the bottom of the table for the corresponding tests[60]).

A similar result follows from column 4. There we include additional dummies indicating the presence of *at least two cities larger than 10,000 inhabitants* in each of the three distance bands. We find that the presence of only one city larger than 10,000 inhabitants exerts a positive influence on the urban chances of locations at 20 – 50km. This significant positive effect disappears when there are more than one already existing cities at that distance. The opposite holds for the 50 – 100km distance band: at that distance there needs to be sufficient urban mass (i.e. at least two cities larger than 10,000 inhabitants) to have any positive influence on a potential location's probability to become a city[61].

Finally, in column 5, we completely abandon our distance bands and include the size of, and distance to, the nearest city larger than 10,000 inhabitants instead. The results show, as when including *UP* in column 1, that a priori imposing an always positive or always negative effect of either the size of, or the distance to, neighboring urban centres, is unable to do justice to the 2nd nature geography effects that are present in the data (these are only revealed when using our more flexible dummy specification). Both variables are insignificant.

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[60] Given the way the different dummy variables are specified (i.e. if there exists a city larger than 25,000 inhabitants within a certain distance band, not only the dummy variable indicating the presence of a city larger than 25,000 inhabitants will be 1, so will be the dummy variable indicating the presence of a city of at least 10,000 inhabitants), the p-values below the coefficients indicate whether or not the effect of a dummy variable is significantly different from the effect of having a smaller city within a distance band.

[61] We also find these results when including the total number of cities or the total urban population within each distance band instead of our dummy variables. Results available upon request.

6.2 Refining the impact of competitor locations

Table 5 shows the results of refining the impact of competitor potential city locations instead, modeling the impact of already existing locations as in the baseline.

Table 5. Extended 2nd nature geography – competitors / 1st nature geography

P(city t | no city t-1)	1 (a) 2 competitors? (b) -	2 (a) ln dist near. comp. (b) -	3 (a) sea/river competitor (b) hub competitor	
1st nature geography results are not reported. They correspond closely to those in column 2 of Table 1.				
Results for the 'already existing city'-dummy variables are not reported. They correspond closely to those in column 2 of Table 1.				
competitor potential city location? (t-1)				
0 - 20 km	-0.014**	-	-0.001	
	[0.022]	-	[0.847]	
20 - 50 km	-0.014	-	0.008	
	[0.24]	-	[0.431]	
50 - 100 km	0.012	-	-0.015	
	[0.666]	-	[0.543]	
(a) t-1			sea comp	river comp
0 - 20 km	-0.003	0.013***	0.004	-0.019**
	[0.657]	[0.002]	[0.631]	[0.011]
20 - 50 km	0.013	-	-0.018***	-0.006
	[0.107]	-	[0.005]	[0.31]
50 - 100 km	-0.047**	-	-0.010	-0.001
	[0.011]	-	[0.124]	[0.877]
(b) t-1			hub comp	
0 - 20 km	-	-	-0.014*	
	-	-	[0.092]	
20 - 50 km	-	-	-0.025***	
	-	-	[0.000]	
50 - 100 km	-	-	-0.015***	
	-	-	[0.006]	
country/century FE	yes	yes	yes	
nr observations	13228	13228	13228	
p-values tests	H0: $\beta_{2\ comp.}$ >0?	*p-values tests*	H0: $\beta_{1st\ nature\ comp.}$ >0?	
0 - 20 km	[0.011]**		sea	river
20 - 50 km	[0.923]	0 - 20 km	[0.738]	[0.005]***
50 - 100 km	[0.147]	20 - 50 km	[0.394]	[0.812]
		50 - 100 km	[0.314]	[0.503]
			hub	
		0 - 20 km	[0.112]	
		20 - 50 km	[0.165]	
		50 - 100 km	[0.218]	

Notes: p-values, based on robust standard errors, between square brackets. *, **, *** denotes significance at the 10%, 5%, 1% respectively. Instead of the estimated coefficients in (2), the table reports average partial effects. The p-values are however based on the estimated coefficients and their standard errors. All regressions contain the same 1st nature geography variables and the same 'already existing city'-dummy variables as in column 2 of Table 1. The estimated parameters on these variable correspond closely to those reported in column 2 of Table 1. They are available upon request. When interpreting the results, it is useful to keep in mind that the unconditional probability of becoming a city is about 12%.

Column 1 adds an additional dummy variable for each distance band indicating the presence of *at least two competitor potential city locations*. Having more than one competitor potential city location within 0 – 20km has a significant negative effect on a location's own urban

chances, but it does not significantly decrease these chances compared to having only one competitor potential city location at this distance[62]. Also, similar to having only one competitor, the presence of more than one competitor does not have any significant effect at larger distances than 20km (again see the p-values at the bottom of column 1).

Column 2 abandons the dummy approach and includes the distance to the nearest competitor potential city location instead. Again, we find a result that is consistent with our baseline findings. The further a potential city location is located from its nearest competitor, the better its urban chances.

Finally, column 3 builds on our baseline finding of a robust positive 1st nature geography effect of being located at a navigable river on a location's urban chances. This result immediately suggests the following implication. Suppose that two potential city locations are located close together. One has direct access to a navigable waterway whereas the other has not. The potential city location without this 1st nature geography advantage faces competition from a nearby potential city location with much better 1st nature geography characteristics. One can expect this potential city location to face much stiffer competition from its neighbour than a similar location facing competition from another potential city location that, like itself, does not have any 1st nature geography advantages. In other words, our baseline results imply that potential city locations face stronger competition effects from other potential city locations with advantageous 1st nature geography characteristics than from those without such an advantage.

To verify this, we include three additional dummy variables for each of the three distance bands. They indicate the presence of at least one competitor potential city location located at sea, at a navigable river, and at a hub of roman roads respectively. Doing this reveals (again also see the p-values at the bottom of column 3) that our baseline, negative, competition effect at close range can be largely attributed to competition with other potential city locations that are located at a navigable waterway. Other potential city locations without this river-advantage do not exert a significantly negative competition effect at 0 – 20km. Although the effect of competitors located at sea or at a hub of Roman roads is sometimes significantly different from the effect of a competitor without this 1st nature geography advantage [see the p-values below the APEs], their overall effect is never significantly different from zero [see the p-values at the bottom of column 3].

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[62] Similar to Table 4, the p-values below the coefficients indicate whether or not the effect of having at least two competitor potential city locations is significantly different from the effect of having only one competitor potential city location within one of the distance bands.

7.   Conclusions

Instead of the largely narrative historical accounts on the importance of geography in shaping the European system, this paper empirically disentangles the different roles of geography in determining the location of European cities. We introduce a new data set that covers all actual European cities as well as many potential city locations during the 800 – 1800 period, when the foundations for the eventual European city system were laid. Using this data, we empirically uncover the (relative) importance of a location's physical, 1st nature, geography characteristics and the, 2nd nature geography, characteristics of the urban system that surrounds it, in determining its urban chances. In doing so, we develop a novel, more flexible, way to empirically model the effect that an already established city exerts on the urban chances of its surroundings.

Our results, that hold up to a wide-variety of robustness checks, show that both 1st and 2nd nature geography played an important role in sowing the seeds of European cities, but very differently so. Most importantly, we find that their (relative) importance changes substantially over the centuries.

First nature geography is the dominant geographical force during the early stages of the formation of the European city system. Locations that are favourably located for water- or land-based transportation, as well as those with excellent agricultural possibilities and good accessibility, have the best urban chances during the Middle Ages. But, this dominance of 1st nature geography gradually decreases over the centuries. Only favourable location for water-based transportation remains an important determinant of city location during the later centuries. Combined with the decreasing importance of location at a hub of overland trade routes, this reflects the increasing importance of water- over land-based transportation. Also, a location's accessibility and the agricultural potential of its immediate hinterland loose their significance as a city seed during the later centuries. The latter a reflection of both improved agricultural production techniques as well as better (and cheaper) possibilities to transport food over ever larger distances.

Second nature geography instead gains in importance over the centuries. Moreover, and by virtue of our flexible modelling strategy, we show that it does so in a way that corresponds closely to predictions from economic geography theory (Behrens, 2007; Fujita and Mori, 1997). In the earlier centuries of our sample we only find evidence of (negative) competition effects with a limited spatial scope: being located too close to an already existing city, or to another competitor potential city location, decreases a location's own urban chances. By contrast, in the later centuries we start to find strong empirical evidence of a

positive effect of being located at medium distance from an already existing city. This finding is consistent with predictions from economic geography theory. With trade costs falling, the advantages of co-locating in cities increasingly outweighing its disadvantages, and overall population increasing due to improvements in agricultural productivity, locations at medium distance from existing cities become preferred city locations. They combine the advantage of cheaper trade with existing cities compared to locations at further distance, with that of weaker competition with existing cities compared to locations at closer distance.

Overall, our results show that geography indeed played a crucial role in laying the foundations of the European city system as we know it today. First nature geography was an especially important determinant of city location during the early stages of the formation of the European city system. Only from about the seventeenth century onwards, and as a result of falling trade costs and increasing net benefits of co-location, does 2nd nature geography become an important positive determinant of city location.

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Figure A1. Urbanization and the number of cities in Europe, 800 – 1800
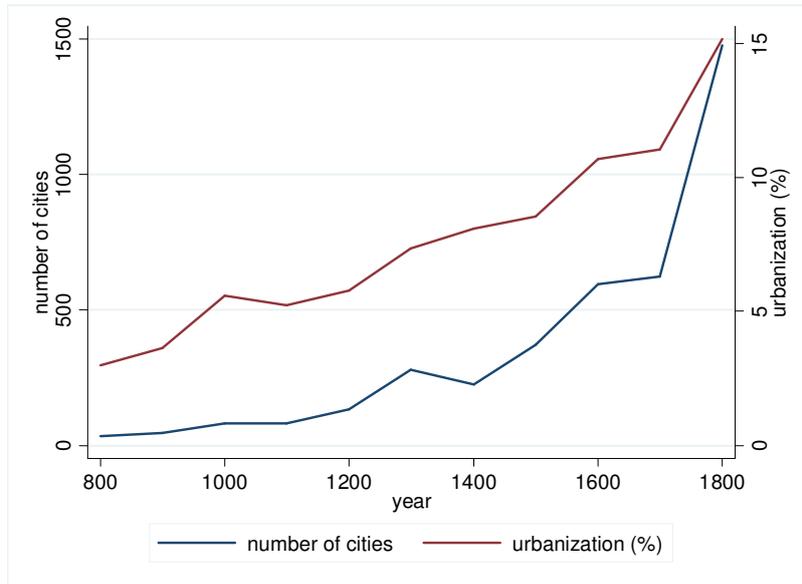
Notes: Both the number of cities and the urbanization rate are based on defining cities as population centres with at least 5,000 inhabitants [see section 3.2 for more detail on this definition]. The urbanization rate is calculated by dividing total urban population (i.e. the total number of people living in cities with at least 5,000 inhabitants) by total population. Total population figures are taken from McEvedy and Jones (1979).

Figure A2. Market potential curves with 1st nature geography

$$\Omega_1(x_1) = \Omega_{11}(x_1) + \Omega_{12}(x_1)$$
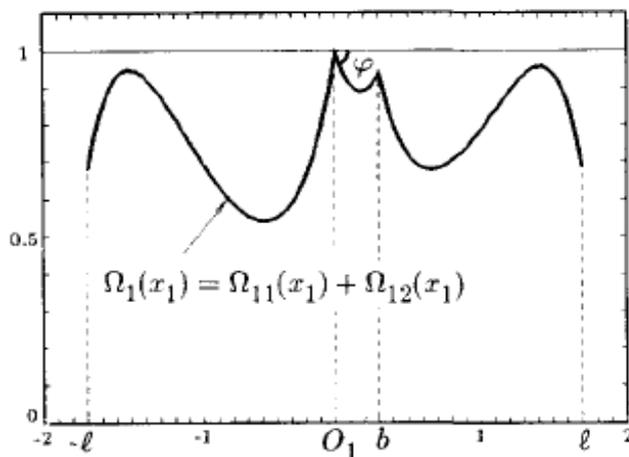
Notes: The figure is taken from Fujita and Mori (1996, p.109). The location at *b* has a first nature geography advantage in the ease of transporting goods (i.e. it is a hub location).

Figure A3 Ecozones according to Buringh et al. (1975)
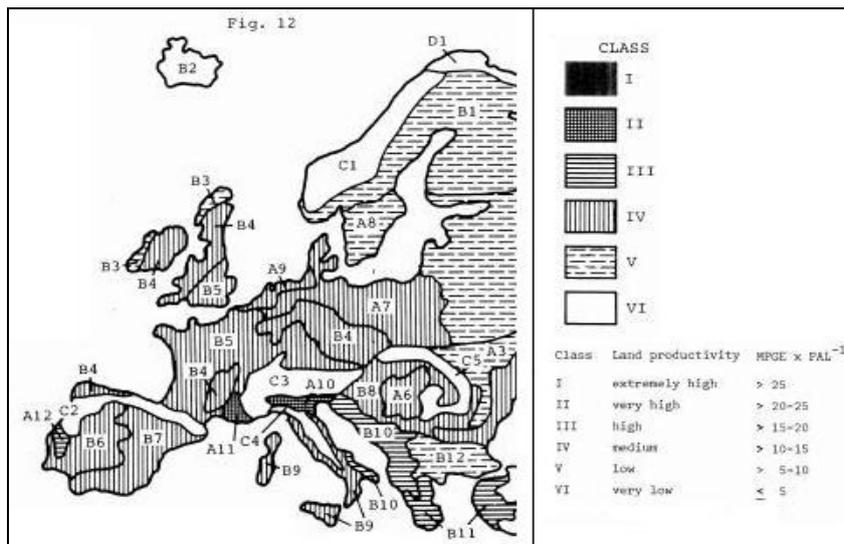
Figure A4a Additional potential city locations (Bairoch's 1850 cities)
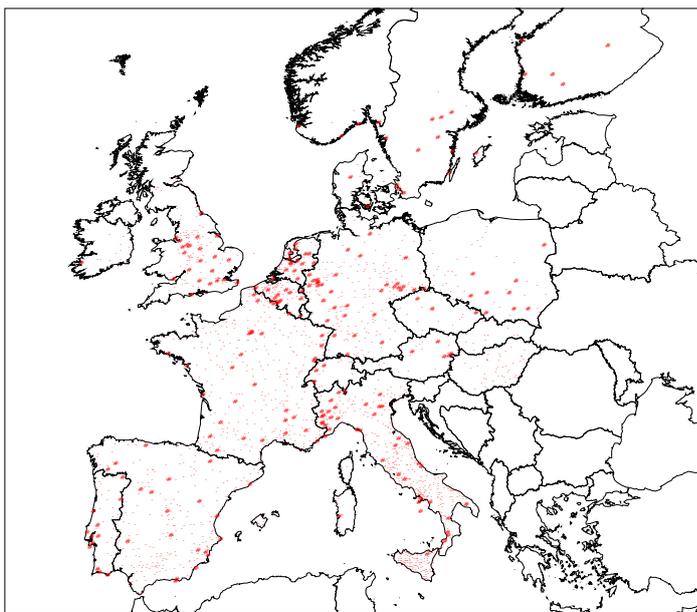
Notes: smallest red dots denote baseline potential city locations [see section 3.1 for more detail].The larger red dots denote the 217 additional '1850 Bairoch' potential city locations used in several robustness checks.

Figure A4b Random sample of coordinate pairs as potential city locations
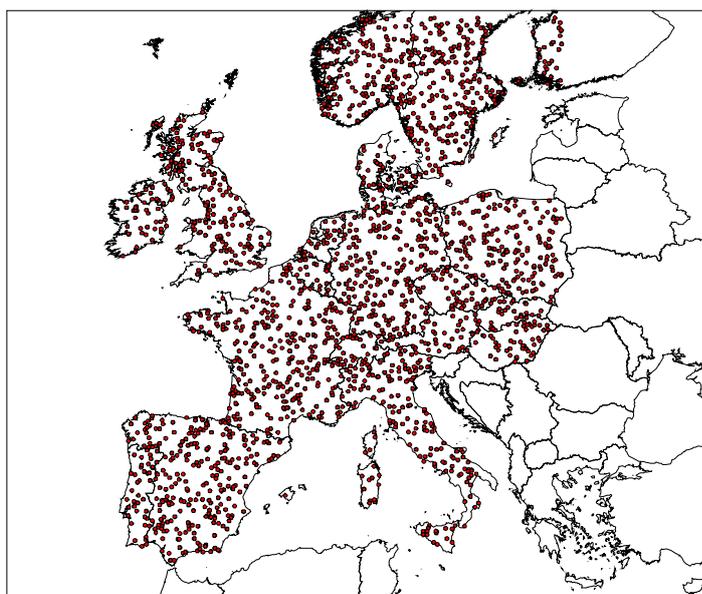
Notes: red dots denote the 2067 randomly drawn coordinates pairs used as potential city locations in column 10 of Table 2 and in column 4 of Table 3.

Table A1. Century specific probability of being a city

	city yes/no?	
year	no: nr (%)	yes: nr (%)
800	1750 (98)	34 (2)
900	1738 (97)	46 (3)
1000	1702 (95)	82 (5)
1100	1703 (96)	81 (5)
1200	1652 (93)	132 (7)
1300	1504 (84)	280 (16)
1400	1561 (88)	223 (13)
1500	1413 (79)	371 (21)
1600	1188 (67)	596 (33)
1700	1159 (65)	625 (35)
1800	306 (17)	1478 (83)

Table A4. Additional '1850 Bairoch' potential city locations by country

country	# obs.	% extra locations	country	# obs.	% extra locations
Austria	5	31	The Netherlands	16	36
Belgium	13	22	Norway	4	67
Czech Republic	3	18	Poland	9	20
Denmark	2	25	Portugal	12	36
Finland	6	600	Slovakia	0	0
France	27	8	Spain	20	8
Germany	33	16	Sweden	12	150
Hungary	0	0	Switzerland	4	27
Ireland	1	4	UK	22	15
Italy	28	6	**total**	**217**	12

Table A2. Potential city locations

country	# potential city locations (% total sample)	% potential city locations with a (arch)bishop in 600	% potential city locations to become city
Austria	16 (0.9)	25.0	75.0
Belgium	58 (3.3)	1.7	100
Czech Republic	17 (1.0)	0	100
Denmark	8 (0.4)	0	100
Finland	1 (0.1)	0	100
France	341 (19.1)	34.6	90.3
Germany	209 (11.7)	2.9	100
Hungary	48 (2.7)	4.2	97.9
Ireland	27 (1.5)	25.9	77.8
Italy	497 (27.9)	48.1	73.6
The Netherlands	44 (2.5)	2.3	100
Norway	6 (0.3)	0	100
Poland	46 (2.6)	0	100
Portugal	33 (1.8)	30.3	93.9
Slovakia	12 (0.7)	0	100
Spain	255 (14.3)	22.8	94.5
Sweden	8 (0.4)	0	100
Switzerland	15 (0.8)	33.3	86.7
UK	143 (8.0)	3.5	97.9
total	1784	25.6	89.0

Notes: The numbers in the third column are based on the city definition explained in section 3.2, i.e. population centres with at least 5,000 inhabitants.

Table A3. Descriptives

1st or 2nd nature characteristic	mean	sd	min	max	mean	sd	min	max
	all locations (1784)				locations ever >= 5,000 (1588)			
seaport	0.14	0.35	0	1	0.13	0.34	0	1
river	0.37	0.48	0	1	0.41	0.49	0	1
hub	0.15	0.36	0	1	0.13	0.34	0	1
rroad	0.42	0.49	0	1	0.37	0.48	0	1
elevation (m)	218	238	-4	1176	214	235	-4	1176
ruggedness	86.8	96.3	0	721	78.9	87.1	0	721
P(cultivation)	0.72	0.24	0.004	0.999	0.71	0.23	0.006	0.999
latitude	45.73	5.45	36.02	63.42	46.06	5.59	36.02	63.42
longitude	6.47	7.66	-9.28	23.25	6.10	7.70	-9.28	23.25
--------------	distance to other potential city location (km)				distance to other potential city location (km)			
median	1086	261	739	2024	1093	266	739	2024
nearest	22	20	1	390	22	20	1	390
--------------	distance to existing city >= 10k (km)				distance to existing city >= 10k (km)			
median	1046	295	502	2400	1047	301	502	2400
nearest	106	124	1	1424	107	128	1	1424
--------------	nr. cities >= 10k				nr. cities >= 10k			
0 – 20km	0.12	0.45	0	7	0.13	0.46	0	7
20 – 50km	0.62	1.23	0	12	0.64	1.27	0	12
50 – 100km	1.67	2.57	0	27	1.70	2.62	0	27
--------------	nr. competitors				nr. competitors			
0 – 20km	1.29	2.05	0	13	1.25	2.08	0	13
20 – 50km	5.86	6.39	0	37	5.63	6.32	0	37
50 – 100km	14.9	12.7	0	66	14.1	12.2	0	64

Table A5. A finer century decomposition

dependent variables: *P(city t | no city t-1)*

period	APE	[p-value]	period	APE	[p-value]
sea			sea		
800 - 900	0.040***	[0.000]	800 – 1000	0.024***	[0.005]
1000 - 1200	0.006	[0.414]	1100 – 1400	0.018*	[0.092]
1300 - 1500	0.008	[0.576]	1400 – 1600	0.007	[0.672]
1600 - 1800	0.007	[0.729]	1700 – 1800	-0.017	[0.522]
river			river		
800 - 900	0.021***	[0.001]	800 – 1000	0.025***	[0.000]
1000 - 1200	0.028***	[0.000]	1100 – 1400	0.056***	[0.000]
1300 - 1500	0.075***	[0.000]	1400 – 1600	0.065***	[0.000]
1600 - 1800	0.088***	[0.000]	1700 – 1800	0.098***	[0.000]
hub			hub		
800 – 900	0.014*	[0.067]	800 – 1000	0.040***	[0.000]
1000 – 1200	0.037***	[0.000]	1100 – 1400	0.034***	[0.001]
1300 – 1500	0.040***	[0.003]	1400 – 1600	0.031**	[0.042]
1600 – 1800	-0.069***	[0.001]	1700 – 1800	-0.111***	[0.000]
ruggedness			ruggedness		
800 – 900	-0.001	[0.832]	800 – 1000	-0.005**	[0.031]
1000 – 1200	-0.006***	[0.001]	1100 – 1400	-0.009***	[0.004]
1300 – 1500	-0.014***	[0.001]	1400 – 1600	-0.014***	[0.003]
1600 – 1800	-0.002	[0.725]	1700 – 1800	0.007	[0.409]
roman road	-0.008	[0.198]	roman road	-0.008	[0.155]
ln elevation	0.002	[0.422]	ln elevation	0.002	[0.423]
P(cultivation)	0.124***	[0.001]	P(cultivation)	0.118***	[0.002]
P(cultivation) * trend	-0.014***	[0.002]	P(cultivation) * trend	-0.013***	[0.004]
city >= 10k? (t-1) 0-20km			city >= 10k? (t-1) 0-20km		
800 – 900	-	-	800 – 1000	-	-
1000 – 1200	-0.021	[0.321]	1100 – 1400	-0.035*	[0.073]
1300 – 1500	-0.035*	[0.060]	1400 – 1600	-0.022	[0.23]
1600 – 1800	0.019	[0.307]	1700 – 1800	0.036	[0.108]
city >= 10k? (t-1) 20-50km			city >= 10k? (t-1) 20-50km		
800 – 900	0.007	[0.357]	800 – 1000	0.006	[0.416]
1000 – 1200	0.001	[0.808]	1100 – 1400	-0.017**	[0.040]
1300 – 1500	-0.015	[0.130]	1400 – 1600	0.021**	[0.047]
1600 – 1800	0.042***	[0.002]	1700 – 1800	0.034**	[0.044]
city >= 10k? (t-1) 50-100km			city >= 10k? (t-1) 50-100km		
800 – 900	-0.011*	[0.088]	800 – 1000	-0.008	[0.119]
1000 – 1200	0.001	[0.767]	1100 – 1400	0.000	[0.954]
1300 – 1500	-0.012	[0.185]	1400 – 1600	0.023**	[0.040]
1600 – 1800	0.062***	[0.000]	1700 – 1800	0.035	[0.125]
competitor potential city location? (t-1) 0-20km			competitor potential city location? (t-1) 0-20km		
800 – 900	0.008	[0.121]	800 – 1000	-0.006	[0.266]
1000 – 1200	-0.012**	[0.028]	1100 – 1400	-0.006	[0.459]
1300 – 1500	-0.014	[0.138]	1400 – 1600	-0.026**	[0.014]
1600 – 1800	-0.020	[0.147]	1700 – 1800	-0.011	[0.514]
competitor potential city location? (t-1) 20-50km			competitor potential city location? (t-1) 20-50km		
800 – 900	-0.002	[0.865]	800 – 1000	-0.002	[0.879]
1000 – 1200	-0.007	[0.488]	1100 – 1400	-0.023*	[0.075]
1300 – 1500	-0.020	[0.219]	1400 – 1600	-0.028	[0.149]
1600 – 1800	-0.004	[0.870]	1700 – 1800	0.034	[0.296]
competitor potential city location? (t-1) 50-100km			competitor potential city location? (t-1) 50-100km		
800 – 900	-0.076**	[0.020]	800 – 1000	-0.068*	[0.094]
1000 – 1200	0.483***	[0.000]	1100 – 1400	0.027	[0.409]
1300 – 1500	-0.024	[0.561]	1400 – 1600	-0.021	[0.674]
1600 – 1800	-0.057	[0.322]	1700 – 1800	-0.110	[0.112]

Notes: p-values, based on robust standard errors, between square brackets. *, **, *** denotes significance at the 10%, 5%, 1% respectively. Instead of the estimated coefficients in (2), the table reports average partial effects. The p-values are however based on the estimated coefficients and their standard errors. The 0 – 20km version of the 'already existing city'-dummy variable drops out during the earliest centuries as it is perfectly captured by the included country-century fixed effects.

A.1 Robustness to choice of estimation technique

The additional robustness checks reported in Table A6 below all concern the estimation technique that we use to obtain our baseline results in Table 1.

Table A6. Robustness (estimation technique)

P(city t | no city t-1)	1 logit	2 LP	3 cox duration model	4 FE logit[a]	5 FE LP
sea	0.011	0.010	1.083	-	-
	[0.238]	[0.191]	[0.355]	-	-
river	0.062***	0.050***	1.532***	-	-
	[0.000]	[0.000]	[0.000]	-	-
hub	0.013	0.010	1.123	-	-
	[0.144]	[0.187]	[0.160]	-	-
road	-0.013**	-0.012**	0.858***	-	-
	[0.025]	[0.018]	[0.002]	-	-
ln elevation	0.003	0.003	1.036	-	-
	[0.238]	[0.187]	[0.114]	-	-
ruggedness	-0.008***	-0.007***	0.924***	-	-
	[0.004]	[0.003]	[0.001]	-	-
P(cultivation)	0.132***	0.036**	4.123***	-	-
	[0.002]	[0.050]	[0.003]	-	-
P(cultivation) * trend	-0.015***	-0.005	0.864***	0.018	-0.001
	[0.004]	[0.229]	[0.001]	[0.925]	[0.787]
city >= 10k? (t-1)					
0 - 20 km	0.000	-0.001	0.981	0.028	-0.004
	[0.979]	[0.912]	[0.747]	[0.933]	[0.832]
20 - 50 km	0.011**	0.011**	1.088*	0.758***	0.039***
	[0.041]	[0.049]	[0.052]	[0.000]	[0.000]
50 – 100 km	0.011*	0.008*	1.099*	-0.092	0.007
	[0.056]	[0.071]	[0.060]	[0.621]	[0.325]
competitor potential city location? (t-1)					
0 - 20 km	-0.014***	-0.012**	0.917**	-0.165	-0.024
	[0.007]	[0.012]	[0.046]	[0.664]	[0.294]
20 - 50 km	-0.007	-0.008	0.923	-0.798*	-0.018
	[0.47]	[0.471]	[0.305]	[0.064]	[0.524]
50 – 100 km	-0.027	-0.022	0.843	0.376	0.059
	[0.261]	[0.329]	[0.325]	[0.431]	[0.118]
country/century FE	yes	yes	yes	country trends + century FE	yes
nr observations	13228	15156	14594	13220	15156
		# (%) of-the-chart predictions			# (%) of-the-chart predictions
		in sample 2614 (17%)			in sample 4229 (28%)
		total 7082 (36%)			total 8697 (44%)

Notes: p-values, based on robust standard errors, between square brackets. *, **, *** denotes significance at the 10%, 5%, 1% respectively. Instead of the estimated coefficients in (2), the table reports average partial effects. The p-values are however based on the estimated coefficients and their standard errors. Column (3) reports hazard rates instead of estimated coefficients, i.e. a hazard rate larger (smaller) than 1 indicates that the corresponding characteristic increases (decreases) the probability to become a city. [a]Given that one cannot calculate average partial effects after estimating a conditional logit model, column (4) reports estimated coefficients. When including country-century FE, conditional logit estimation has difficulties converging which is why in this column we include time dummies and country-specific time trends instead. Given that we do not include country-century FE, we also include ln country population and D ln country population in the estimated model. The estimated coefficients [p-values] on these variables are 5.343 [0.000] and 5.358 [0.000] respectively.

Instead of assuming *F* to be the standard normal CDF, column 1 and 2 show the results when taking the logistic distribution function or the identity function instead, and estimating (2) using logit or OLS techniques respectively. All our main baseline results do not crucially depend on the assumption made on *F*.

Our column 3 results show that our baseline results also come through when we completely change our modelling strategy and adopt a duration model (of the time until becoming a city) instead of the transition model (becoming a city conditional upon not being a city before) that we employ throughout the paper. Using a duration model can be argued to take better account of any duration-dependence in the probability of becoming a city (i.e. this probability may not be the same depending on the time a location has already not become a city). Although the inclusion of country-century fixed effects in all our baseline specifications can be argued to already go a long way in controlling for duration-dependence [in duration terms: they allow the baseline hazard to (arbitrarily) change over the centuries in a moreover possibly different way across countries], it is reassuring that we basically find the same results when adopting a semi-parametric Cox proportional hazard model. Column 3 reports hazard ratios. A hazard ratio significantly larger than 1 indicates that the corresponding characteristic increases a location's baseline hazard to become a city. Similarly, a hazard ratio significantly smaller than 1 indicates that the corresponding characteristic decreases a location's baseline hazard to become a city (e.g. location on a navigable river increases a location's baseline hazard to become a city by 53.2%, the presence of a competitor potential city location within a 0 – 20km range decreases it by 8.3%, and the presence of an already existing city within a 20-50km range increases it by 8.8%).

As in columns 1 and 2, the results in columns 4 and 5 are also based on using either logit or linear probability techniques, but in these two columns we, in addition to controlling for unobserved *country-century* specific heterogeneity, control for unobserved *time-invariant location-specific* heterogeneity. As such, these two columns are readily comparable to column 6 in Table 1 that employs a CRE-probit estimation strategy. Instead of sticking to this CRE probit technique, one could instead turn to a conditional logit approach, that by virtue of the properties of the logistic function, allows one to condition out the unobserved location-specific heterogeneity without making any explicit assumptions about its nature (as CRE probit does, see the specification on p. 22). However, because the unobserved heterogeneity is conditioned out, one can no longer calculate APEs which requires actual estimates of the unobserved location-specific effects [see (3)]. A big cost, as it becomes impossible to say anything about the absolute magnitude of the effect of any of the included variables on a

location's urban chances. Another alternative is to turn to a simple linear probability model and employ standard linear fixed effect panel data estimation techniques. However, the linear probability model does not take account of the fact, as both probit and logit do, that the dependent variable is restricted to the [0,1] interval. It can result in severe off-the-chart predictions (especially so in the fixed effects case – see the bottom of column 2 and 5).

Column 4 and 5 show the results of using each of the two above-mentioned different methods to control for unobserved time-invariant location-specific heterogeneity. As in column 6 of Table 1, in both cases the effect of 2nd nature geography is somewhat weakened compared to our main baseline results in column 2 of Table 1. We no longer find evidence of any significant competition effect among potential city locations at close range. The nonlinear effect exerted by an already existing city is however still present: locations at medium distance (20-50km) from an already existing city have a significantly higher probability to become a city than those located closer to, or farther away from, that city.

A.2   *Changing the distance bands*

Another set of robustness checks we did, concerns the sensitivity to the chosen distance bands (0 – 20km, 20 – 50km and 50 – 100km) to construct our 2nd nature geography variables. Table A7 shows the results using various different distance bands[63].

Doing this leaves the effect of a competitor potential city location largely unaffected: a competitor potential city location at too close distance always diminishes a location's urban chances and is quite insensitive to the specific distance band used.

Similarly, the effect of an already existing city is also largely unaffected. Changing only the lowest distance cutoff to 15 or 25 km in column 1 and 2 respectively leaves the results unchanged. Being located too close to an existing city has a (significantly) negative on a location's urban chances. The positive effect of an already existing city at medium distance is also very robust to making small changes in the lowest distance cutoff. Its significance falls slightly when decreasing the lowest distance cutoff (see column 1), an indication that at this distance the 2nd distance band starts to overlap too much with the existing city's urban shadow[64].

The results are most sensitive to the specification of the third distance band (see columns 3 – 5). When changing one of this band's cutoff distances (its lower distance

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[63] Our pre- and post-1600 results are also robust to the same changes in distance bands as presented in Table A7. Results are available upon request.
[64] It turns insignificant when further lowering the first distance cutoff to 10km.

Table A7. Robustness: using different distance bands (whole sample)

P(city t | no city t-1)	x = 15 y = 50 z = 100	x = 25 y = 50 z = 100	x = 20 y = 40 z = 100	x = 20 y = 60 z = 100	x = 20 y = 50 z = 125	baseline + 100 – 150 km 150 – 200 km
sea	0.013	0.012	0.012	0.013	0.012	0.013
	[0.136]	[0.157]	[0.183]	[0.148]	[0.179]	[0.127]
river	0.061***	0.061***	0.061***	0.061***	0.061***	0.061***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
hub	0.015*	0.014*	0.015*	0.015*	0.014*	0.014*
	[0.072]	[0.073]	[0.071]	[0.067]	[0.075]	[0.08]
road	-0.010*	-0.010*	-0.011*	-0.010*	-0.010*	-0.010*
	[0.067]	[0.076]	[0.065]	[0.071]	[0.082]	[0.077]
ln elevation	0.002	0.002	0.002	0.002	0.002	0.002
	[0.332]	[0.397]	[0.375]	[0.308]	[0.369]	[0.400]
ruggedness	-0.008***	-0.008***	-0.008***	-0.008***	-0.008***	-0.008***
	[0.002]	[0.001]	[0.001]	[0.001]	[0.001]	[0.002]
P(cultivation)	0.112***	0.115***	0.117***	0.112***	0.115***	0.110***
	[0.002]	[0.002]	[0.001]	[0.002]	[0.002]	[0.003]
P(cultivation) * trend	-0.013***	-0.013***	-0.013***	-0.013***	-0.013***	-0.013***
	[0.004]	[0.003]	[0.003]	[0.004]	[0.004]	[0.005]
city >= 10k? (t-1)						
0 - x km	-0.005	-0.012*	-0.002	-0.003	-0.003	-0.003
	[0.617]	[0.084]	[0.772]	[0.755]	[0.737]	[0.749]
x - y km	0.009*	0.015***	0.010*	0.011**	0.010*	0.010*
	[0.091]	[0.005]	[0.078]	[0.025]	[0.053]	[0.057]
y - z km	0.009*	0.010*	0.005	0.008	0.006	0.009
	[0.083]	[0.064]	[0.362]	[0.132]	[0.365]	[0.107]
100 – 150 km	-	-	-	-	-	0.008
	-	-	-	-	-	[0.159]
150 – 200 km	-	-	-	-	-	-0.001
	-	-	-	-	-	[0.907]
competitor potential city location ? (t-1)						
0 - x km	-0.011**	-0.014***	-0.014***	-0.014***	-0.014***	-0.015***
	[0.043]	[0.01]	[0.007]	[0.006]	[0.006]	[0.004]
x - y km	-0.013	-0.007	-0.011	-0.027**	-0.006	-0.007
	[0.228]	[0.448]	[0.123]	[0.036]	[0.516]	[0.468]
y - z km	-0.028	-0.032	-0.035	-0.025	-0.063*	-0.024
	[0.243]	[0.173]	[0.235]	[0.192]	[0.060]	[0.308]
100 – 150 km	-	-	-	-	-	-0.049
	-	-	-	-	-	[0.135]
150 – 200 km	-	-	-	-	-	0.000
	-	-	-	-	-	[0.995]
country/century FE	yes	yes	yes	yes	yes	yes
nr observations	13228	13228	13228	13228	13228	13228

Notes: p-values, based on robust standard errors, between square brackets. *, **, *** denotes significance at the 10%, 5%, 1% respectively. Instead of the estimated coefficients in (2), the table reports average partial effects. The p-values are however based on the estimated coefficients and their standard errors. When interpreting the results, it is useful to keep in mind that the unconditional probability of becoming a city is about 12%.

cutoff in columns 3 and 4, or its highest distance cutoff in column 5), the positive effect of an already existing city in the furthest distance band turns insignificant. Finally, the last column shows the results when adding two additional distance bands (100 – 150 km, and 150 – 200 km) to our baseline model. Again our baseline results come through. The results on the two added distance bands further confirm the nonlinear effect that an existing city exerts on its

surroundings: both the presence of an already-existing city within 100 – 150 km or within 150 – 200 km does not significantly affect a location's urban chances.

Overall, the negative competition effect at close range and the positive effect of an existing city at medium range are the two baseline results that are most robust to changes in the distance bands.

A.3   Changing the city definition

In addition to assessing the sensitivity of our results to possible measurement error (see column 8 in Table 3), we also looked at the sensitivity of our results with respect to our city definition based on an *absolute* population cutoff of having at least 5,000 inhabitants. Table A8 shows the results when using a different absolute cutoff, or a time-varying population cutoff instead. Note that in each column we also change the definition of a competitor potential location accordingly (when e.g. increasing our size criterion to 6,000 inhabitants we also consider all locations that, at *t-1*, have fewer than 6,000 inhabitants as competitor potential city locations).

In columns 2 and 3, we lower our absolute population criterion to 3,000 and 4,000 inhabitants respectively. Bairoch et al. (1988) only provide these population numbers for a very limited set of city locations, stressing that these numbers are subject to a much greater margin of error than those larger or equal than 5,000 inhabitants (see also our discussion of the results in column 3 of Table 2). However, when taking this data seriously in columns 2 and 3, we find that doing this leaves our baseline results unchanged.

This is not the case when raising our population cutoff. When increasing our population cutoff to 6,000 inhabitants, our main results still come through. However, when increasing it to 7,000 inhabitants, we find a slight change to our 2nd nature geography results that is further exacerbated when increasing the population cutoff to 10,000 inhabitants. In particular, we find that the positive effect of having an already existing city at medium distance disappears when raising our population cutoff. The positive effect is still there at 20 – 50km and at 50 – 100km when raising the criterion to 6,000 inhabitants. When raising it to 7,000 inhabitants the effect only remains in the farther 50 – 100 km range. Raising it even further to 10,000 inhabitants, the positive effect disappears entirely.

However, this result does not necessarily invalidate our baseline results. In combination with our baseline findings in column 1 of Table 3, the results in columns 2 – 5 show a consistent pattern: the positive effect of an already existing city at medium distances

Table A8. Sensitivity to the choice of city definition

P(city t | no city t-1)	>= 3,000	>= 4,000	>= 6,000	>= 7,000	>= 10,000	step-wise
sea < 1600	0.021**	0.021***	0.011*	0.008	0.008	0.009
	[0.013]	[0.008]	[0.090]	[0.187]	[0.121]	[0.204]
sea >= 1600	-0.023	-0.003	0.027	0.016	0.045***	0.045**
	[0.340]	[0.883]	[0.207]	[0.407]	[0.003]	[0.012]
river < 1600	0.058***	0.052***	0.041***	0.037***	0.028***	0.047***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
river >= 1600	0.107***	0.099***	0.065***	0.061***	0.060***	0.058***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
hub < 1600	0.042***	0.042***	0.029***	0.029***	0.018***	0.033***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
hub >= 1600	-0.088***	-0.090***	-0.024	-0.013	-0.014	-0.014
	[0.000]	[0.000]	[0.225]	[0.479]	[0.272]	[0.395]
ruggedness < 1600	-0.010***	-0.010***	-0.008***	-0.007***	-0.005***	-0.009***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.001]	[0.000]
ruggedness >= 1600	-0.008	-0.003	-0.010	-0.006	-0.013***	-0.011**
	[0.317]	[0.699]	[0.143]	[0.320]	[0.005]	[0.047]
roman road	-0.011*	-0.011*	-0.003	-0.001	0.008*	0.003
	[0.081]	[0.061]	[0.634]	[0.839]	[0.061]	[0.536]
ln elevation	0.004*	0.004	0.002	-0.001	-0.003*	0.000
	[0.091]	[0.127]	[0.461]	[0.540]	[0.099]	[0.862]
P(cultivation)	0.116***	0.117***	0.099***	0.095***	0.071***	0.102***
	[0.004]	[0.002]	[0.003]	[0.002]	[0.003]	[0.002]
P(cultivation) * trend	-0.013***	-0.013***	-0.011***	-0.011***	-0.007***	-0.013***
	[0.008]	[0.005]	[0.003]	[0.003]	[0.008]	[0.002]
city >= 10k? (t-1)			**0 - 20 km**			
< 1600	-0.037***	-0.031***	-0.015	-0.008	-0.006	-0.025**
	[0.004]	[0.008]	[0.104]	[0.306]	[0.454]	[0.021]
>= 1600	0.027	0.022	0.015	0.024	0.018	0.015
	[0.206]	[0.266]	[0.400]	[0.153]	[0.145]	[0.349]
city >= 10k? (t-1)			**20 - 50 km**			
< 1600	-0.005	-0.009	-0.001	0.000	0.002	-0.004
	[0.398]	[0.123]	[0.761]	[0.955]	[0.657]	[0.412]
>= 1600	0.041***	0.044***	0.023*	0.018	-0.001	0.011
	[0.007]	[0.002]	[0.087]	[0.147]	[0.928]	[0.335]
city >= 10k? (t-1)			**50 - 100 km**			
< 1600	-0.005	-0.006	0.002	0.000	-0.002	-0.005
	[0.324]	[0.228]	[0.585]	[0.952]	[0.498]	[0.237]
>= 1600	0.071***	0.063***	0.037**	0.045***	0.017	0.037***
	[0.000]	[0.001]	[0.025]	[0.004]	[0.143]	[0.007]
competitor potential city location? (t-1)			**0 - 20 km**			
< 1600	-0.012**	-0.011**	-0.011**	-0.009**	-0.006*	-0.012**
	[0.031]	[0.029]	[0.013]	[0.029]	[0.057]	[0.017]
>= 1600	-0.027*	-0.032**	-0.014	-0.007	0.011	0.004
	[0.089]	[0.032]	[0.294]	[0.577]	[0.241]	[0.717]
competitor potential city location? (t-1)			**20 - 50 km**			
< 1600	-0.019*	-0.013	-0.001	0.002	0.006	-0.010
	[0.052]	[0.132]	[0.863]	[0.816]	[0.352]	[0.263]
>= 1600	0.016	-0.003	-0.006	0.003	-0.014	-0.019
	[0.582]	[0.907]	[0.803]	[0.893]	[0.445]	[0.368]
competitor potential city location? (t-1)			**50 - 100 km**			
< 1600	-0.011	-0.018	-0.013	-0.011	-0.023	-0.022
	[0.658]	[0.45]	[0.547]	[0.529]	[0.128]	[0.355]
>= 1600	-0.037	-0.102*	-0.036	-0.077	-0.001	-0.033
	[0.568]	[0.096]	[0.548]	[0.147]	[0.972]	[0.51]
country/century FE	yes	yes	yes	yes	yes	yes
nr observations	12814	13139	13828	14084	13832	13370

TABLE A8 CONTINUED	p-value H0: pre 1600 = post 1600					
sea	[0.014]**	[0.051]**	[0.775]	[0.717]	[0.297]	[0.258]
river	[0.151]	[0.111]	[0.001]***	[0.001]***	[0.073]*	[0.015]**
hub	[0.000]***	[0.000]***	[0.000]***	[0.000]***	[0.000]***	[0.000]***
ruggedness	[0.083]*	[0.006]***	[0.049]**	[0.023]**	[0.826]	[0.189]
city >= 10k? (t-1)						
0 - 20 km	[0.002]***	[0.005]***	[0.066]*	[0.106]	[0.176]	[0.015]
20 - 50 km	[0.012]**	[0.001]***	[0.177]	[0.327]	[0.691]	[0.205]
50 - 100 km	[0.000]***	[0.001]***	[0.163]	[0.024]**	[0.120]	[0.004]***
competitor? (t-1)						
0 - 20 km	[0.902]	[0.902]	[0.289]	[0.229]	[0.029]**	[0.065]*
20 - 50 km	[0.094]*	[0.367]	[0.962]	[0.935]	[0.229]	[0.968]
50 - 100 km	[0.927]	[0.529]	[0.953]	[0.635]	[0.271]	[0.859]

Notes: the last column shows the results when employing a step-wise city definition, i.e. from 800 – 1500 the size criterion is >= 5,000 inhabitants, from 1600 – 1700 it is >= 6,000, and in 1800 it is >= 10,000. p-values, based on robust standard errors, between square brackets. *, **, *** denotes significance at the 10%, 5%, 1% respectively. Instead of the estimated coefficients in (2), the table reports average partial effects. Whenever the effect of a variables is split in a pre- and post-1600 effect, the average partial effect is calculated using only the observation in the pre- or post-1600 period only. The p-values are however based on the estimated coefficients and their standard errors.

gradually disappears when raising the absolute size criterion used to define a city. Having an existing city at medium range may significantly improve a location's probability of becoming a city of 5,000 or 6,000 inhabitants, it becomes increasingly difficult to grow larger in the shadow of an already existing urban centre. An existing city, as it were, does only tolerate moderately sized new cities to appear in its immediate backyard.

Note that when raising the absolute size criterion to 10,000 inhabitants we also find two additional changes in the post-1600 period results. First, location at sea starts to exert a positive influence on locations' urban chances. Second, ruggedness does not lose its negative influence on city location. The former confirms the notion that location at sea becomes increasingly important in order to attract larger numbers of inhabitants (see e.g. the results in Acemoglu et al. (2005) that find that location at sea (and at Atlantic shores in particular) has strong effects on city size when focussing on a sample of cities with more than 10,000 inhabitants. The latter is an indication that locations in more rugged areas find it more difficult to host larger urban populations.

Finally, column 7 shows results when using a time-varying population cutoff to define a city. We employ the following step-wise increasing population cutoff: 5,000 inhabitants before 1600, 6,000 in 1600 and 1700, and 10,000 in 1800. We choose this particular stepwise increase as it leaves the unconditional probability of becoming a city in any century around 11% in the period 1500 – 1800 (instead of increasing substantially over this period when using our absolute 5,000 inhabitants cutoff). Using such a time-varying definition is in itself not without difficulties. In particular, given that we condition on not already being a city in *t-1* and include our three 'competitor potential city location'-dummies one century lagged (i.e. in

t-1), one has to choose which definition to use when constructing these variables (i.e. the 'new' definition in period *t* or the 'old' definition in period *t-1*). To give an example, say we increase our city definition in period *t* from 5,000 to 6,000 inhabitants. Should we, in period *t*, look at the probability of a location becoming a city (at least 6,000 inhabitants) given that it was not a city in period *t-1* according to its new definition in period *t* (at least 6,000 inhabitants) or to its old definition in period *t-1* (at least 5,000 inhabitants)? Similarly, should we define competitor potential city locations in period *t-1* as locations with less than 5,000 or less than 6,000 inhabitants?

In column 7 we use the city definition in period *t-1* to construct all our century lagged variables and our conditioning variable (i.e. was there a city in period *t-1*)[65]. The results show that our main findings are again generally robust to using this time-varying city-definition. Only the effect of an already existing city within 20 - 50 km is no longer significant (similar to our results when using an absolute cutoff of 7,000 inhabitants), and location at sea and ruggedness remain significant determinants of city location in the post-1600 period (echoing the results when using an absolute cutoff of 10,000 inhabitants).

Appendix A.4 A final robustness check: 2nd nature geography results by construction?

Given the steady increase in the number of cities over the centuries, one may be worried that especially our 2nd nature geography results could be obtained by construction. Europe's urban system becomes denser over the centuries. Besides decreasing the number of potential city locations, this has its effect on our 2nd nature geography variables. The number of potential city locations in vicinity to already existing cities increases, whereas the number of potential city locations facing competition from other potential city locations decreases. Does this change in variation drive our finding of a changing importance of 2nd nature geography over the centuries?[66].

To assess this possibility we adopt the following *Dartboard Approach* in the spirit of Duranton and Overman (2005) and Ellison and Glaeser (1997) as our final robustness check[67]. Using a simulation approach we verify whether we would obtain the same results regarding our 2nd nature geography variables when cities appeared randomly at one of our potential

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[65] This choice is arbitrary however. The results are also robust to using the city definition in period *t* instead. Also using a different 'step-wise' city definition (i.e. 5,000 before 1800 and 10,000 in 1800) all our baseline results come through. These results are available upon request.

[66] Note that this issue is different, yet related, to the possibility of dynamic selection bias. However, where dynamic selection bias concerns the dependent variable, the concern that we address here is that the increasing number of cities over time affects our 2nd nature geography regressors with possibly unwanted consequences for our results.

[67] We thank Marius Brülhart for suggesting this approach to us.

locations instead of at the locations where they appeared in reality. If we do, this means we could be getting our results by construction, shedding doubts on our findings. This *Dartboard Approach* is operationalized as follows:

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1. In each century t, randomly allocate n_t cities, the number of new cities actually appearing in century t, over the k_t available potential city locations in that century. We do this either:

   a. *unconditionally*, i.e. $n_t \sim Binomial(k_t, p_t)$, where $p_t = n_t / k_t$

   b. *conditional on each potential city location's 1st nature geography characteristics, i.e.* $n_t \sim Binomial(k_t, p_t(X_i))$, where $p_t = \Phi(X_i b + a_{ct})$ and *b* an a_{ct} are the estimated parameters on our included 1st nature geography variables and the estimated country-century fixed effects respectively, obtained by estimating (2) including only our 1st nature geography variables and country-century dummies as explanatory variables.

2. Using this hypothetical city configuration, we estimate our baseline model as in (2) and store the estimated parameters on each of the six 2nd nature geography variables.

3. Repeat the above-outlined procedure 2,500 times to obtain the empirical distribution of all six estimated 2nd nature geography coefficients. Next, for each respective 2nd nature geography variable we establish the (in)significance of its effect by comparing its estimated coefficient to the 0.5%, 2.5%, 5%, 95%, 97.5%, or 99.5% quantile of its simulated empirical distribution instead of to the 0.5%, 2.5%, 5%, 95%, 97.5%, or 99.5% quantile of a standard normal distribution with variance corresponding to the estimated standard error of its estimated effect (as in all other Tables in this paper).

The results of doing this are shown in Table A9. We verify the possibility of obtaining 'results by construction' for three different cases. The first two concern the baseline results in Table 1, randomly drawing new cities either unconditionally or conditional upon each potential city location's 1st nature geography characteristics. The third case concerns the baseline pre- and post-1600 results in Table 3, reporting only the results when randomly drawing new cities conditional upon 1st nature geography[68]. Besides reporting the significance of each estimated coefficient on the basis of our simulated empirical distributions, Table A9 also shows (for all six 2nd nature geography variables) the percentage of simulation runs that the null hypothesis of $\beta_1 \neq 0$ is *falsely rejected* when using the standard z-tests to establish the significance of an estimated coefficient at the 1%, 5%, and 10% respectively. Given that we allocate new cities

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[68] The results regarding the (in)significance of each of our six 2nd nature geography variables when randomly drawing new cities *unconditionally* are the same (both pre- and post-1600). Results available upon request.

randomly in each century, this percentage should be close to 1%, 5%, and 10% respectively to conclude that the standard tests perform well.

Table A9. Dartboard Approach – simulation results

unconditional	parameter est. [simulated 5% cv]	at 1%	at 5%	at 10%	conditional upon 1st nature geo.	parameter est. [simulated 5% cv]	at 1%	at 5%	at 10%
city >= 10k? (t-1)					city >= 10k? (t-1)				
0 - 20 km	-0.022 [-0.127]	0.8%	5.5%	10.6%	0 - 20 km	-0.022 [-0.132]	1.0%	5.5%	10.6%
20 - 50 km	0.078** [0.072]	0.8%	5.0%	10.4%	20 - 50 km	0.078* [0.083]	1.0%	5.7%	10.6%
50 - 100 km	0.072* [0.083]	1.0%	5.5%	10.7%	50 - 100 km	0.072* [0.085]	1.6%	6.0%	11.1%
competitor potential city location? (t-1)					competitor potential city location? (t-1)				
0 - 20 km	-0.113*** [-0.072]	1.0%	5.2%	10.1%	0 - 20 km	-0.113*** [-0.080]	1.0%	5.6%	11.0%
20 - 50 km	-0.055 [-0.138]	1.2%	6.2%	11.0%	20 - 50 km	-0.055 [-0.145]	0.9%	5.0%	10.1%
50 - 100 km	-0.207 [-0.331]	1.3%	6.6%	12.7%	50 - 100 km	-0.207 [-0.380]	1.8%	6.6%	11.6%

pre 1600	parameter est. [simulated 5% cv]	at 1%	at 5%	at 10%	post 1600	parameter est. [simulated 5% cv]	at 1%	at 5%	at 10%
city >= 10k? (t-1)					city >= 10k? (t-1)				
0 - 20 km	-0.273** [-0.236]	1.1%	5.5%	11.0%	0 - 20 km	0.08 [0.151]	1.1%	5.2%	10.6%
20 - 50 km	-0.047 [-0.120]	1.3%	5.5%	11.0%	20 - 50 km	0.175** [0.112]	0.9%	5.0%	10.0%
50 - 100 km	-0.06 [-0.107]	1.6%	5.4%	9.9%	50 - 100 km	0.262*** [0.140]	0.9%	4.7%	10.2%
competitor potential city location? (t-1)					competitor potential city location? (t-1)				
0 - 20 km	-0.128** [-0.108]	0.7%	5.2%	10.6%	0 - 20 km	-0.084 [-0.116]	1.4%	5.5%	11.6%
20 – 50 km	-0.114 [-0.204]	1.2%	5.4%	12.0%	20 - 50 km	-0.019 [-0.208]	0.9%	5.9%	11.1%
50 - 100 km	-0.241 [-0.549]	3.0%	9.6%	14.4%	50 - 100 km	-0.238 [-0.484]	1.7%	5.8%	12.4%

Notes: *, **, *** denotes significance at the 10%, 5%, 1% respectively based on the critical values of the simulated empirical distribution function. All simulated critical values and the '% falsely not rejected' are based on 2,500 simulation runs. The pre- and post-1600 results are 'dart-throws' conditional upon 1st nature geography (where 1st nature geography is also allowed to have a possibly different pre- and post-1600 effect).

Our simulation results suggest that using the standard z-statistics to assess the (in)significance of the estimated coefficients on our 2nd nature geography variables may indeed not be without problems. In case of our baseline results in Table 1, we find that the standard tests perform reasonably well in case of our three 'already existing city'-dummy variables. The percentage of simulation runs in which we falsely reject the null hypothesis is always quite close to 1%, 5% or 10% respectively (with the exception of the '50 – 100 km'-variant when randomly allocating new cities conditional upon 1st nature geography). This is not the case for the three 'competitor potential city location'-dummy variables, where we falsely reject the null hypothesis too frequently (up to 0.8, 1.6, and 2.7 percentage points more in case of the '50 – 100km' variant than the respective 1%, 5% and 10% it is supposed to be).

The simulation results when distinguishing between the pre- and post-1600 period further corroborate that the denser city system during the later centuries can result in drawing the wrong conclusions when using the standard z-statistics. Again the standard tests perform particularly bad in case of the 'competitor potential city location'-dummy variables,

especially in the pre-1600 period (with false rejection rates even up to 2, 4.6 or 4.4 ppt higher than acceptable). Their performance does improve in the post-1600 period.

Based on these results we must conclude that obtaining 'results by construction' could indeed be a reality: the standard tests do appear to falsely reject the null hypothesis more frequently than the acceptable 1%, 5%, or 10% respectively. However, taking proper account of the 'results by construction'-possibility, by using the critical values of each 2nd nature geography coefficient's simulated empirical distribution, reveals that, in our case, the conclusions regarding the (in)significance of each of our six 2nd nature geography variables do not change. When using the, generally larger (in absolute value) critical values of each simulated empirical distribution instead of those from the theoretical standard normal distribution, the same estimated coefficients are significantly different from zero as in our baseline results.