Czech University of Life Sciences Prague

Faculty of Environmental Sciences

Department of Land use and Improvement

The use of long-term historical data in exploring landscape-ecological issues

PhD thesis

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ČESKÁ ZEMĚDĚLSKÁ UNIVERZITA V PRAZE

Fakulta životního prostředí

ZADÁNÍ DISERTAČNÍ PRÁCE

Ing. arch. Václav Fanta

Aplikovaná a krajinná ekologie

Název práce

The use of long-term historical data in exploring landscape-ecological issues

Název anglicky

The use of long-term historical data in exploring landscape-ecological issues

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Cíle práce

The aim of this thesis is to use historical-geographical data for answering landscape-ecological questions. The results will be presented via papers published in peer-reviewed journal with IF.

Metodika

The student will use the following historical data and their editions: archaeological data, written sources, old maps and cadasters, historical environmental records. These datasets will be compared with environmental characteristics of the current landscape. Detailed methodology will be presented within each paper. The thesis will be written as a commented set of papers.

Doporučený rozsah práce

80

Klíčová slova

historical geography, historical landscape, landscape ecology, big data, interdisciplinary studies

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Doporučené zdroje informací

BRŮNA, Vladimír, ed. a BENEŠ, Jaromír, ed. Archeologie a krajinná ekologie. 1. vyd. Most: Nadace Projekt Sever, 1994. 159 s.

HRNČIAROVÁ, Tatiana, ed. et al. Atlas krajiny České republiky = Landscape atlas of the Czech Republic. 1. vyd. Praha: Ministerstvo životního prostředí České republiky, 2009. Požadavky na systém: Adobe Acrobat Reader (na disku). ISBN 978-80-85116-73-1

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I would like to thank Tarapacá winery for inspiration.

Author’s statement

I hereby declare that this dissertation is my work unless stated otherwise. I also declare that I have properly cited all references.

Key words:

historical geography, historical landscape, landscape ecology, medieval settlement, big data, interdisciplinary studies, human carrying capacity, Thirty Years’ War, long term memory, floods, dating, written sources, medieval archaeology

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Abstract:

The original aim of this thesis was to study the influence of environmental conditions on settlement history (more precisely: on selected processes in settlement history). Simultaneously, I wanted to use the “ecological” approach, i.e. to work with bigger data sets and apply solid statistical processing. In total, we investigated 3 sub-questions of various topics, which examined the usability of the above-mentioned approaches in different fields.

The first paper (“Equilibrium dynamics of European pre-industrial populations: The evidence of carrying capacity in human agricultural societies”) describes population dynamics during the period of the Thirty Years’ War and subsequent centuries in the context of human carrying capacity. We have found that human communities were limited by environmental carrying capacity even in the 17th century, i.e. deep into the modern period. Our paper shows that the main limiting factor for population growth was the soil fertility and cadastre size – in other words, food availability.

The second paper (“How long do floods throughout the millennium remain in the collective memory?”) was focused on the influence of big floods on the historical memory of people. The main question was whether people are able to pass information regarding catastrophic floods to younger generations, and whether this passed memory can affect the decision making of younger generations regarding the selection of settlement locations. The results show that the flood memory exists, but its effects are limited only up to approximately 25 years (i.e. one generation). We credit this limitation to ageing of the population and the loss of eye-witnesses. The younger generations might have heard about the floods from the story-telling of their parents and grandparents, but it obviously had no effect on their behaviour.

The third paper (“How old are the towns and villages in Central Europe? Archaeological data reveal the size of bias in dating obtained from traditional historic sources”) studied a more specialized (and more practically-oriented) topic: time-lag in the dating of historical sites. While time-lag was quite long (150 to 300 years) during the early and high medieval periods, it became significantly shorter in the late medieval and early modern period. At the end of the 16th century, the probability of time-lag was less than 5 % (towns) or 25 % (villages). Unfortunately, the data for younger periods (17th and 18th centuries) was not available. However, we expect that during the 17th and 18th centuries, time-lag would be permanently decreasing.

The big data approach brings a *different* type of evidence than the conventional historiographical studies. However, I think that neither of these two methods alone can discover all the mysteries of nature and history. Only a combination of different approaches can help us to understand the world. The combination of settlement history and environmental sciences can result in a remarkable interdisciplinary study; the conclusion of this collaboration can describe interesting, large scale trends and analyse general processes. Moreover, the settlement history data can become an engaging proxy description of human behaviour or ecology. I think that this type of research can add a broader perspective to conventional, micro-regional historiographical research and vice versa. I suggest that a cooperation between both approaches (“big data” as well as “single features / micro-regions”) should be a subsequent step in settlement and landscape history research.

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Content

1 Introduction

The aim of this thesis is (1) to study settlement history in the environmental context and (2) to use a big data approach for solving this question.

Ad (1): The effect of geographical conditions on the spatial distribution of settlements during the prehistoric period has been studied intensively (Neustupný, 1986, 1994; Rulf, 1994; Smrž, 1994; Dreslerová, 2011; Dong *et al.*, 2013; Garcia, 2013; Garcia-Moreno, 2013). Unfortunately, complex processing of this topic from the medieval and modern period is missing. However, this theme is quite interesting, because: (a) there is a high mass of various, available historical sources (archaeology, written sources, old maps), (b) it was an era of many transformations (Klápště, 2012a), and (c) the results and traces of the settlement and landscape processes taking place in the above-mentioned periods are still visible in the landscape.

Ad (2): The settlement history of the medieval and modern periods in Central Europe has been traditionally studied by archaeology, history, historical geography, historical demography and other history-related disciplines (e.g. Barry, 1996; Roberts, Wrathmell and Stocker, 1996; Skre, 1996; Žemlička, 2002, 2007, 2014; Semotanová, 2006; Klápště, 2012a). These disciplines deal largely with particular sites or micro-regions (e.g. Žemlička, 1974; Ježek, 2007; Semotanová, 2007; Vařeka *et al.*, 2008, 2011, Čapek, 2010b, 2011; Lipský *et al.*, 2011; Klír and Beránek, 2012; Klápště, 2013; van Beek, Groenewoudt and Keunen, 2014; Fanta *et al.*, 2014; Šantrůčková and Klvač, 2014; Novák and Vařeka, 2015). This is surely meritorious and praiseworthy research. However, the data acquired by such studies is rarely processed by modern statistical/ecological methods (Neustupný, 1986). In other disciplines, such an approach is a common practice (e.g. Pokorný, 2011; Poschlod, 2015). That is a pity, as the statistical methods could bring new insight into settlement history and landscape history – and maybe even into other fields of science.

The aim of this thesis is to try to fill up the above-mentioned niches, i.e. to process data on settlement history and the environment through statistical/ecological methods in an attempt to find generalizable ("macroecological") conclusions. In other words, I want to apply methods used in ecology and geography to a subject traditionally studied by history and archaeology. As a case study, I will focus on the settlement [1] (and landscape) history of the Czech lands in the medieval and modern period (approx. AD 900 – 1900). Since this topic is quite broad, I will look at selected processes only; namely the colonization of the landscape in an environmental context ("How did environmental or geographical factors affect various settlement processes?").

A brief review of archaeological, historical and geographical approaches to settlement studies is presented in the forthcoming chapter. The crux of this thesis is Chapter 2, which consists of my original papers. The results are further discussed and commented in the final chapter.

1.1 Archaeology and history

It is generally assumed that environmental conditions significantly influenced the historical development of human settlements. This dependence is indirectly supported by many studies, which focused primarily on the effect of changes of the environmental conditions of prehistoric settlements and cultures (Tinner *et al.*, 2003; Mayewski *et al.*, 2004; Bouzek, 2005; Turney *et al.*, 2006; Tóth, Demján and Griačová, 2011; Dong, Jia, *et al.*, 2012; Dong, Yang, *et al.*, 2012; Dreslerová, 2012; Dong *et al.*, 2013; Fiorentino *et al.*, 2013; Birks *et al.*, 2014; Neil, Gajewski and Betts, 2014). Other examples of

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[1] Unless stated otherwise, by the term "settlement" I mean (1) a single town, village, hamlet etc. or (2) the structure (pattern) of many individual inhabited places (towns, villages) in the cultural landscape.

the influence of climate changes on culture, society, politics, state administration or folk traditions were presented by Behringer (2007). However, political, social or economic factors should not be omitted (Kates, 1985; Žemlička, 2002; Beneš, 2005; Seabrook, McAlpine and Fensham, 2006; Dong, Yang, *et al.*, 2012), as well as humanity's cultural adaptability to unfavourable environmental conditions (Beneš, 2005; Dreslerová, 2005; Magny *et al.*, 2009) and its variety of subsistence strategies. For example, populations with specialized (i.e. less diversified) means of subsistence were more vulnerable to climate changes (Dreslerová, 2005). Dreslerová (2005, 2011, 2012) also points out that the importance of environmental conditions decreased for the duration of the prehistoric period. But there are still several open, underlying questions: which factors (environmental *vs.* social, cultural, economic) were more important for which processes (e.g. when choosing settlement locations during colonization)? How did the relative importance of various factors change over time? How were these factors affected by technological development and subsistence strategies?

The relation between prehistoric agricultural societies in Bohemia and their environment was recently described by Dreslerová (2011). However, a complex overview of this topic for the medieval and modern periods is missing. The following analysis – focused on Bohemia – is therefore based on historical, archaeological and historical-geographical studies dealing with micro-regions (see Tables 1.1 and 1.2).

1.1.1 The medieval colonization of the Czech lands

At the dawn of the 2nd millennium, the most fertile soil in the "old settlement area" (= lowlands near major rivers with permanent settlement since the Neolithic era) had already been occupied (Beranová and Lutovský, 2009). Therefore, new settlements had to be established on less fertile soil or in higher altitude. In the 11th century, colonization still remained under the submontaneous zone and it had an island-like pattern (Beranová and Lutovský, 2009). In the 12th century, overpopulation of the old settlement area and the economic interests of the nobility gave rise to an extraordinary colonization wave, leading to the establishment of settlements in higher, less suitable and more distant places. This process continued until the 14th century (Žemlička, 2002; Beranová and Lutovský, 2009). The peak of this colonization activity was reached at the turn of the 12th and 13th century (Žemlička, 2002). This colonization process is shown in Figs. 1.2 – 1.5.

In the 12th and 13th centuries, new technical improvements and inventions (plough innovation, water mill, horse collar, horseshoes) led to the need for more effective land division. As a result, the traditional settlement pattern was completely redesigned: The dense network of older settlements disappeared, while newer, bigger villages – with more regular layouts – were established. These new settlements have remained in our landscape in the present era (Žemlička, 2002). During this process, the layouts of many existing villages and their field patterns ("Flur" in German or "plužina" in Czech) were often newly redesigned ("Flurbereinigung" in German) on the basis of *ius teutonicum* ("the German law"; Klápště, 2012a). It is worth mentioning that the ownership structure during the high middle ages affected field pattern types: Villages singularly owned by a nobleman had sectional and croft field patterns in the maps of 19th century cadastral mapping. On the other hand, villages owned by more legal subjects (i.e. villages divided into two or more parts with different owners) had irregular segmental field patterns (Žemlička, 2002). In other words, the field patterns of villages owned by more subjects was less likely to be redesigned on the basis of the German law.

The population boom starting in the 11th century resulted in widespread settlement and migration movements, which continued up to the 13th century. In this period, settlements were established in higher locations with worse climatic conditions (Boháč, 1987; Žemlička, 2002). Similarly, in 12th and 13th century Western Europe, colonization continued into foothills and wetlands (Žemlička, 2002). As colonization of the 13th century and subsequent deforestation proceeded into the highlands, the ecological consequences showed the power of nature: the deforested land was not able to retain water, which led to flooding. Therefore, the settlements were translocated into safer (higher) river terraces than those that were occupied from the 11th to 13th centuries (Žemlička, 2002).

The dawn of the 14th century is characterized by new agricultural inventions (more efficient agricultural tools, three-field crop rotation) (Beranová and Kubačák, 2010). In the 14th century, the occupying of new sites continued, but with decreasing intensity. In the inland, smaller settlements of internal settlers were established, while bigger and more regular settlements of foreign settlers were established in the borderland (Žemlička, 2002). The main colonization wave in the Czech landscape ended in the late medieval and early modern period, but the establishment of new villages continued the trend of lesser intensity until finally ending in the 18th and 19th centuries (Růžková *et al.*, 2006).

In older historical literature, the question of the influence of environmental conditions on settlement development was usually omitted (e.g. Šimák, 1938). However, later historical-geographical works put more emphasis on this topic. For example, Boháč (1978) carefully described the environmental conditions of his study area and identified them as prerequisites for colonization. According to his study, the oldest centres were located in the lowlands and in the floodplains of big rivers. He found that the proximity of rivers and vegetation composition of forests were the main factors for the selection of locations for colonization (Boháč, 1978, 1988). Other authors agree on the importance of watercourses and fortified centres (Beranová and Lutovský, 2009), or add other factors, such as soil quality, climate changes, rainfall distribution and geomorphology for these settlements (Žemlička, 2002). Finally, Semotanová (2006) claims that both the distribution and density of settlements were affected by altitude, terrain undulation, soil fertility, relation to water and vegetation. Beside the environmental conditions, relations to older settlements and other cultural factors have also been found as important predictors for the choosing of the settlement locations: From the 10th century, new settlements had been established in the proximity of hillforts, courts, monasteries, customhouses, and former castles, or along important roads (Beranová and Lutovský, 2009; Hoffman, 2009).

Buchvaldek *et al.* (1985) distinguished three zones of agricultural colonization with respect to environmental conditions:

(1) **the oldest area** (under 300 m a. s. l., average temperature around 8°C, short period of snow cover),

(2) **areas colonized in the 12th and 13th centuries** (under 500 m a. s. l., average temperature around 7°C, less favourable for agriculture), and

(3) **later colonization** (above 500 m a. s. l., lower temperature, less fertile soil, long period of snow cover). The authors claim that the colonization of the third zone was possible only due to the medieval warm period.

Klápště (2012a), on the other hand, distinguishes the oldest period more in detail:

(1) **early Slavic settlements, 6th to 7th century** (the most fertile lands below 300 m a. s. l.),

(2) **8th to 9th century** (less fertile lands above 400 m a. s. l.), and

(3) **until the half of the 13th century** (all areas suitable for agriculture had already been colonized).

Almost all papers and books on medieval settlement development consider suitable environmental conditions as a necessary requirement for colonization (Tables 1.1 and 1.2). There is also a wide consensus that the most favourable places for agriculture were occupied in the early medieval period (e.g. Buchvaldek *et al.*, 1985; Klápště, 2012a). Later, colonization proceeded into higher and less favourable places (Smetánka, 1978b; Klápště, 2012a). That shift could have been motivated by the unavailability of fertile soils in lower altitudes, which was caused by overpopulation (Žemlička, 2002, 2014; Beranová and Lutovský, 2009). Many authors also stress the proximity of older settlements and communications as an important factors in the choosing of the locations for new settlements (Beranová and Lutovský, 2009; Hoffman, 2009). The colonization of relatively unfavourable places (i.e. higher altitude locations) in the high medieval period was perhaps possible due to the climatic optimum (Smetánka, 1978b; Buchvaldek *et al.*, 1985; Žemlička, 2002). However, this opinion is not generally accepted, as some authors do not find this climate change as an important factor (Klápště, 2012a). Unfortunately, all the above-mentioned findings are mostly based solely on empirical observations. Studies on medieval settlement development are rarely based on statistical analysis (exceptions: Bubeník, 1991; Somer, 2012). Similarly, the importance of various factors, their relative impact, and the changes in different centuries have only been mentioned by a few authors (e.g. Beneš and Brůna, 1994a; Žemlička, 2002).

1.1.2 Archaeological predictive modelling

Archaeological predictive modelling (APM) is a method that describes the probability of a presence of a specific archaeological culture within a delimited area, usually based on environmental predictors (e.g. Jarosław and Hildebrandt-Radke, 2009). Yet, the landscape history may also play a role (Neustupný, 2000). The main principle is very simple: if we know the preferred environmental (and other) conditions for a specific archaeological culture, we expect that other (yet unknown) sites of that culture could be located in places with the same or similar conditions. The same principle is used in ecology (species distribution modelling; Gallien *et al.*, 2012), and in astrobiology (the concept of the habitable zone; Domagal-Goldman *et al.*, 2016). The main limitation of APM is that it creates a probabilistic model, which is derived from already-known trends and regularities, thus the interpretation of such model can be challenging (Kuna *et al.*, 2004). The APM is used not just for primary archaeological prediction, but also as an input for spatial planning or cultural heritage protection (Fry *et al.*, 2004; Balla *et al.*, 2013).

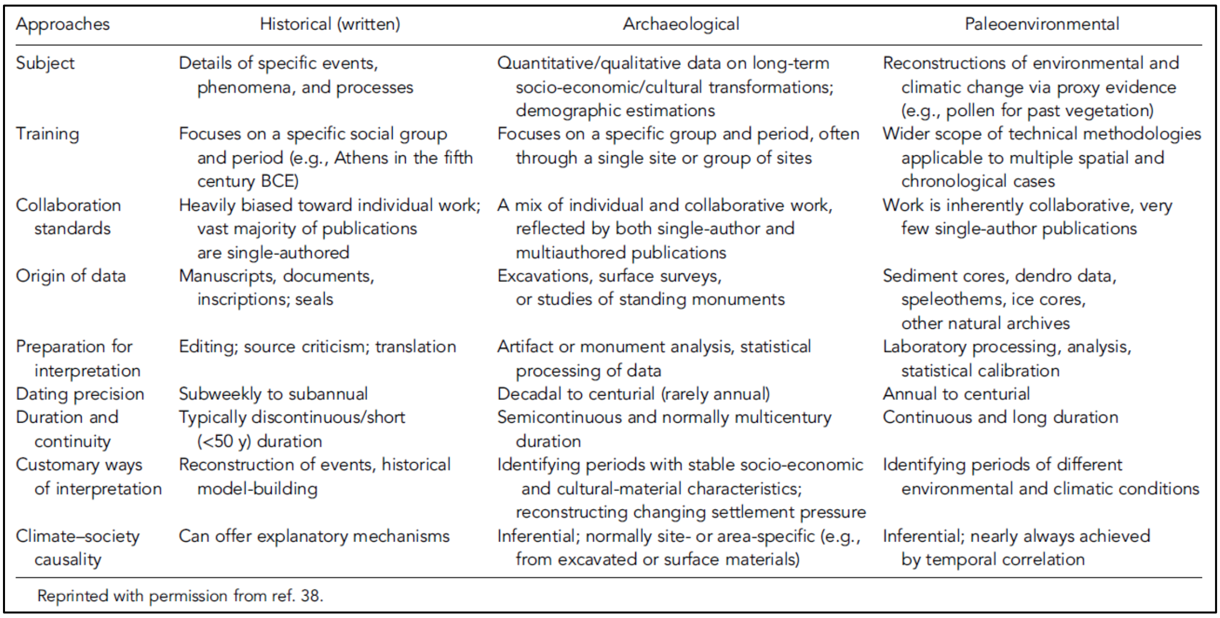
1.1.3 The use of statistics in the research of medieval settlements

It would not be correct to claim that my dissertation is the first study dealing with a big data approach and statistics in the field of settlement history. Reversibly, such an approach has been used by many scientists. In the Czech scientific community, one of the first occurrences of the interdisciplinary research of historical landscape was the famous and influential book *Archaeology and landscape ecology* (Beneš and Brůna, 1994a), followed by a detailed description of archaeological and geographical views on cultural landscape (Gojda, 2000). More than 25 years prior, at the point of publication, the archaeologist already knew that comparing big datasets may bring different types of findings (Meduna and Černá, 1992). Unfortunately, though, this approach is quite rare (Novák, 2014). Some researchers actually do not recommend the “statistical” approach, stating we can never describe all potential influencing factors in sufficient detail (Stone, 1996). Other also believe that, in the context of individual sites, micro-history could be more important than general trends (Klápště, 2012a). Recently, a paper by Haldon *et al.* (2018) calls for a deeper collaboration amongst historians, archaeologists and environmental scientists (Fig. 1.1).

Bubeník (1991) studied early medieval settlement changes in north-western Bohemia. His study nicely compared different phases of the settlement pattern and its relation to environmental conditions. Holata (2013) followed Černý’s (1992) investigation of deserted medieval villages in Drahany uplands in Moravia. Moreover, Holata puts emphasis on a detailed GIS analysis of the environmental factors of the settlement sites, as well as on the reasons of site abandonment. Novák (2014) intentionally and directly focused on the big data approach in his study about fortified manors in Central Bohemia. Sadravetzová (2015) analysed medieval colonization in the Vimperk region (Southern Bohemia). She used a big dataset of medieval villages (*n* > 150) while focusing on the influence of village establishment dates on field pattern types. The methodology is elegant and remarkable; however, she only worked with the dates from written sources, which may have been skewed towards the later centuries. A similar problem arises in the study by Szabó, Šipoš and Müllerová (2017), which put the founding dates, obtained from written records, of all Moravian towns and villages into a geographical and environmental context. Again, this is an immensely interesting study, but it may be methodologically problematic. Maybe it is better to use archaeological data, as presented in a study describing the environmental conditions of Native American settlement sites (Jones, 2010), or to study later periods with more reliable data (Lukezic, 1990). For example, Fang and Jawitz (2019) analysed the changes in the relation between human settlements and rivers in the USA during the industrial revolution, a well-documented time period.

The use of big datasets is almost necessary for a proper description of the colonization process, as can be seen in papers on the European colonization of the Canadian frontier in the late 19th century and early 20th century (Lehr and McGregor, 2008; McGregor and Lehr, 2016). Big datasets can also help to discover interesting connections. For example, a voluminous study (*n* = 49 640 dendrochronological samples) by Ljungqvist *et al.* (2018) showed that European building activity had been strongly affected by plague outbreaks. Therefore, it is important to make databases, such as a recently launched British database of building archaeology surveys (Moir, Wild and Haddlesey, 2012). An extensive overview of archaeological methods dealing with big datasets and landscape was presented in the respective chapters of the book *Non-destructive archaeology* (Kuna *et al.*, 2004).

To conclude, "big data" studies can bring completely new types of evidence or even reveal some causal links (Lee, 2018). This approach is common in prehistoric archaeology. Unfortunately, the medieval and post-medieval periods are "left" to historiography, which usually prefers a detailed, simple feature analysis rather than a statistical comparison of big data samples.



Approaches	Historical (written)	Archaeological	Paleoenvironmental
Subject	Details of specific events, phenomena, and processes	Quantitative/qualitative data on long-term socio-economic/cultural transformations; demographic estimations	Reconstructions of environmental and climatic change via proxy evidence (e.g., pollen for past vegetation)
Training	Focuses on a specific social group and period (e.g., Athens in the fifth century BCE)	Focuses on a specific group and period, often through a single site or group of sites	Wider scope of technical methodologies applicable to multiple spatial and chronological cases
Collaboration standards	Heavily biased toward individual work; vast majority of publications are single-authored	A mix of individual and collaborative work, reflected by both single-author and multiauthored publications	Work is inherently collaborative, very few single-author publications
Origin of data	Manuscripts, documents, inscriptions; seals	Excavations, surface surveys, or studies of standing monuments	Sediment cores, dendro data, speleothems, ice cores, other natural archives
Preparation for interpretation	Editing; source criticism; translation	Artifact or monument analysis, statistical processing of data	Laboratory processing, analysis, statistical calibration
Dating precision	Subweekly to subannual	Decadal to centurial (rarely annual)	Annual to centurial
Duration and continuity	Typically discontinuous/short (<50 y) duration	Semicontinuous and normally multicentury duration	Continuous and long duration
Customary ways of interpretation	Reconstruction of events, historical model-building	Identifying periods with stable socio-economic and cultural-material characteristics; reconstructing changing settlement pressure	Identifying periods of different environmental and climatic conditions
Climate–society causality	Can offer explanatory mechanisms	Inferential; normally site- or area-specific (e.g., from excavated or surface materials)	Inferential; nearly always achieved by temporal correlation

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Fig. 1.1 (on the previous page). *Data sources and the characteristics of different scientific disciplines dealing with history. Source: Haldon et al. (2018), after Haldon et al. (2014)*

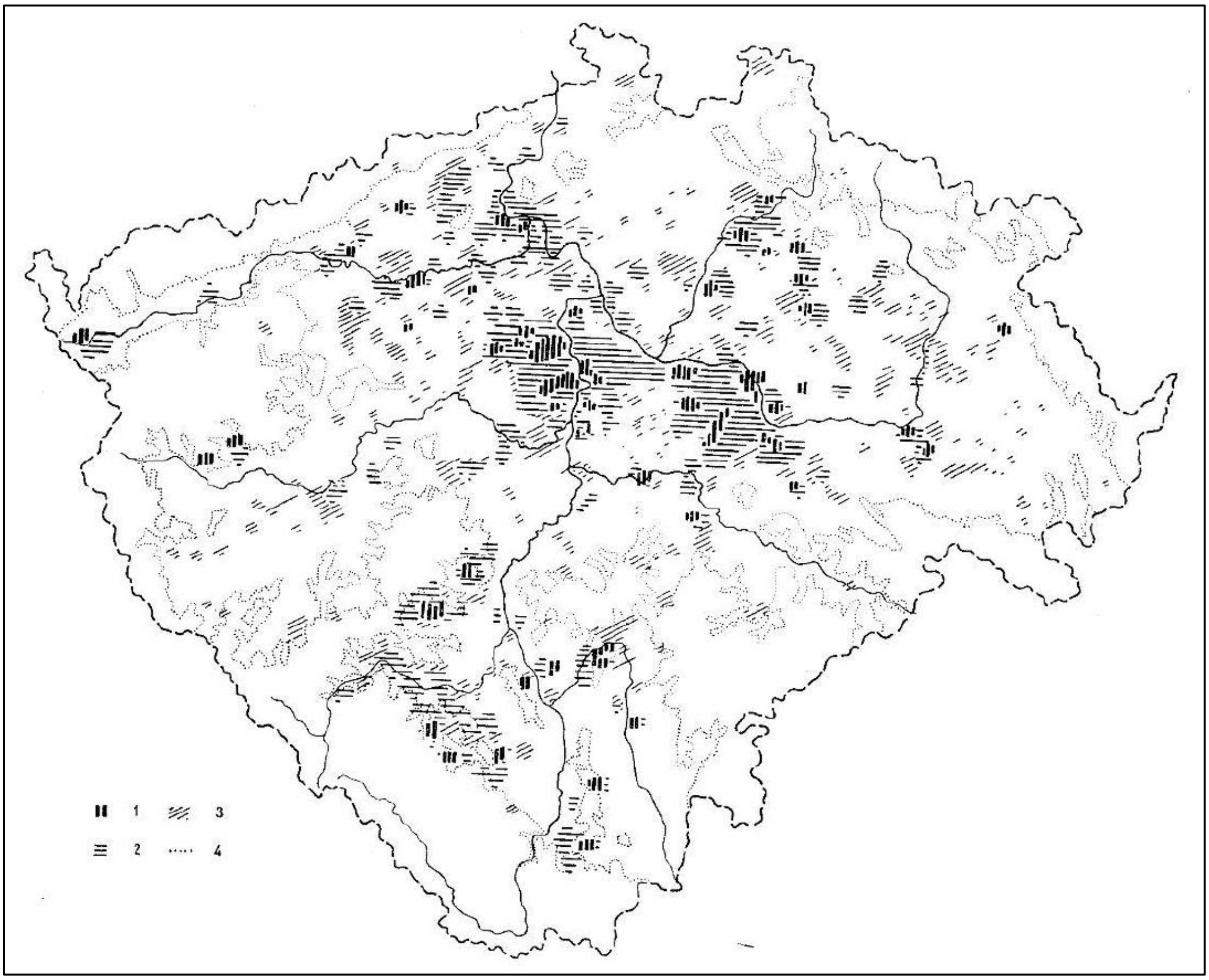
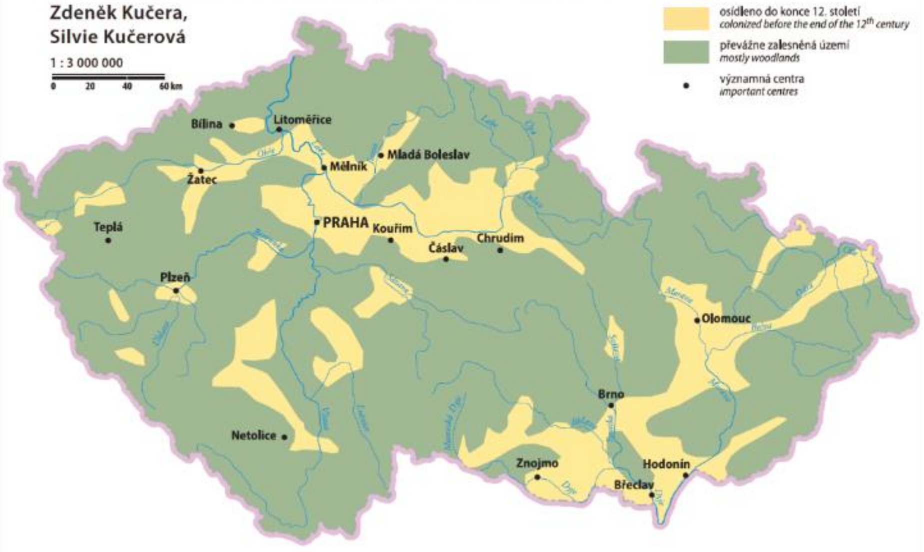


Fig. 1.2. *Slavic settlements in Bohemia. Legend: 1) areas of the oldest settlements, 2) colonization until the mid-10th century, 3) colonization until the mid-11th century, 4) contour line 400 m a. s. l. The map only depicts the most important centres. Source: Sláma (1967)*

ÚZEMÍ OSÍDLENÉ DO KONCE 12. STOLETÍ

AREAS COLONIZED BEFORE THE END OF THE 12th CENTURY

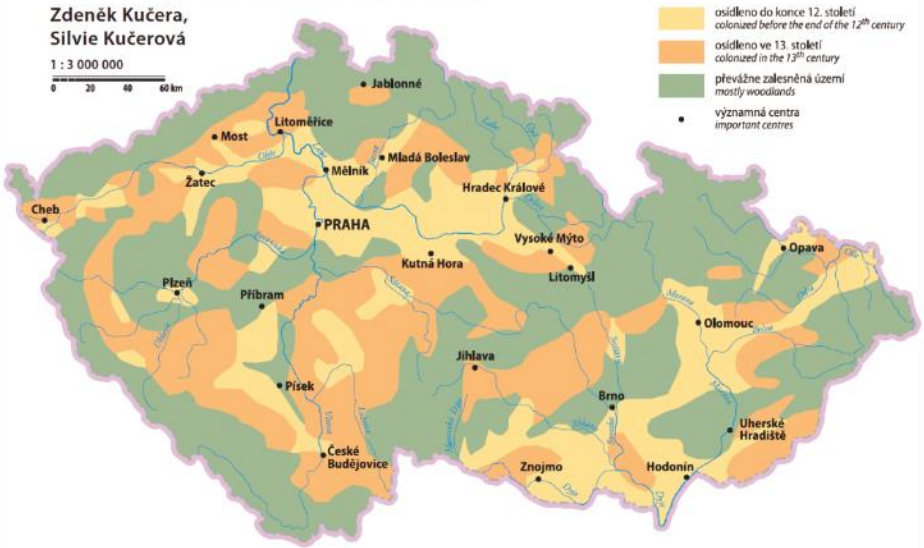
Zdeněk Kučera,
Silvie Kučerová



OSÍDLOVÁNÍ ÚZEMÍ KOLONIZACÍ VE 13. STOLETÍ

AREAS COLONIZED DURING THE 13th CENTURY

Zdeněk Kučera,
Silvie Kučerová



OSÍDLOVÁNÍ ÚZEMÍ KOLONIZACÍ VE 14. STOLETÍ

AREAS COLONIZED DURING THE 14th CENTURY

Zdeněk Kučera,
Silvie Kučerová

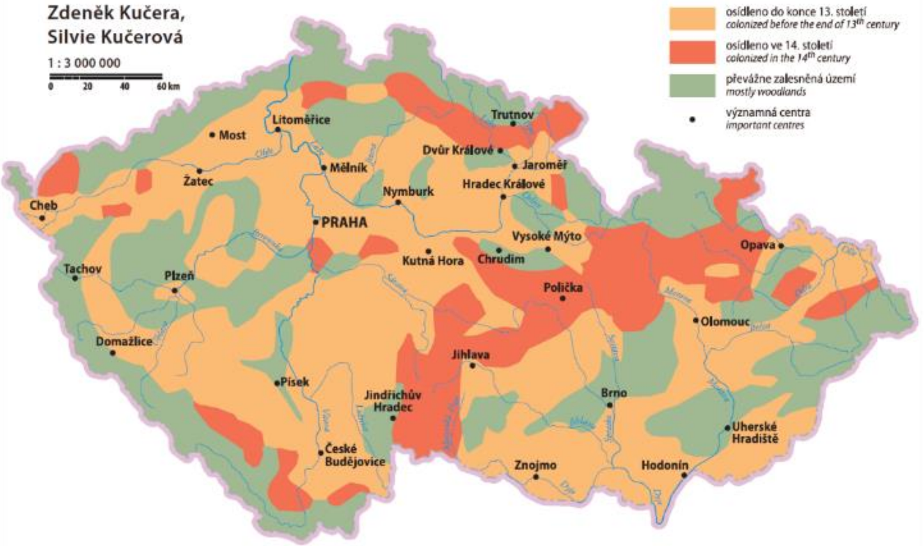


Fig. 1.3 (on the previous page). *Colonization of the Czech Republic in the middle ages. Source: Hrnčiarová, Mackovčin and Zvara (2009), based on data by Beneš and Petráň (1997)*

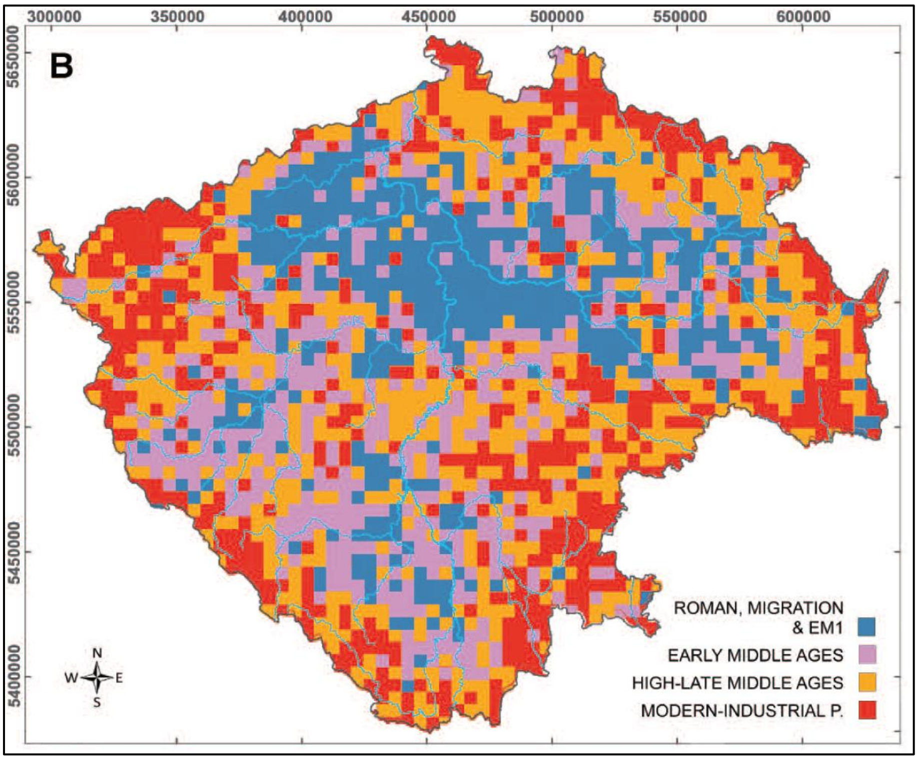


Fig. 1.4. *The medieval and modern colonization of Bohemia according to archaeological data. Source: Kuna (2015)*

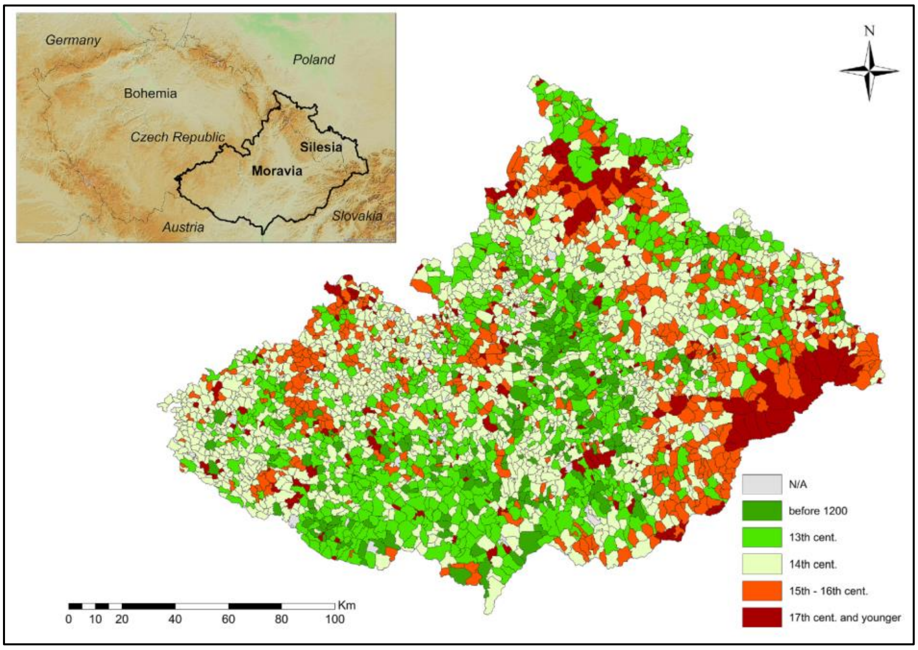


Fig. 1.5. *The colonization pattern in Moravia as evidenced by first mentions in written sources. Source: Szabó, Šipoš and Müllerová (2017)*

Table 1.1. *An overview of papers and reviews dealing with the influence of environmental conditions on the development of medieval settlements in the Czech lands*

historical period	**number of analysed settlements**	**environmental conditions and their influence on settlement development**	**type of paper**	**source**
"since the beginnings of settlement"	not specified	altitude, terrain undulation, soil fertility, relation to water, and vegetation affected the distribution and density of settlements in the landscape	review	Semotanová (2006)
perhaps early medieval	not specified	the oldest centres were located in meadows, lowlands, and the floodplains of big rivers; settlements were spreading along the rivers	research article, no statistical analysis	Boháč (1978)
perhaps early medieval	not specified	the vegetation composition of forests affected the direction of expansion of colonization	research article, no statistical analysis	Boháč (1988)
early medieval	not specified (cca 10)	preferred settlement locations: altitude below 330 m, most fertile soils, river valleys and their terraces	research article, no statistical analysis	Vařeka *et al.* (2012)
older and middle hillfort period (7th to 10th century)	155	potential natural vegetation: more than 40 % of locations were connected to oak-hornbeam forests or bordered with meads and alder groves; approx. 30 % of localities were connected to oak forests	research article	Bubeník (1991)
younger hillfort period (10th to 12th century)	180	potential natural vegetation: more than 40 % of locations were connected to oak-hornbeam forests or bordered with meads and alder groves; approx. 10 % of localities were connected to meads and alder forests, approx. 8 % connected to oak groves	research article	Bubeník (1991)
9th and 10th century	not specified	preferred settlement locations: proximity of rivers and creeks	review	Beranová and Lutovský (2009)
11th century	not specified	settlements moved to higher places, but still remains under the submontaneous and montaneous zone of reconstructed environmental conditions	review	Beranová and Lutovský (2009)
12th century	not specified	colonization proceeded to higher and less favourable locations	review	Žemlička (2002)
12th century	not specified	the water source became the deciding factor in place selection	review	Smetánka (1978a)
since the half of 12th century	not specified	preferred settlement locations: highlands and hilly landscapes, proximity to water sources	review	Žemlička (2002), Beranová and Lutovský (2009)

later hill-fort period (12th to 13th century)	105	potential natural vegetation: almost 40 % of localities were connected to oak-hornbeam groves, slightly more than 10 % connected to meads and alder forests; the number of findings in highlands grew	research article	Bubeník (1991)
13th century	21	mining activity indirectly influenced the development of agrarian settlements, which led to a higher number of churches	research article	Somer (2012)
13th century	not specified	soil quality, forest vegetation composition, relation to water sources, climate changes and rainfall frequency affected the distribution and density of the settlements pattern	review	Žemlička (2002)
13th century	not specified	preferred settlement locations: higher river terraces (due to the risk of floods caused by deforestation)	review	Žemlička (2002)
13th century	not specified (cca 50)	preferred settlement locations: higher locations, often with a less favourable climate	research article, no statistical analysis / review	Boháč (1978), Žemlička (2002)
13th century	not specified	colonization proceeded to places that were previously considered useless; colonization of higher locations	review	Smetánka (1978a)
13th and 14th century	115	preferred settlement locations: altitude under 500 m a. s. l., proximity of water source, appropriate slope	research article, no statistical analysis	Vařeka *et al.* (2011)
high medieval	23	preferred settlement locations: quaternary sediments, valleys of streams or springs in higher locations	research article, no statistical analysis	Vařeka *et al.* (2012)
late medieval and early modern	not specified	fertile lowlands were connected by agriculture; non-agricultural mountain areas were connected by other types of subsidence	research article	Klír (2009)
period of agricultural colonization	not specified	three zones of agricultural colonization: (1) the oldest area (under 300 m a. s. l., average temperature around 8°C, short period of snow cover), (2) areas colonized in the 12th and 13th centuries (under 500 m a. s. l., average temperature around 7°C, less favourable for agriculture), and (3) later colonization (above 500 m a. s. l., lower temperature, less fertile soil, long period of snow cover)	review	Smetánka (1978b), Buchvaldek *et al.* (1985)
universally	not specified	geomorphology and climate were the main determinants of both animate and inanimate systems in the landscape	essay	Beneš and Brůna (1994b)

Table 1.2. *An overview of papers and reviews dealing with the influence of cultural conditions on the development of medieval settlements in the Czech lands*

historical period	number of analysed settlements	cultural conditions and their influence on settlement development	type of paper	source
6th to 12th century	not specified, prob. tens	preferred settlement locations: in proximity to primary centres or in greater distance from primary centres (emergence of secondary centres)	review	Kuna *et al.* (2004)
9th and 10th century	not specified	preferred settlement locations: in proximity to fortified centres	review	Beranová and Lutovský (2009)
10th century	1	preferred settlement locations: long-distance communication of European importance	research article	Vařeka *et al.* (2012)
since the 10th century	not specified	newly established settlements in the proximity of castles were not primarily agricultural; however, their hinterland was fertile and occupied by agricultural villages	review	Beranová and Lutovský (2009), Hoffman (2009)
since the 10th century	not specified	preferred settlement locations: in proximity to important trade roads	review	Beranová and Lutovský (2009)
since the 10th century	not specified	preferred settlement locations: in proximity to hillforts, courts, monasteries and customhouses	review	Hoffman (2009)
11th century	not specified	within the old settlement area, the most fertile soils were already occupied → the settlements moved to higher locations	review	Beranová and Lutovský (2009)
12th century	not specified	colonization proceeded to more distant places; overpopulation of the old settlement area, coupled with economic interests of the nobility led to the start of colonization	review	Žemlička (2002), Beranová and Lutovský (2009)
13th century	not specified	colonization connected to the spread of the German law → older settlements are diffused, new settlements are more compact	review	Žemlička (2002)
13th century	21	preferred settlement locations: the ethnic composition of the population had no significant impact	research article	Somer (2012)
13th and 14th century	not specified (cca 20)	the type of ownership of villages affected the type of field pattern, perhaps a more important factor than environmental conditions	review	Žemlička (2002)
period of colonization	not specified	economic interests of the nobility	discussion	Skružný (1978)

1.2 Geography

While changes in time are studied by archaeology and history, geography focuses on changes in space. Social, economic and settlement geography can therefore bring insight to the study of the influence of environmental factors on spatial distribution and dynamics of settlements. The advantage of the geographical approach is the field's tendency toward a general description of patterns, distributions or dynamics (Fig. 1.6). Such patterns can be applied almost everywhere (with little uncertainty). However, the disadvantage of a geographical approach is a common omission of the historical development of settlements. Geographic theories usually only deal with the current situation and do not reflect the historical development.

1.2.1 Settlement geography

The idea of environmental determinism (i.e. the settlement pattern is affected by environmental condition) is very old. For instance, it was mentioned already by Aristotle (Johnston, Gregory and Smith, 1994). The field of settlement geography gradually evolved from attempts to interpret the distribution and properties of towns as a consequence of environmental factors (Pacione, 2009) – continuing with analyses of street pattern development and spatial organization of towns – to the application of economic, social and ecological approaches (Toušek *et al.*, 2008). Incidentally, a similar evolution of paradigms was observed in the field of spatial archaeology (Kuna *et al.*, 2004).

The factors affecting population distribution and the formation of towns and street patterns can be divided into two groups: environmental and socio-economic. Environmental factors were mostly the primary determinants of population distribution; later, their impact was overcome by social, economic and political factors. In a planet-scale population distribution, the most important environmental factors are the distance from the seashore (Cohen and Small, 1998; Small, Gornitz and Cohen, 2000), altitude and climatic factors (which are becoming more significant in the current period due to global warming). The most important socio-economic factors are agricultural production, transport and the interconnection between industry and consumers (Toušek *et al.*, 2008). Other authors also put emphasis also on the technological level, government qualities, cultural level of the community (Węcławowicz, 2003) and the economic activities of inhabitants (Votrubec, 1980). However, the importance of all these factors have differed throughout the course of time.

The history of towns can be divided into four time periods (Herbert and Thomas, 1997; Pacione, 2009):

(1) **settlements of pre-agricultural societies** (small compact towns with no hinterland, low specialization and weak connections between individual towns),

(2) **towns of traditional societies** (until the industrial revolution),

(3) **industrial towns** (emergence of centre and periphery, higher specialization and hierarchy), and

(4) **post-industrial towns** (characterized by efficient communication, spatial dispersion, intensive inter-city relations).

Similar evolutionary periods can be recognized in the history of cultural landscapes (Antrop, 2004). While environmental factors played an important role in the pre-industrial period, especially in regards to the spatial distribution of towns and their population size, the localization of raw materials and transport efficiency became more important during the industrial period. However, during the post-industrial period, environmental factors have played very minor role (Herbert and Thomas, 1997; Toušek *et al.*, 2008). Other authors have underlined the importance of geomorphology (Fialová, 2008), water sources, defendable locations, cover from weather conditions and other useful reasons, especially in the pre-industrial period (Votrubec, 1980). Bašovský and Mládek (1989) distinguish four basic types of geographical positions of a town in the landscape with respect to socio-economic factors:

(1) **defence position** (defence and hiding are the primary function),

(2) **transport position** (position in a proximity of an important road),

(3) **raw material position** (position in a proximity of a source of raw materials), and

(4) **artificial position** (completely man-made position).

It is expected that the most important factors of future town development will be changes in demographics, population mobility, telecommunication technologies, further developments of inter-city networks and requirements of new industry and services (Toušek *et al.*, 2008).

1.2.2 Theories of settlement patterns

Geographers have discovered several theories that describe settlement patterns, distribution and other properties of human settlements. Some of these theories describe stationary situations (they do not reflect the historical development or the dynamics of a system), while others describe dynamic/evolutionary changes (with a reflection of the historical development) (Pumain, 2000). The most important of these theories are the following:

(1) **The rule of the leading city** – The largest city in a country is usually much larger than other cities. This rule is valid only in some situations, especially in smaller countries or in the process of newly developing settlement systems (Toušek *et al.*, 2008).

(2) **Rank-size rule** – This rule describes the size distribution of towns according to the following equation: $S_x = \frac{S_1}{n_x}$, where S_x is population size of town *x*, S_1 is the population size of the largest city and n_x is order of town *x* according to its population size. This rule is more likely to be valid in older, more developed settlement systems (Toušek *et al.*, 2008).

(3) **Christaller's central places theory** – This famous theory describes the emergence/distribution of services (i.e. secondary settlements) in the hinterland of a major town (Fig. 1.7). It requires a relatively homogenous landscape with a homogenous population distribution. Each service creates a market area with a pattern of hierarchically and spatially organized settlements (Toušek *et al.*, 2008). This theory models a hexagonal hinterland around each town. The size of the hinterland corresponds with the importance of the major town. The hinterland also generates requirements for services, which are thus fulfilled in the major town (Kitchin and Thrift, 2009b). The original theory, proposed in the 1920s, was later modified for practical purposes, e.g. spatial planning (Kitchin and Thrift, 2009c).

(4) **Thresholds** – The growth of towns can be limited by obstacles, such as: (1) environmental conditions of the surrounding area, (2) persisting land use type, (3) persisting technologies, (4) necessity to rebuild the structural elements of the town (Bašovský and Mládek, 1989). To overcome these obstacles, higher expenses are necessary. Such obstacles (thresholds) are overcome when sufficient resources are available. Thus, the overcoming of obstacles is not fluent, but emerges after a certain period (Bašovský and Mládek, 1989).

(5) **Thiessen's / Voronoi's polygons** – This is a geometrical construction of polygons, where the joint borders have the same distance from each nucleus (Fig. 1.8). This method has a variety of applica-

tions in geography (e.g. calculation of spheres of influence or delimitation of theoretical boundaries of an area), astronomy, mathematics, geology, biology, anatomy, and other scientific disciplines (Kitchin and Thrift, 2009a).

(6) **Gravity models** – This model is based on the classical Newton's gravity law: $F_{ij} = \kappa \cdot \frac{m_i \cdot m_j}{r_{ij}^2}$, where F_{ij} is the force between objects i and j, r_{ij} is the distance between these two objects, m_i and m_j are their masses and κ is the gravity constant. An analogy to this relation can be applied in various geographical issues dealing with moving matter or information (e.g. migration, phone calls, transport, commodity flow etc.). However, for geographical purposes, the original Newton's relation had to be adjusted (Johnston, Gregory and Smith, 1994). The gravity model can be used for many applications, e.g. archaeology (Wilson, 2007), spatial planning (Bruno and Improta, 2008) or economic relations (Řehák, Halás and Klapka, 2009).

(7) **Von Thünen's model** – This model from the first half of the 19th century describes the spatial distribution of agricultural (land use) zones based on the distance from the market place (Fig. 1.9). In other words, the distance from the market determines the land use pattern (Johnston, Gregory and Smith, 1994; Bičík *et al.*, 2015).

(8) **Geographical processes** – Bennett (1978) described four basic types of geographical processes (Fig. 1.10): (1) barrier process (the growth is limited by a barrier), (2) hierarchical process (the parent structure establishes its daughter structures), (3) network process (the structure grows along a network) and (4) contiguity process (a new structure emerges through the merging of two distinct structures; (Bennett, 1978; Johnston, Gregory and Smith, 1994).

(9) **Fractals** – Several authors have suggested that the geometrical distribution of human settlements and/or their properties are similar to that of fractal structures. Brown and Witschey (2003) identified several fractal relations within settlement systems:

a) *"the size-frequency distribution of settlements is fractal,*

b) *the rank-size relation among sites is fractal, and*

c) *the geographical clustering of sites is fractal"*.

Chen (2009) studied fractal and power-law properties of river networks and cities. Gomes (2001) found that the distribution of spontaneous settlements in present-day Rio de Janeiro have a distinctive fractal dimension. Brown and Witschey (2003) also discovered that the ancient Maya settlement had a fractal dimension. They also hypothesize that this fractal pattern was produced by socio-political activities.

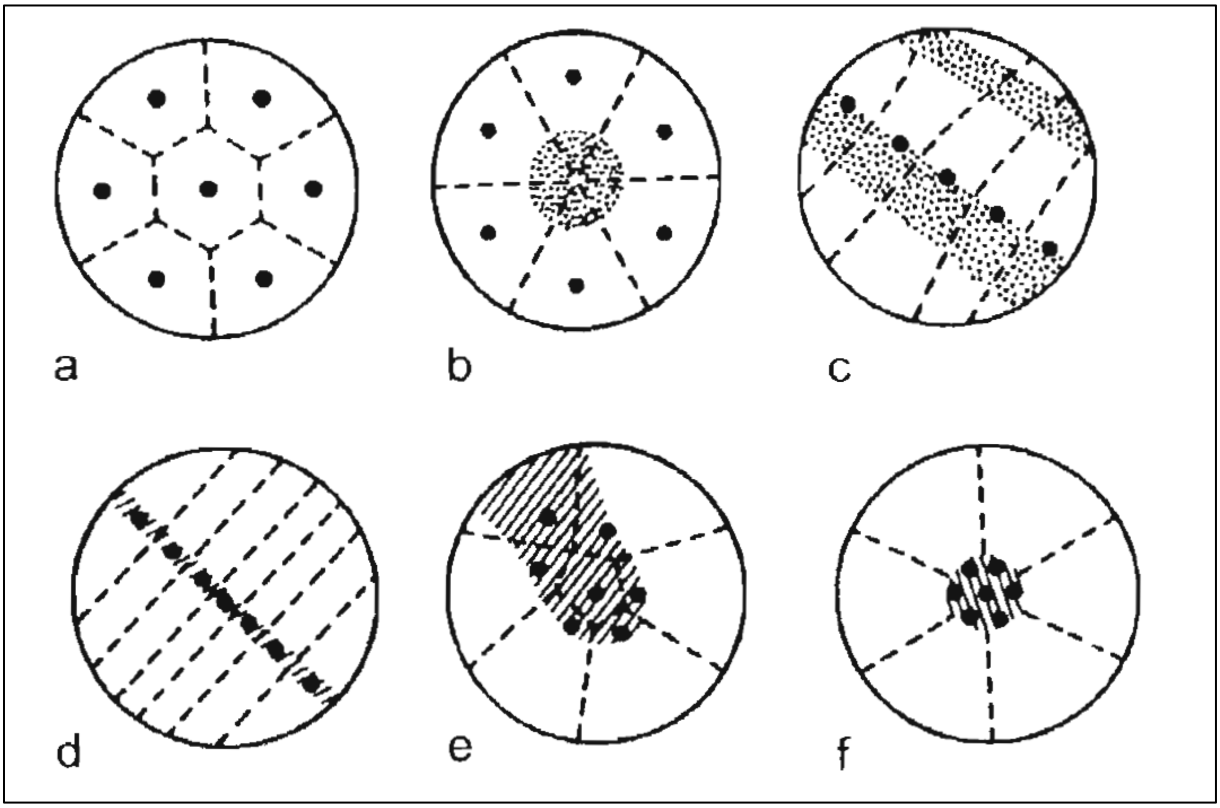


Fig. 1.6. *The influence of the allocation of natural resources on settlement structures and the shape of settlement areas: (a) homogenous environment, (b) limited complementary resource (e.g. forest), (c) zonal arrangement of resources (plough soil, pasture, forest), (d) zonal occurrence of basic resources (e.g. water), € spatially limited basic resources (e.g. plough soil), (f) a highly concentrated occurrence of basic resources (e.g. water, strategic location). Source: Kuna et al. (2004), after Roberts (1996)*

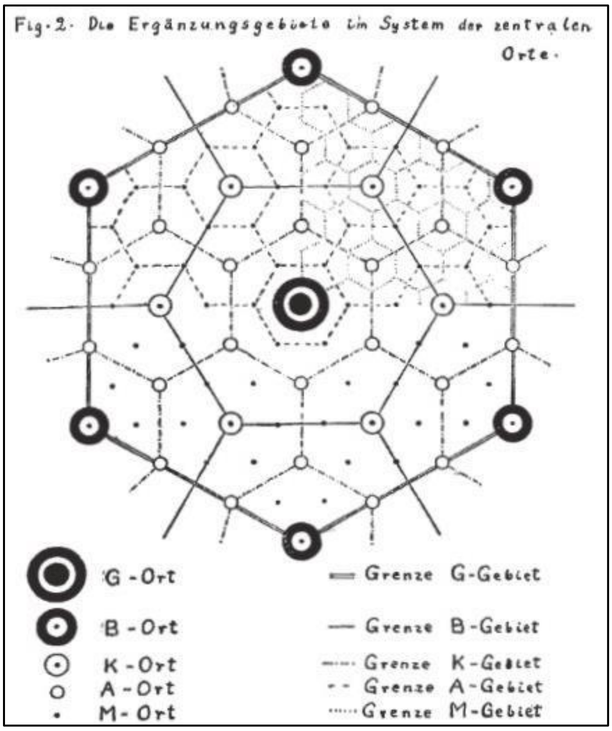


***Fig. 1.7.** Christaller's central places theory. Source: Michel (2016), original image: Christaller (1933)*

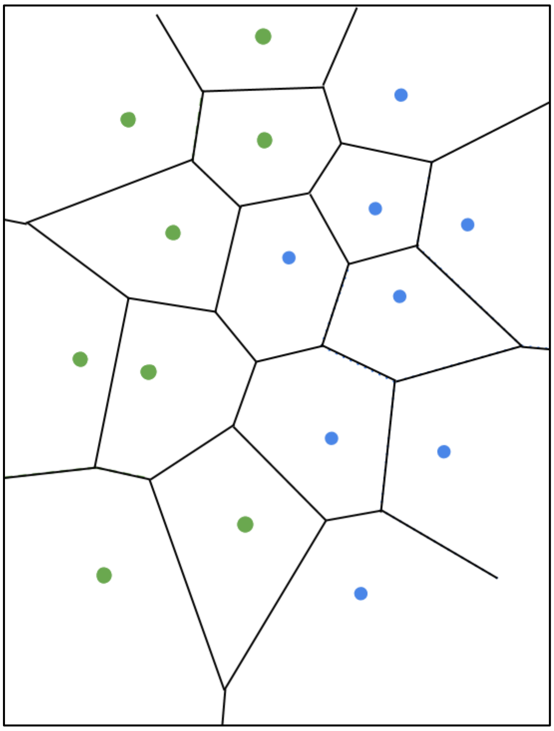


***Fig. 1.8.** Thiessen's / Voronoi's polygons. Source: Wikimedia Commons contributors (2016)*

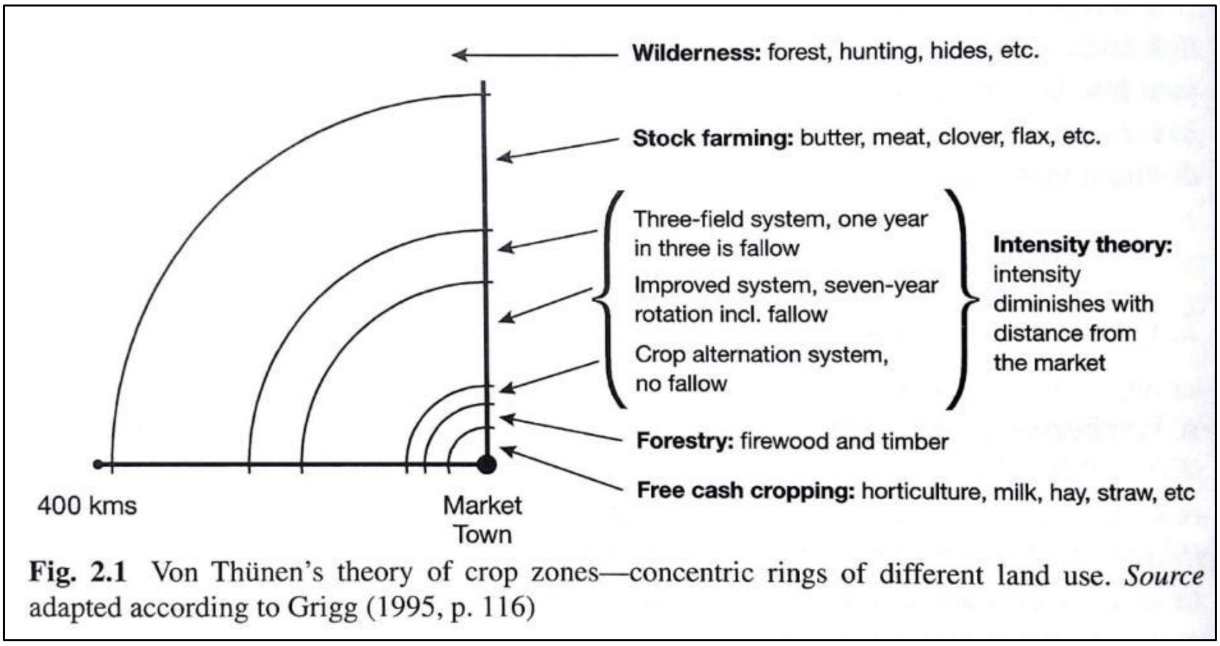


Fig. 2.1 Von Thünen's theory of crop zones—concentric rings of different land use. *Source* adapted according to Grigg (1995, p. 116)

***Fig. 1.9.** Land use pattern according to von Thünen's theory. Source: Bičík et al. (2015)*

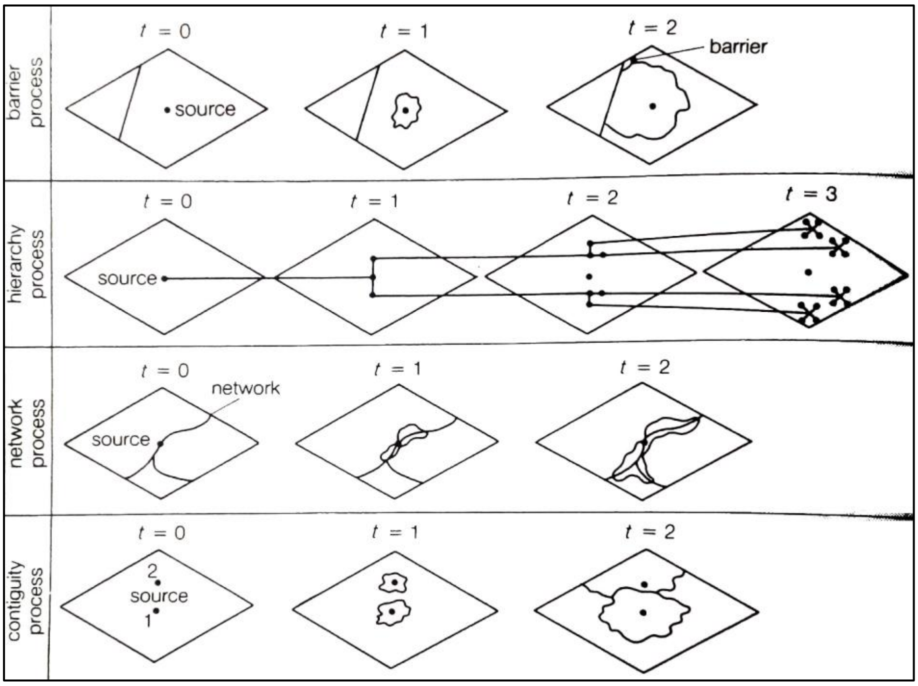


Fig. 1.10. *Spatial patterns produced through time (t) by various processes. Source: Johnston, Gregory and Smith (1994), after Bennett (1978)*

1.2.3 Geography of agriculture and industry

Geographical conditions, as predictors for spatial distribution, are also important for the agricultural geography. They determine the distribution of arable farming and animal husbandry. The environmental and socioeconomic factors are considered as the most important ones for the spatial distribution. It is also important to distinguish natural or man-made favourable conditions (Toušek *et al.*, 2008).

The main environmental factors are the climate, soil quality and topographical relief. The climate affects agricultural production through the quantity and form of precipitation, temperature, wind and sunshine. The climate also determines the areas for efficient crop production. Precipitation is responsible for 55 – 65 % of crop yields. Temperature influences the growth of crops, in that crops need an optimal temperature in certain stages of their growth. Soil quality is fundamental for agricultural production. Soil quality depends on the parent material and on soil-forming processes, including climate and vegetation cover. Regarding topographical relief, the following sub-factors are the most important: type of the relief (in higher latitudes, for example, the lowlands are the most suitable landscapes for agriculture), altitude (vertical zonation of climate and altitude limitation) and slope (related to technical abilities of agriculture, level of mechanization and erosion). The cost of agricultural production is much higher in higher altitudes and more undulated terrain (Toušek *et al.*, 2008). The altitude limit for agricultural settlements is approximately 3500 m at the equator, 1000 m at 50° – 60° latitude and 10 m at 70° latitude (Votrubec, 1980).

Socioeconomic factors result from the activities of human societies. They are the final determinants of the distribution in agricultural production. The main socioeconomic factors are the technical level of the society, ownership rules, manners of soil exploitation, transport capabilities, location, size and efficiency of the agricultural enterprise, level of mechanization, production intensity, and interventions of state authorities. The location of agricultural production is important in respect to (1) customers, (2) substantial transport routes, (3) other agricultural enterprises, and (4) distribution of the agricultural and non-agricultural populations (Toušek et al., 2008). Hajn (1999) distinguishes 4 types of environments, according to the suitability for agricultural production:

(1) environment is not enabling agricultural activity at all,

(2) limited agricultural activity, risk of rapid soil exhaustion,

(3) high yields possible only through the employment of special procedures (fertilization, irrigation, crop rotation), and

(4) high yields possible without special procedures.

Since historical settlements were often bound to industrial production, it is necessary to also focus on the geography of industry. Toušek *et al.* (2008) divide the industrial localization factors according to

(1) their **spatial extent** into:
    a) macro-factors (climatic conditions, settlement structure) and
    b) micro-factors (availability of raw materials, infrastructure, transport to customer),

(2) their **dynamics** into:
    a) factors with decreasing value (climate, raw material etc.),
    b) factors with constant value (infrastructure, capital etc.), and
    c) factors with increasing value (information, environmental topics etc.), and

(3) their **character** into:
    a) environmental factors (see above),
    b) socioeconomic factors (energy, prices, demand, production costs, infrastructure etc.), and
    c) other factors (environmental topics, political interests etc.).

For example, the availability of raw materials was an important factor in the beginning of industry. A specific socioeconomic factor for the development of industry is energy with its remarkable changes of energy sources during the development of civilization (wood, coal, petroleum, natural gas, nuclear energy, alternative sources etc.) (Toušek *et al.*, 2008).

1.2.4 Driving forces of the landscape change

More evidence regarding factors that influence settlement development come from current observations, known as “driving forces”. Similar processes could have also influenced towns and villages in the past (cf. the geological doctrine of uniformity). Bürgi, Hersperger and Schneeberger (2004) define driving forces as, *“the forces that cause observed landscape changes, i.e. they are influential processes in the evolutionary trajectory of the landscape”*. There are five main types of driving forces: socioeconomic, political, technological, natural (site factors and natural disturbances), and cultural (Brandt, Primdahl and Reenberg, 1999; Bürgi, Hersperger and Schneeberger, 2004). Bürgi, Hersperger and Schneeberger (2004) noted that global warming can be an example of a natural disturbance. Political decisions have been perhaps the main driving force of landscape change in the current Czech Republic over the last 150 years (Bičík, Jeleček and Štěpánek, 2001). The political factors played also an important role even in the distant past: e.g. in 1293, a *locator* (= founder of a village) called Rudlin was ordered to re-establish the land division (and field pattern) of town Lysá with respect to *ius teutonicum* (Kuča, 1997). Kuča (1997) identified that the field pattern designed by Rudlin has remained visible in the landscape until today. Other authors stress the importance of current land use, nature conservation, economic influence, technological innovations and spatial planning (Seabrook, McAlpine and Fensham, 2006; Schneeberger *et al.*, 2007; Sklenička *et al.*, 2009).

1.2.5 Landscape and settlement typology

While searching for dependencies between settlement characteristics and geographical factors, it is necessary to focus (1) on landscape typology (since it reflects various natural, historical and cultural processes in the landscape) and (2) on settlement layout typology and its relation to environmental factors.

The typology of European cultural landscapes has been delimited by the "Dobříš Assessment", for which 30 landscape types have been identified (Meeus, 1995; Löw and Míchal, 2003). However, this typology is too coarse for use within the Czech Republic. A more detailed European landscape typology was presented by Mücher *et al.* (2010), who defining 350 landscape types in Europe. The landscape typology of the Czech Republic, based strictly on natural factors (geology, climate, altitude, soils, vegetation etc.) was delimited by Chuman and Romportl (2010), for which the researchers identified 11 landscape types. Landscape typology of the Czech cultural landscape has been studied by Löw and Míchal (2003) and Löw and Novák (2008). The latter study also reflects various characteristics of cultural and historical values (e.g. types of vernacular architecture, urban layouts or field patterns). An interesting approach to landscape typology was presented by Klír (2009), who divided the country into three zones, according to a prevailing subsistence strategy in the medieval and early modern periods.

The typologies of village layouts and field patterns in the Czech lands have been intensively studied by many authors since the 1950s (Pešta, 2000). Important ideas were introduced in the *Encyclopaedia of Vernacular Architecture* (Frolec and Vařeka, 1983) or in the research of abandoned medieval villages in Drahany uplands (Černý, 1992). Despite intensive research, the typology has not been unified until today (Pešta, 2000). Kuča has made a map showing the layout types of all villages within the Czech Republic (Hrnčiarová, Mackovčin and Zvara, 2009). The latest methodology by the Czech National Heritage Institute (Pešta, 2014) proposes the following types of village layouts (Fig. 1.11):

(1) **Cluster villages**[2] are characterized by an irregular layout with no intentional geometric composition (natural growth). They may be organized in linear or concentric forms. They occur especially in regions with an indented topography.

(2) **Square villages**[3] have a regular geometric composition (the homesteads are arranged along a regular – often rectangular – village square). This type of villages is usually found in the "old settlement area" (see chapter 1.1.1).

(3) The homesteads in **hide villages**[4] are arranged next to their neighbours along a road. A long strip of field (hide) belongs to each homestead. This type is common in regions that were colonized during the medieval or early modern period (e.g. the borderline mountains).

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[2] Czech: "hromadné (shlukové) vesnice".

[3] Czech: "návesní vesnice".

[4] Czech: "lánové vesnice".

(4) **Parcel / row villages**[5] are usually organized in a regular linear shape, often in one or two rows along a road. Typically, these were established between the 18th – 19th centuries.

(5) **Chain villages**[6] resemble hide villages, but they lack a regular field pattern. They may be clustered along a stream. These villages are common in Moravia/Slovakia borderland.

(6) **Other forms of villages** include mixed or transition forms, disperse mountain settlement etc.

Interestingly, this methodology often points out a clear relation between a village layout type and environmental conditions, especially in regards to topography.

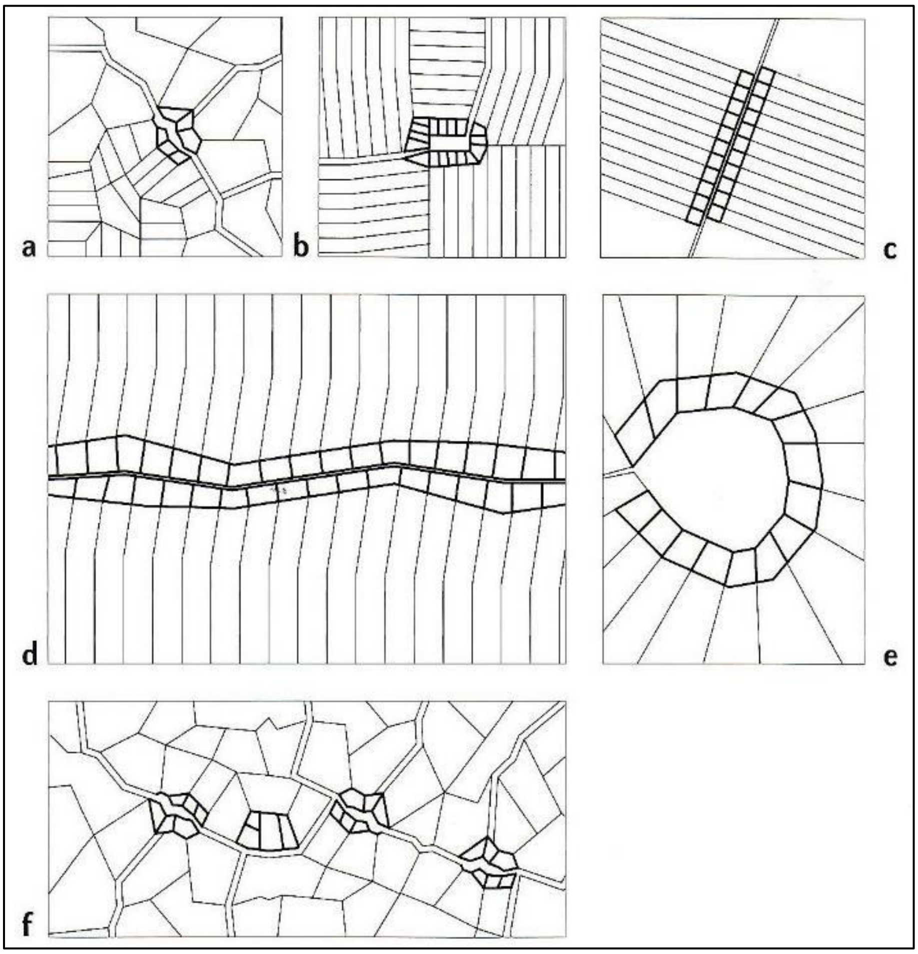

Fig. 1.11. *The basic types of village layouts: (a) cluster village, (b) square village, (c) row village, (d) hide village (linear form), (e) hide village (radial form), (f) chain village. Source: Pešta (2014)*

Other authors engaged in village typology reflect their topographical position. Bašovský and Mládek (1989) recognized five main topographical positions for Slovakia. A much more detailed review was presented by Valena (1991), who identified several tens of topographical positions. In his synthesis

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[5] Czech: “řadové vesnice”.

[6] Czech: “řetězové vesnice”.

on vernacular architecture, Pešta (2014) divided the Czech Republic into 41 regions with a characteristic form of vernacular architecture. Pešta also claims that this relatively high diversity has been caused by different geographical and topographic conditions in each respective region.

1.3 Ecology

Investigations into the effect of environmental conditions on the growth, distribution and other characteristics of individuals as well as whole population are classic topics in ecology. Therefore, it can be helpful to gather a few pieces of ecological knowledge related to our topics. It should be noted that the following notes are just a basic overview and are not aimed to analyse the mentioned problems. The main source for the following paragraphs was the textbook *Essentials of Ecology* by Townsend, Begon and Harper (2008).

Ecological theory distinguishes between environmental *factors* (its properties, such as temperature, humidity or altitude; the factors are not consumed by organisms) and *sources* in environment (energies and chemical matters, such as like water or raw materials; the sources are consumed by organisms) (Townsend, Begon and Harper, 2008). This principle can also be applied to human settlements: for example, soil quality or transport possibilities are *factors*, meanwhile drinking water, iron, coal or space are *sources*. Diverse organisms prefer different factors, and what is “mild” for one species, can be “harsh” for the others. Therefore, such an evaluation of factors is always related to a specific species, subsistence strategy and way of living (Townsend, Begon and Harper, 2008). Similarly, human communities can benefit differently from environmental factors based on their subsistence strategies (types of agriculture / grazing / mining / hunting). Technological innovations can very efficiently change the level of this benefit (e.g. nitrogen fertilizers pushed agricultural yields to a higher level, which enabled to grow crops in regions with lower natural soil fertility). The occupation or subsistence strategy of inhabitants could also determine the position and other characteristics of their settlements (Klír, 2009; Dong *et al.*, 2013). Interestingly, environmental conditions can even significantly affect the traditions and customs of communities (Diamond, 2014). The environment becomes a limitation of growth rather than a strict restriction. However, a concentration of many limiting factors can contribute to settlement abandonment (e.g. Šantrůčková and Fanta, 2014). Finally, the concept of the ecological niche can be also applied to human communities.

Ecology recognizes three general patterns of organism distribution (Fig. 1.12): aggregated/clumped (the organisms are in clusters), random (the distribution does not reflect interactions between organisms) and regular/uniform (the distances among individuals are even); organism distribution may also depend on the scale (Townsend, Begon and Harper, 2008). The same rules are also obviously valid for human settlements.

Population dynamics are another important factor which may shape the human settlements: if enough resources are available, small populations can grow rapidly. However, when population becomes more dense, the resulting competition effect starts to limit the growth (Townsend, Begon and Harper, 2008). Thus, with limited resources, populations cannot grow ad infinitum.

Several trade-offs, which were possibly considered during the selection of a place for settlement establishment, remind me patterns describing the foraging behaviour of predators. Townsend, Begon and Harper (2008) recognize a series of dilemmas regarding the foraging behaviour of predators when choosing living spaces:

(1) Will an individual prefer a place with long-term high energy gain, or a place with the lowest risk of long-term periods of low energy gain?

(2) Will an individual select a place with abundant resources albeit a higher risk of predation, or a place with no risk of predation but with low resources?

(3) Will an individual stay in a single place, or will it search for a second one?

(4) Is it better to settle in a location with high resources and high competition, or in a place with low resources and low competition?

(5) How many sources (originally: prey species) should be considered before settlement? How many subsistence strategies should be used?

It can be argued that all these dilemmas reflect in human behaviour, respectively in the manners of settlement establishment and development. For example, was it better in the 17th century to live close to a main road, benefitting from better trade possibilities, but risking damage from by-passing foreign armies, or in the "wilderness", sacrificing trade for safety? I also expect that we could find different human settlement strategies, dependent on various environmental conditions.

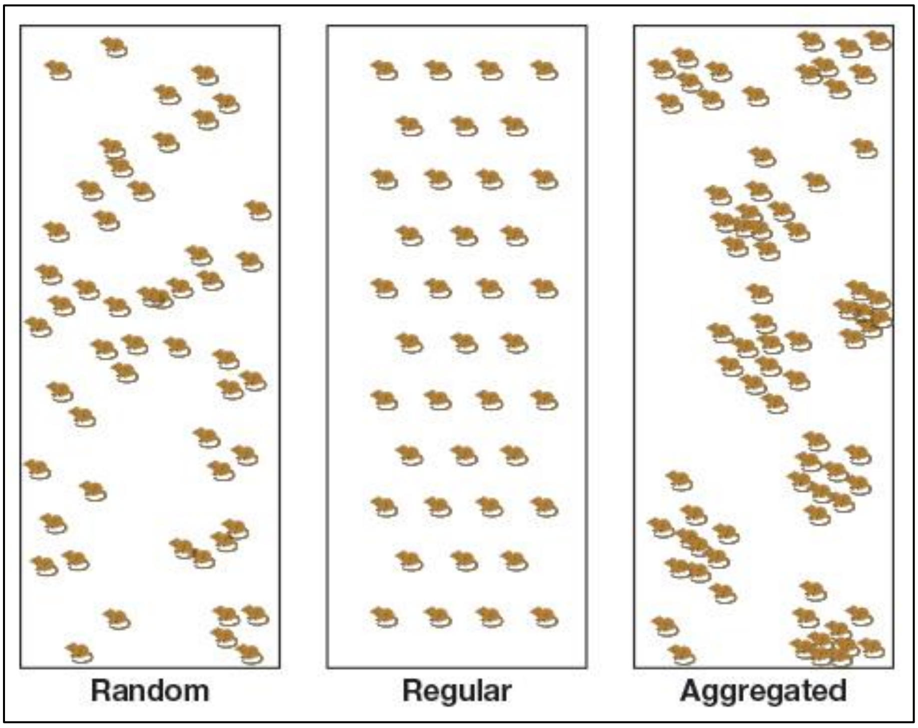

Fig. 1.12. *Patterns of organisms' distribution. Source: Townsend, Begon and Harper (2008)*

1.4 Questions

A substantial part of historical and archaeological studies engages interpretations of single historical sources. The next step may be putting the information into a broader context (social, cultural, historical, ecological etc.). This phase of research can bring remarkable results and may be necessary for solving continuing questions, e.g. settlement dynamics on longer spatial or temporal scales. Unfortunately, the topic of settlement dynamics dependence on environmental conditions has not yet been described in sufficient detail, although its importance has been underlined by many authors.

Due to a lack of historical sources from the medieval period, micro-regional studies are sometimes the only possibility for historical-geographical research (Eva Semotanová, personal communication, July 2014). This results in a clear limitation of the historians' work (too few of too small study samples, low possibilities of generalization). Nevertheless, historians are aware of this issue, as stated by Žemlička (1974) already 45 years ago: *"If we find out which soil types and geo-botanical units, which terrain and altitudes were bound with particular settlement layers, we may formulate serious, yet not generalizable conclusions. The same applies to field pattern development, to structural changes of the settlement, to the age of local names,"* [7]. The situation in archaeology is much better, as, in this field, interdisciplinary cooperation with environmental archaeology and other disciplines has become standard (e.g. Beneš and Brůna, 1994a; Gojda, 2000; Dreslerová and Pokorný, 2004; Kuna *et al.*, 2004; Beneš and Pokorný, 2008; Gojda *et al.*, 2010; Pokorný, 2011; Malina, 2012, 2015).

I tried to sum up the issue of settlement development from the points of view of various scientific disciplines. It is interesting, that the same remarks have been unanimously proposed by different fields (e.g. that the importance of environmental factors has been decreasing with increasing technological abilities). We can thus conclude that:

(1) Since the 19th century, it has been popular to explain (especially prehistoric) settlement distribution through an environmental determinist lens; however, current archaeology considers environmental factors more as a limitation or support for settlement development rather than as a strict determinant (Kuna *et al.*, 2004). Environmental determinism is therefore not considered an all-explaining theory, but it is believed to be only one of many possible factors influencing settlement development. Many authors claim that environmental and socioeconomic conditions previously and currently have a significant influence on settlement development. However, hardly any authors express:

   a) which factors (environmental or cultural) were more important and how this relation developed throughout the history,

   b) what and how factors affected which historical processes, and

   c) a description of causal links of such influence (e.g. Zhang, Lee, Wang, Li, Pei, *et al.*, 2011; Lee, 2014).

   These topics have been more intensively studied for the prehistoric period. However, much less interest has been given to the medieval or modern period.

(2) The current theories of settlement patterns can construct immensely remarkable models. Unfortunately, though, these models have been mostly used to describe or analyse the stationary state of a landscape. It may be very interesting to use these models in order to analyse the historical development of settlements (e.g. Brown and Witschey, 2003).

(3) We can expect the existence of a relationship between various landscape types and specific answers for certain settlement processes, resulting in a specific settlement pattern. However, such a relation has not yet been exactly proven.

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[7] Czech original: *"Zjištěním, na které půdní typy a geobotanické jednotky, na jaký terén a na které výškové oblasti se vázaly jednotlivé vrstvy sídlišť, získáme podklady, z nichž můžeme formulovat závažné, i když ne generalizující závěry. Totéž platí o vývoji plužiny, o strukturálních změnách osídlení, o stáří místních jmen."* Source: Žemlička (1974).

(4) Transfer of analogies between different scientific disciplines may result in great adventure with unclear ending. But we cannot exclude that such a way could lead to interesting findings.

The above-mentioned thoughts can be reformulated into the following questions / study topics: How did the influence of environmental and geographical conditions affect settlement structure, settlement dynamics, settlement distribution, and agricultural activities throughout different historical periods and what were the causal links of such an influence? Can we speak about settlement structure "archetypes" based on topography, landscape types or biomes? Can we derive an "agricultural potential" of historical landscapes or potential natural settlement distribution? How did the ecosystem of medieval or modern age villages work in Central Europe? What were its ecological requirements? How did settlement dynamics function during colonization or regeneration after a disturbance, such as war or natural disturbances? Can we construct a simulation model of medieval colonization based on a known influence of environmental conditions? Is it possible to find analogies between human subsistence strategies or historical settlement processes with strategies of other species? Can we use some physical or natural laws to explain settlement processes in human history?

For detailed research during my PhD study, I focused on three of these question: **(1) How did environmental conditions affect the settlement regeneration after the Thirty Years' War? (2) How did extreme historical floods affect the selection of places for settlement establishment during the medieval and modern period? (3) How much can we trust the dating of historical settlements obtained from written sources?**

An uncovering of all these topics should lead to three objectives: (1) primary historical research [the level of dependence on nature and its evolution, unusual approaches to the landscape and settlement history, exact statistics instead of rough estimates etc. (cf. Žemlička, 1974)], (2) a historical and environmental contribution to the current discussion on sustainable development and future development of the cultural landscape (cf. Antrop, 2004) and (3) a combination of historical and ecological approaches as a methodological contribution.

2 Dissertation papers

Paper I: Equilibrium dynamics of European pre-industrial populations: The evidence of carrying capacity in human agricultural societies

The first paper describes population dynamics in the period of the Thirty Years' War, and subsequent centuries, in the context of human carrying capacity. We have found that human communities in this period were limited by environmental carrying capacity even in the 17th century, i.e. deep within the modern period. Our paper shows that the main limiting factor for population growth was soil fertility and cadastre size – or, in other words, food availability [this result is in accordance with previous findings regarding human carrying capacity (Seidl and Tisdell, 1999; Hopfenberg, 2003; Zhang *et al.*, 2007)].

Published in *Proceedings of the Royal Society B: Biological Sciences*, IF_{2017} = 4.847, category ranking: Biology 9 of 85 (Q1), Ecology 18 of 160 (Q1), Evolutionary biology 8 of 49 (Q1).

Authorship claims: Václav Fanta 30 %, Miroslav Šálek 15 %, Jan Zouhar 15 %, Petr Sklenička 10 %, David Storch 30 %.

Paper II: How long do floods throughout the millennium remain in the collective memory?

The second paper was focused on the influence of big floods on the historical memory of people. The main question was whether people are able to transmit prior catastrophic flood information to younger generations, and whether this passed memory can affect the decision making of younger generations in decisions for settlement locations. The results show that the flood memory really exists, but its effects are limited only up to approximately 25 years (i.e. one generation). We attribute this limitation to population ageing and a loss of eye-witnesses (Vansina, 1985; Pfister, 2016). It could be stated that the younger generations might have heard about floods from generational storytelling, but it obviously had no effect on their behaviour.

Published in *Nature Communications*, IF_{2017} = 12.353, category ranking: Multidisciplinary sciences 3 of 64 (Q1).

Authorship claims: Václav Fanta 45 %, Miroslav Šálek 25 %, Petr Sklenička 30 %.

Paper III: How old are the towns and villages in Central Europe? Archaeological data reveal the size of bias in dating obtained from traditional historic sources

The third paper studied a more specialized and practically oriented topic: time-lag in the dating of historical sites. While time-lag was quite long (150 to 300 years) in the early and high medieval periods, it became strongly shortened in the late medieval and early modern period. At the end of the 16th century, the probability of time-lag was less than 5 % (towns) or 25 % (villages). Unfortunately, data for the 17th and 18th centuries was not available. However, we expect that the time-lag would be permanently decreasing during these centuries.

Submitted into *Journal of Archaeological Science*, currently after revision, IF_{2017} = 3.061, category ranking: Anthropology 7 of 85 (Q1), Geosciences, multidisciplinary 49 of 190 (Q2).

Authorship claims: Václav Fanta 50 %, Jan Zouhar 25 %, Jaromír Beneš 10 %, Jiří Bumerl 5 %, Petr Sklenička 10 %.

Note: IF values and category rankings are from Web of Science (5th May 2019).

2.1 Paper I: Equilibrium dynamics of European pre-industrial populations: The evidence of carrying capacity in human agricultural societies

Authors:

Václav Fanta, Miroslav Šálek, Jan Zouhar, Petr Sklenička, David Storch

Abstract:

Human populations tend to grow steadily, because of the ability of people to make innovations and thus overcome and extend the limits imposed by natural resources. It is thus questionable whether traditional concepts of population ecology, including environmental carrying capacity, can be applied to human societies. The existence of carrying capacity cannot be simply inferred from population time-series, but it can be indicated by the tendency of populations to return to a previous state after a disturbance. So far only indirect evidence at a coarse-grained scale has indicated the historical existence of human carrying capacity. We analysed unique historical population data on 88 settlements before and after the Thirty Years War (1618 – 1648), one the longest and most destructive conflicts in European history, which reduced the population of Central Europe by 30 – 50%. The recovery rate of individual settlements after the war was positively correlated with the extent of the disturbance, so that the population size of the settlements after a period of regeneration was similar to the pre-war situation, indicating an equilibrium population size, i.e. carrying capacity. The carrying capacity of individual settlements was positively determined mostly by the fertility of the soil and the area of the cadastre, and negatively by the number of other settlements in the surroundings. Pre-industrial human population sizes were thus probably controlled by negative density dependence mediated by soil fertility which could not increase due to limited agricultural technologies.

Key words:

Thirty Years War, disturbance, regeneration, rural settlement, historical geography, population ecology, demography, human carrying capacity

Authors’ contributions:

V. F., M. Š., D. S. and P. S. designed the research, V. F. collected the data, M. Š. and J. Z. performed the data analyses, and D. S., V. F., P. S., J. Z. and M. Š. wrote the paper.

Published as:

Fanta, V. *et al.* (2018) ‘Equilibrium dynamics of European pre-industrial populations: the evidence of carrying capacity in human agricultural societies’, *Proceedings of the Royal Society B: Biological Sciences*, 285(1871). doi: 10.1098/rspb.2017.2500.

2.1.1 Introduction

One of the fundamental principles of population ecology is negative density-dependence, i.e. population regulation via a negative feedback between population density and growth rate (Turchin, 2003). Such a feedback implies that there is some level of population density above which the population growth rate is negative. We call this level the carrying capacity, and the population density is assumed to oscillate around this stable equilibrium. However, population time-series often reveal long-term trends, either decreasing or increasing. This can be interpreted either as a trajectory from a state which is far from the equilibrium towards an as yet unreached equilibrium, or, alternatively, as a continuous change in the carrying capacity itself. The latter interpretation is the most conventional in the case of human population dynamics. It is mostly assumed that people are able to overcome limitations imposed by the environment. In this way, they continually increase the carrying capacity, potentially even above the level reached by the population at any particular moment. This interpretation would imply that the carrying capacity may never actually be reached in human populations, making the very concept problematic. However, it is possible that this ability characterizes modern civilization with its advanced technologies, while pre-industrial human populations may have been relatively stable due to density-dependent effects. Human populations may therefore have been controlled by negative density dependence mediated by the environment for most of the history of mankind.

While the issue of human carrying capacity has been widely discussed in recent decades, especially in the context of the potential carrying capacity of the planet (e.g. Hardin, 1968; Cohen, 1995b; Townsend, Begon and Harper, 2008; Ehrlich and Ehrlich, 2013), there is surprisingly little evidence of its existence during human history. Most studies have either been purely theoretical, or have studied historical population changes at very coarse scales (Zhang *et al.*, 2007; Lee, 2014). There is some indirect evidence of population limitation in pre-industrial human populations: population densities of hunters-gatherers, for example, correlate well with environmental net primary productivity (Hamilton, Burger and Walker, 2012), indicating resource limitation, and human population size increased very slowly before the modern period (U. S. Census Bureau, 2013) [rapid changes of human population has been reported even in the distant history, but such events occurred only occasionally (Shennan *et al.*, 2013; Goldberg, Mychajliw and Hadly, 2016)]. However, these lines of evidence do not reveal whether human population dynamics did indeed have a tendency to approach stable equilibrium. Density-dependent equilibrium dynamics is characterized by the relationship between the deviation from the equilibrium population size (carrying capacity) and the change in the population growth rate. A proper demonstration of population regulation via negative density dependence should therefore include a disturbance effect that arguably moves the population out of equilibrium, and a recovery which leads back to the equilibrium density. Data of this kind are difficult to obtain, compromising our ability to reveal equilibrium density-dependent dynamics, and thus the existence of carrying capacity, in human populations.

There are a few cases that can be considered to provide evidence in this matter. At the beginning of the 15th century, the population of the Czech lands was reduced by the Hussite Wars (1419 – 1434). Since that time, the population has been growing, but at the end of the 16th century several famines occurred (Fialová *et al.*, 1998). Historians have interpreted this situation as the achievement of the country's production potential (i.e. the carrying capacity) after a long period of population growth (Fialová *et al.*, 1998). Similarly, about 100 million people died due to famines, epidemics, wars and riots in China in the 18th and 19th centuries (Lee, 2014). Lee (2014) has suggested that all the unrests and famines were primarily caused by overpopulation in combination with the little ice age – the population growth was faster than the growth of agricultural yields, so the per capita food availability decreased severely. After the famines and wars erupted, many people died, lowering the population pressure, and the situation stabilized (Lee, 2014). A decrease in population size due to a disturbance and a subsequent return to the previous population level was also inferred on the basis of a simulation model of human population dynamics during the last glacial maximum (30 – 13 ky BP) in Europe (Tallavaara *et al.*, 2015). However, all the cases mentioned above represent post-hoc interpretations of observed population crises. Equilibrium population dynamics has never been tested in a proper quantitative way, demonstrating that negative density dependence really led to population stabilization.

Here we utilize a unique historical data set comprising population count data from 1618 – 1757 that include the Thirty Years' War (1618 – 1648), a major disturbance in European history (Wilson, 2011). The war affected different settlements in central Europe differently, sometimes extirpating almost all the inhabitants directly or indirectly (due to destruction of food reserves, subsequent starvation and the spread of disease (Steinberg, 1966; Asch, 1997; Fialová *et al.*, 1998; Lederer, 2011)), while sometimes there was only a negligible effect on population size (Kirsten, Buchholz and Köllmann, 1965). We thus have a unique opportunity to explore quantitatively the recovery dynamics of individual settlements (Fig. 2.1.1) after this extensive disturbance event, and to assess which factors determined settlement population sizes. If equilibrium population size is determined by the environmental carrying capacity of a given settlement, we should expect the following three patterns: (A) the rate of recovery should be positively related to the extent of the disturbance, i.e. to the distance from the assumed equilibrium; (B) the population size of the settlements after regeneration should be similar to the pre-war population size, and should not depend on the extent of the disturbance; (C) the equilibrium population size of settlements should be positively related to the area of land managed by each settlement and to the soil fertility, and negatively to the number of neighbouring settlements that share the land.

2.1.2 Materials and Methods

2.1.2.1 Data collection

88 villages were selected within the historical borders of Bohemia (Semotanová, 2006) in the present-day Czech Republic, using geodata from the ArcČR 500 database (Arcdata Praha, 2014). The selection was based on a random placement of 90 points (using the Random Points tool in QGIS software), which were set at least 10 km apart to reduce repetition of the same attribute sets in neighbouring settlements. This requirement resulted in a relatively even spatial distribution of the tested villages in the study area (Fig. 2.1.1). To each of the 90 points we assigned the nearest village from the CZ RETRO database (Kuča, 2014), which was recorded in the Tax Register of 1654 (Doskočil, 1953, 1954). Two points were excluded from the dataset, as there was no village within a distance of 5 km. These steps were processed in the QGIS 2.4.0, QGIS 2.6.0, QGIS 2.8.1 (QGIS Development Team, 2017), GRASS GIS 7.0.0RC2 (GRASS Development Team, 2014) and ArcGIS 10.2 (ESRI, 2017).

The data for the analysis of the population dynamics were collected using two editions of historical documents, which recorded the numbers of farmers (= the numbers of farms = population size) in villages. The period immediately after the Thirty Years' War is documented by the Tax Register from 1654 (Doskočil, 1953, 1954), while the Theresian Cadastre captures the situation in 1757, more than a hundred years after the war (Chalupa *et al.*, 1964, 1966). The Tax Register lists the numbers of "abandoned" farms (which were destroyed or abandoned during the Thirty Years' War). These abandoned farms were added to the number of farmers in 1654 to yield the number of farmers before the war (in 1618). In this way, we established the numbers of farmers/farms in each village in ca. 1618 (before the war), in 1654 (just after the war), and in 1757 (after the regeneration period). Additional time points were not available, as no other comparative data for the whole country were recorded until the end of 18th century (we checked the "Tax Register Revisitation" from 1670s (Anonymous, 1670), but it covers approximately just one third of selected villages). The Theresian Cadastre from 1757 is the only source of data covering the whole country between the end of Thirty Years' War and the beginning of the industrial revolution.

Table 2.1.1. *List of used predictors and settlement characteristics*

Variable name	**Data type**	**Data sources**
Size of the settlements:		
settlement size before war	Number of farmers in the village in 1618, i.e. before the Thirty Years' War [No.]	Tax Register of 1654 (Doskočil, 1953, 1954)
settlement size after war	Number of farmers in the village in 1654 [No.]	Tax Register of 1654 (Doskočil, 1953, 1954)
settlement size after regeneration period	Number of farmers in the village in 1757 [No.]	Theresian cadastre (Chalupa *et al.*, 1964, 1966)
Cultural conditions:		
settlement age	Date of the first written note in historical documents [year]	Historical lexicons (Profous, 1947, 1949, 1951; Růžková *et al.*, 2006)
settlement density before war	Number of settlements within a radius of 4 km from the studied village in 1618 [No.]	Geodatabase and historical lexicon (Růžková *et al.*, 2006; Arcdata Praha, 2014)
cadastre size	Size of cadastre [m^2]	Geodatabase and historical maps (Arcdata Praha, 2014; Land Survey Office, 2015)
Environmental conditions:		
density of rivers and streams	Total length of rivers and streams within a radius of 4 km from the centre of the studied village [m]	Database of rivers and streams (T. G. Masaryk Water Research Institute, 2012)
terrain undulation	difference in elevation per unit area [m]	Digital terrain model (GISAT, 2007)
altitude	Altitude [m]	Digital terrain model (GISAT, 2007)
soil fertility	Weighted average of relative natural soil fertility in the cadastre [%]	Database of soil units (Bečvářová, Vašek and Vaníček, 1988; Czech Office for Surveying Mapping and Cadastre, 2014)

Village characteristics were taken from several sources. The age of the settlement (referred to as *settlement age* in all tables and figures) was retrieved from the Historical Lexicon of Municipalities (Růžková *et al.*, 2006). In the case of abandoned villages, which were not listed in this lexicon, the age was established from the database of local names in the Czech territory (Profous, 1947, 1949, 1951). The settlement density in 1618 (*settlement density before war*) was calculated as the number of neighbouring villages within a radius 4 km from the village. This is justified by contemporary ethnographic observations: in traditional agricultural central and eastern European societies, the majority of cultivated agricultural land is usually located within 2 km (a 30-minutes' walk) from the village (Hajnalová and Dreslerová, 2010). As we were interested in the interaction with neighbouring villages, we multiplied this distance by two. The settlement density was calculated using the ArcČR 500 database (Arcdata Praha, 2014). The calculation included only villages actually existing in 1618 [their founding dates were obtained from the Historical Lexicon of Municipalities (Růžková *et al.*, 2006)]. The size of the cadastre (*cadastre size*) was determined from current cadastres listed in the ArcČR 500 database (Arcdata Praha, 2014). If the cadastre belonging to the village was later incorporated into a larger unit (e.g., if it later became a part of a military training area) or if a cadastre adjacent to the studied cadastre was established after 1618, we used the size of the cadastre documented in the Stable Cadastre from the first half of the 19th century, the oldest available cadastral map (Land Survey Office, 2015). To determine the *density of rivers and streams*, we used the current data from the HEIS database (T. G. Masaryk Water Research Institute, 2012). Subsequently, using the Sum Line Lengths tool in the QGIS program, we calculated the total length of rivers and streams within a radius of 4 km from the centre of the village (as in the case of settlement density). The values describing the undulation of the terrain (*terrain undulation*) were derived from the STRM digital terrain model (GISAT, 2007). Terrain undulation was calculated using the Roughness Index tool in the QGIS software, which records the differences in elevation per unit area. For each studied settlement, we calculated the average value for a circle 4 km in radius, using the Zonal Statistics tool in the QGIS. *Altitude* was calculated using data from the STRM digital terrain model (GISAT, 2007). Data for individual villages were recorded in the GRASS GIS program, using the r.what tool. *Soil fertility* was calculated using the database of soil units in the Czech Republic (Czech Office for Surveying Mapping and Cadastre, 2014). Each soil unit was assigned a specific natural soil fertility value, expressed relatively as a percentage of the most productive soil unit in the Czech Republic (the values varied between 4.9 % and 100 %) (Bečvářová, Vašek and Vaníček, 1988). The values were calculated as a weighted average of the soil fertility in the cadastre of the village.

With one exception, all cultural variables were derived from editions of historical documents or from historical literature, and they related directly to the time being investigated (Table 2.1.1). The only exception is the size of the cadastre, which was derived from more recent maps. However, other studies have shown that the cadastre boundaries have not changed significantly over time (e.g. Buterez, Cepraga and Brezoi, 2015). The analyses of environmental factors utilized data from current databases and maps. In some factors (density of rivers and streams, terrain undulation and altitude), the current state can be assumed to correspond with the state in the first half of the 17th century. Because soil fertility could have changed with time, we decided to use a relative comparison, as is commonly used, e.g. in the study of prehistoric settlements (Dreslerová *et al.*, 2013).

All data used here are available in Dataset S1. The dataset also contains two additional variables, derived from the indicators of settlement size. Settlement growth during regeneration period is defined as the average annual percentage growth between 1654 and 1757, obtained from the post-war settlement size and size after the regeneration period as 100[(size after regeneration period / size after war)1 / (1757 − 1654) − 1]. Extent of disturbance measures the percentage decrease of settlement size between the pre-war and the post-war period, i.e. is calculated as 100[(size before war − size after war) / size before war].

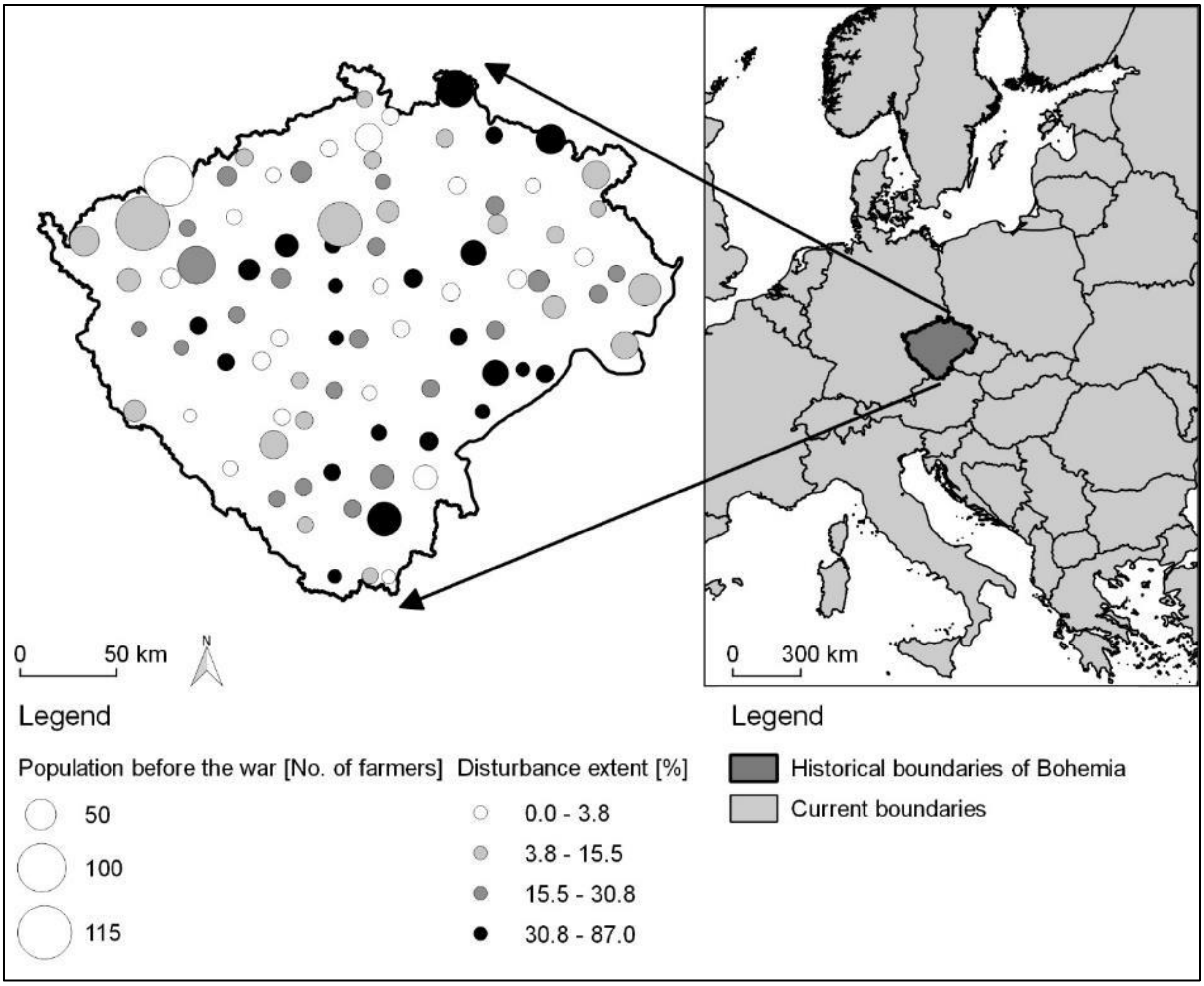

Fig. 2.1.1. *Position of Bohemia within Europe, the villages selected for analysis, with denoted pre-war population size and extent of disturbance. Data sources: Doskočil (1953, 1954), Semotanová (2006), Arcdata Praha (2014), ESRI (2015)*

2.1.2.2 Data analysis

All cultural and environmental variables were considered as potential predictors for determining the pre-war size of the settlements as an indicator of carrying capacity. Three predictors (*cadastre size*, *terrain undulation*, *settlement density before war*) exhibited substantial positive skewness; these variables were logarithmically transformed in all analyses. Collinearity among the predictors was assessed using variance inflation factors (VIFs). The maximum VIF was 2.91 (*soil fertility*), way below the usual threshold of 10; nevertheless, to check the robustness of our results, we inserted the variables into regressions in a hierarchical manner.

We applied two different modelling strategies to assess predictor effects. Firstly, we used a nonlinear regression model that directly accounts for the discrete nature of the outcome variable, namely the Poisson count regression. To adjust for overdispersion, we used a Poisson quasi-maximum likelihood (QML) estimator with a robust sandwich estimator of the coefficient covariance matrix (Crawley, 2015).

Secondly, since significant patterns of spatial autocorrelation were detected for both the dependent variable (Geary's $C = 0.953$, $p = 0.004$) and the residuals from (non-spatial) linear regressions

($C = 0.945$, $p = 0.001$ for the most saturated model), we complemented the Poisson regression with a linear model that allowed for spatially autoregressive random errors, known as the spatial error model. In order to both eliminate excessive skewness and make coefficients comparable across the two models, we logarithmically transformed the dependent variable. The spatial weighting matrix was based on Euclidean distances of the villages (obtained from latitude and longitude of the village centre), and we used Pisati's (2001) implementation of the ML estimator for the spatial error model.

As the number of observations is rather small, statistical inference is not very reliable and has to be treated with caution. Therefore, we decided to complement traditional analysis of variable significance with a measure called *relative variable importance* (RVI). This measure is recommended e.g. by Arnold (2010) and based on the ideas of model selection through Akaike's information criterion with small-sample correction (AIC_c). Its calculation was carried out in three steps: (1) we estimated the spatial error model for all possible subsets of the 7 predictor variables, giving us a total of $2^7 - 1 = 127$ different model specifications; (2) for each model, we calculated the Akaike weight, see e.g. Burnham and Anderson (2002); (3) for each predictor, RVI was obtained by summing the Akaike weights across all models that included the predictor. Thus, RVI can loosely be interpreted as the probability that the predictor is contained in the most accurate model out of the 127 candidates.

An analogous analysis was carried out to study the determinants of *settlement growth during regeneration period*. Identical explanatory variables we included, with the addition of *extent of disturbance* and *size before war*. Due to the continuous nature of the dependent variable, only the spatial error model was applied.

2.1.3 Results and discussion

The regeneration rate of the settlements was positively correlated with the extent of the disturbance – the increase in the population of a settlement (numbers of inhabited farms) between 1654 and 1757 was proportionate to the percentage of farms within the settlement that were destroyed during the war (Fig. 2.1.2A). This is in accord with Dokoupil *et al.* (1999), who argued that settlements in more damaged regions regenerated faster than settlements in less damaged regions within the region of Bohemia. In fact, the extent of disturbance was the only significant factor explaining the settlement growth during regeneration period (Table 2.1.2, Fig. 2.1.3) and its relative variable importance almost attained the theoretical bound of 1 (RVI > 0.999). This finding represents a direct evidence of the negative density dependence at the level of individual human settlements, regardless of whether the carrying capacity (the equilibrium population size) was constant or not. However, the fact that the resulting settlement size after regeneration was similar to the settlement size before the war (Fig. 2.1.2B, 2.1.2D), irrespective of the size of the disturbance (Fig. 2.1.2C), indicates that carrying capacity did not substantially change in this period. We cannot, however, exclude the possibility that the size of the settlement increased after the study period due, e.g. to changes in agricultural technologies or some other effects.

The negative density dependence was probably mediated by increasing demand for food when the number of farmers increased relative to the area of available land and the soil fertility [availability of food has been stressed as the most important population size limiting factor (Seidl and Tisdell, 1999; Hopfenberg, 2003; Zhang *et al.*, 2007; Zhang, Lee, Wang, Li, Pei, *et al.*, 2011; Zhang, Lee, Wang, Li, Zhang, *et al.*, 2011)]. We therefore tested the factors affecting the pre-war settlement size with respect to the variables potentially affecting food production (Table 2.1.1). The results from alternative model formulations, the Poisson model and the spatial error model, tell a reasonably consistent story. Two variables stand out in terms of relative variable importance (Fig. 2.1.4), *soil fertility* and *settlement density before war*, followed by *cadastre size* and *settlement age* (the latter two scoring differently in both models); the remaining variables (*altitude*, *terrain undulation*, *density of rivers and streams*) seem to be largely uninformative. In table 2.1.3, we present hierarchical regressions where predictors are entering the models in an order reflecting the relative importance results. In both specifications, *soil fertility*, *settlement density before war*, and *cadastre size* are the significant predictors, although the former two lose their statistical significance as additional variables are included, presumably due to a combination of collinearity and small sample size.

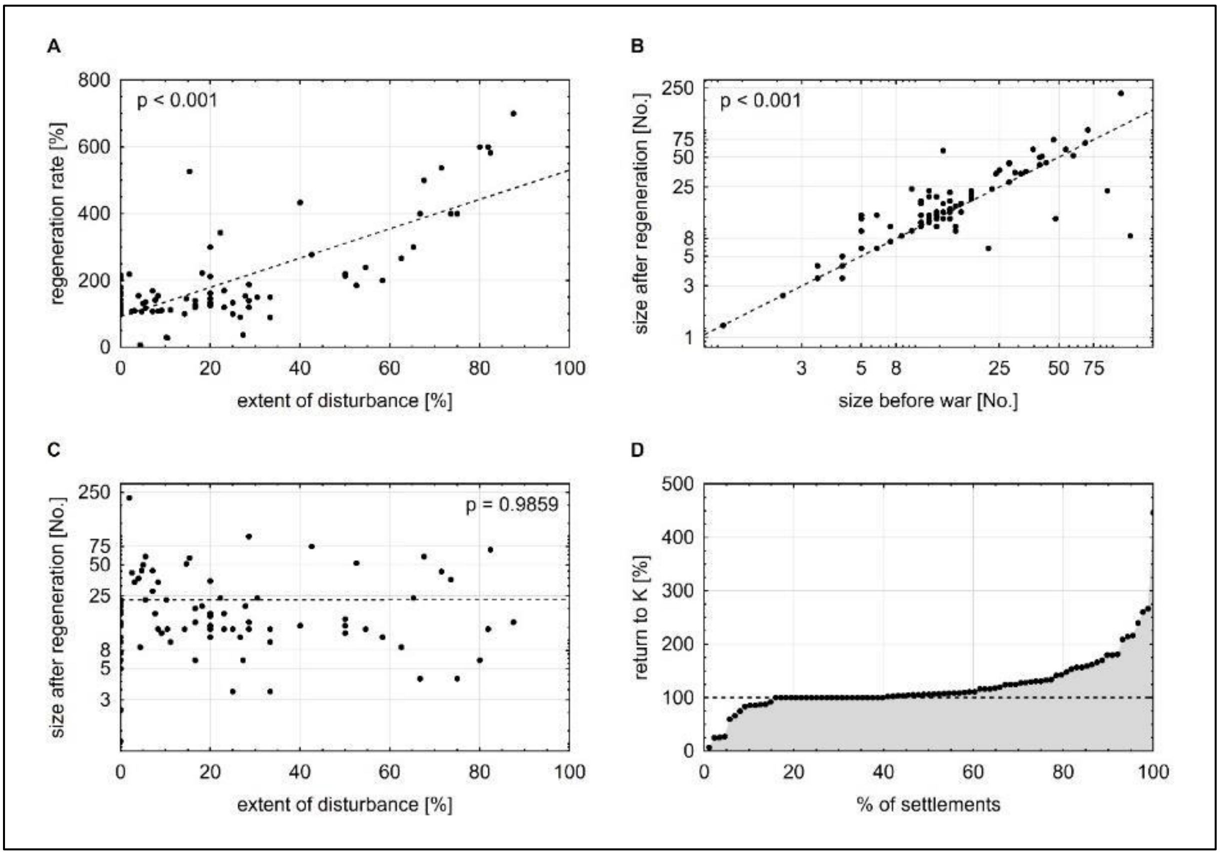

Fig. 2.1.2. *(A) Relationship between the regeneration rate and the extent of the disturbance. (B) Relationship between settlement size after regeneration (in 1757) and size before the war (in 1618). (C) Relationship between settlement size after regeneration (in 1757) and the extent of the disturbance. (D) Cumulative distribution of the ratio of post-war and pre-war settlement size (return to K).*

Legend: extent of the disturbance = percentage of farms destroyed during the war; regeneration rate = 100 × (number of farms in 1757, i.e. after regeneration)/(number of farms in 1654, i.e. after the war); return to K = 100 × (number of farms in 1757)/(number of farms in 1618, i.e. before the war). The dashed lines in panels A and C refer to linear least squares regression, while in panel B to y = x line. The dashed line in panel D refers to the 100 % value of the return to K

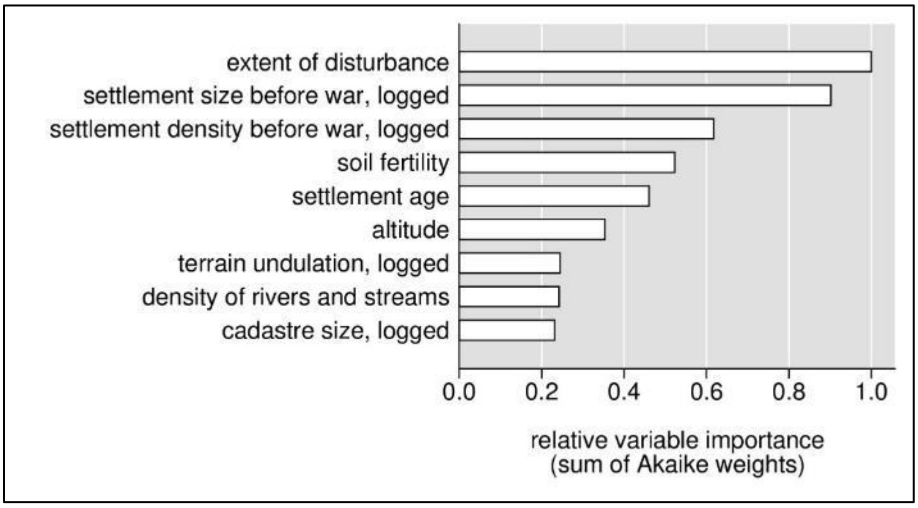

Fig. 2.1.3. *Relative importance of predictors of settlement growth during the regeneration period*

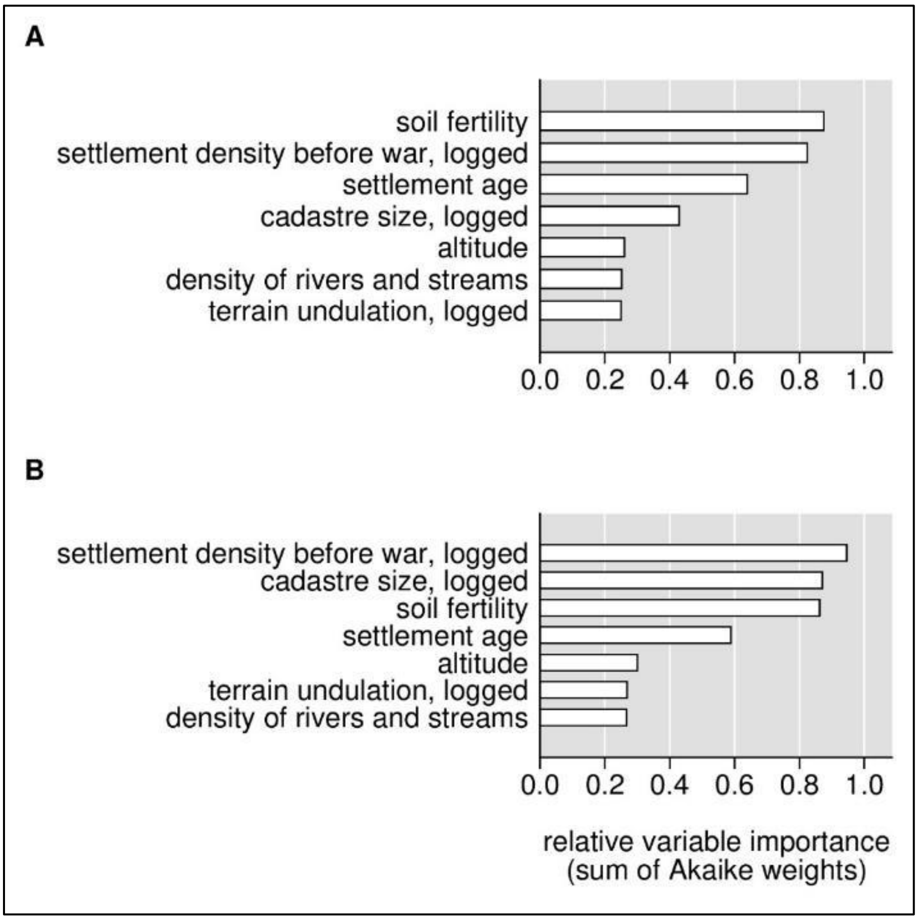

Fig. 2.1.4. *Relative importance of predictors of pre-war settlement size, based on (A) Poisson regression and (B) the spatial error model*

Table 2.1.2. *Predictors of settlement growth during the regeneration period*

Dependent variable:	***settlement growth during regeneration period***			
Regression model:	**Spatial error model**			
	Model 1	**Model 2**	**Model 3**	**Model 4**
extent of disturbance	0.0180*** (0.000)	0.0178*** (0.000)	0.0184*** (0.000)	0.0189*** (0.000)
settlement size before war, logged		−0.150 (0.131)	−0.192 (0.072)	−0.191 (0.090)
settlement density before war, logged			−0.0903 (0.366)	−0.129 (0.189)
soil fertility			−0.00210 (0.352)	−0.00432 (0.327)
settlement age				0.000545 (0.314)
altitude				−0.000531 (0.125)
terrain undulation, logged				−0.0238 (0.864)
density of rivers and streams				−0.00128 (0.549)
cadastre size, logged				0.0137 (0.928)
Constant	0.0188 (0.716)	0.418 (0.077)	0.774 (0.053)	0.354 (0.890)
Observations	88.0	88.0	85.0	84
AIC$_c$	134.604	130.464	128.636	137.660
Max. VIF	1.000	1.001	1.105	2.961
Sig. of additional terms		0.131	0.323	0.554

Notes: (i) p-values based on Student's t distribution are shown in parentheses, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; (ii) last row shows the p-value of a Wald test for joint significance of terms added to previous model.

Table 2.1.3. *Predictors of pre-war settlement size*

Dependent variable:	***settlement size before war***			***settlement size before war*, logged**		
Regression model:	**Poisson QML (robust std. errors)**			**Spatial error model**		
	Model 1A	Model 2A	Model 3A	Model 1B	Model 2B	Model 3B
soil fertility	0.00341*	0.00316	0.00291	0.00906*	0.00791	0.00747
	(0.020)	(0.051)	(0.224)	(0.023)	(0.111)	(0.288)
settlement density before war, logged	−0.148*	−0.0419	−0.0603	−0.385*	−0.113	−0.168
	(0.040)	(0.634)	(0.483)	(0.042)	(0.601)	(0.447)
cadastre size, logged		0.150*	0.154*		0.385*	0.389*
		(0.046)	(0.035)		(0.012)	(0.012)
settlement age		−0.000320	−0.000384		−0.000843	−0.00100
		(0.346)	(0.266)		(0.320)	(0.242)
altitude			−0.000250			−0.000640
			(0.240)			(0.382)
terrain undulation, logged			0.0708			0.192
			(0.332)			(0.385)
density of rivers and streams			−0.000411			−0.00150
			(0.812)			(0.723)
Constant	1.164***	−0.958	−0.949	3.139***	−2.206	−2.091
	(0.000)	(0.534)	(0.544)	(0.000)	(0.488)	(0.538)
Observations	85	84	84	85	84	84
AIC_c	268.962	268.468	275.257	216.868	211.268	217.334
Max. VIF	1.076	1.427	2.908	1.076	1.427	2.908
Joint sig. of additional terms		0.346	0.378		0.320	0.671

Notes: (i) *p*-values based on Student's *t* distribution are shown in parentheses, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; (ii) last row shows the *p*-value of a Wald test for joint significance of terms added to previous model.

Soil quality positively affected the pre-war size of settlements (Table 2.1.3) – settlement size was higher in areas with better soil quality, irrespective of (non-significant) elevation. On the other hand, the settlement size was negatively affected by the numbers of other settlements within a radius of 4 km, suggesting a competitive effect of neighbouring settlements. Since the cadastre borders had already been delimited at that time, the competition between neighbouring settlements must have comprised an access to shared resources, e.g. to common pastures or to deposits of raw materials. Finally, cadastre size positively affected settlement size. Settlement size thus increased with soil production capacity, combined with the area available for agriculture, and it decreased due to the competitive effect of other settlements in the surroundings. Historical human populations were thus locally and regionally limited by factors affecting food availability.

Human carrying capacity may not be constant. It depends on many circumstances, including technologies for exploiting resources, patterns of production and consumption, and various exogenous factors (Arrow *et al.*, 1995; Cohen, 1995b; Seidl and Tisdell, 1999; Hopfenberg, 2003). We focus here on the near-equilibrium dynamics during the pre-industrial period. However, the subsequent industrial era brought a new dimension to human population dynamics due to the ability of humans to increase local carrying capacity much more rapidly than any time before. This era proceeded by a series of evolutionary transitions characterized by technological innovations that stimulated population growth. This in turn increased demands on the productivity of farmland, stimulating further boom in the agricultural sciences [the intensification of agriculture began in Central Europe in the first half of 19th century (Novák, 2007; Beranová and Kubačák, 2010; Matoušek, 2010)], leading to the intensification of agriculture and broad changes to the ecosystem (Steffen, Crutzen and McNeill, 2007). Transitions from rural and agricultural societies to urban and industrial societies may be considered as the most important global change process of the industrial age (Grimm *et al.*, 2015). Escalating rural-to-urban migration (Lambin *et al.*, 2001), which started after the abolition of serfdom in the Czech lands in 1848 (Nováček, 2005), makes it almost impossible to analyse the role of any potential equilibrium dynamics. The pre-industrial period that we have studied is therefore probably the last period that enabled the data to be interpreted in a straightforward way in terms of human carrying capacity. This does not necessarily preclude a role for carrying capacity even in modern times, but the concept becomes problematic whenever changes in carrying capacity take place in time scales comparable to the population growth itself, i.e. when the rate of the increase of carrying capacity is comparable to the rate in which a population itself approaches an equilibrium.

In summary, we have found that the traditional concept of environmental carrying capacity can be applied to historical human societies. Pre-industrial human population size was apparently controlled by negative density dependence mediated by soil fertility. Although there were certainly occasional increases of population carrying capacity driven by changes in subsistence technologies at least since the Neolithic revolution [e.g. the use of heavy plough and water mill or three-field crop rotation in the medieval period (Bartlett, 1994; Klápště, 2012a)], these changes were relatively rare and were followed by long periods of approximately constant population size driven by the negative density dependence mediated by limited soil fertility. Human carrying capacity is thus not just a theoretical concept, but a useful tool for understanding historical human population dynamics, even at a local scale.

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Ethics statement:

We did not perform any research on humans nor animals.

Data accessibility statement:

All data are available in the Dataset S1 (https://doi.org/10.6084/m9.figshare.c.3980847.v2).

Competing interests statement:

The authors have no competing interests.

2.2 Paper II: How long do floods throughout the millennium remain in the collective memory?

Authors:

Václav Fanta, Miroslav Šálek, Petr Sklenička

Abstract:

Is there some kind of historical memory and folk wisdom that ensures that a community remembers about very extreme phenomena, such as catastrophic floods, and learns to establish new settlements in safer locations? We tested a unique set of empirical data on 1293 settlements founded in the course of nine centuries, during which time seven extreme floods occurred. For a period of one generation after each flood, new settlements appeared in safer places. However, respect for floods waned in the second generation and new settlements were established closer to the river. We conclude that flood memory depends on living witnesses, and fades away already within two generations. Historical memory is not sufficient to protect human settlements from the consequences of rare catastrophic floods.

Key words:

flood zone, historical floods, historical geography, long-term memory, medieval settlements

Authors' contributions:

V. F., M. Š. and P. S. designed the research, V. F. collected the data, M. Š. performed the data analysis, and V. F., M. Š. and P. S. wrote the paper.

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2.2.1 Introduction

It is generally assumed that our predecessors were able to hand information down from generation to generation, and thus to avoid adverse effects of negative events – such as natural catastrophes (Munzar, 2001; Vaishar and Munzar, 2002; Brody *et al.*, 2009; Pfister, 2009). Collective memory could therefore play a major role in human and communal decision-making, as has been shown by works focused on the ability of humans to learn from technological or natural disasters (Choularton, 2001; Collenteur *et al.*, 2015; Raška and Brázdil, 2015). Other studies however have suggested that this concept works imperfectly, and that learning from history has its limitations (Colten and Sumpter, 2009; de Vries, 2011; Schad *et al.*, 2012; Lübken, 2016; Cook, 2018).

People are able to recall memories for decades (Bahrick, Hall and Da Costa, 2008; Larzabal *et al.*, 2017). Diamond (1993) underlines the importance of old people for the survival of a community, especially in the past. Before the age of print media, old people acted as keepers of the collective memory of crucial events and issues. Nevertheless, people keep forgetting information. The forgetting curve is logarithmic – the more time that has passed since an event, the weaker are the memories about it (Eysenck and Keane, 2000). There are many theories on why people forget: spontaneous decay of memory traces, repression of traumatic events, interference with other information, memory noise or loss of the ability to retrieve information stored in the brain (Eysenck and Keane, 2000; Chaudhuri and Fiete, 2016; Shaughnessy and Washburn, 2016). As a result, a person or a whole community can forget what was learned in the past.

It is not easy to state for how many years people can reliably remember an item of information, because very few psychological studies about forgetting have dealt with time scales longer than one year (Squire, 1989). Squire (1989) found that the answers in a fixed-choice test became random 8 year after an event; however, after 15 years people can recall approximately 50 to 60 % of information. Hirst *et al.* (2015) reported that even memories of an event as traumatic as the September 11 attacks became inconsistent within one year; over the subsequent 9 years, the forgetting curve was approximately constant. Ellis, Semb and Cole (1998) showed that students' knowledge declines rapidly 3 to 7 years after attending a course, though some memories persist for as long as 16 years. On the other hand, memories connected with strong emotions can last for a lifetime (Berntsen and Rubin, 2006), as the emotions strongly support memory formation (Dolcos and Cabeza, 2002).

Studies published so far have usually focused on the period for which a fact or an event is retained in the memory of an individual. Evaluations are usually made on the basis of questionnaires, and not on the basis of the effect that the memory can have on real-life decision-making. More importantly, these studies deal with individuals and not with their interaction inside a group or a community. Only a few studies have dealt with the intergenerational transmission of memory (Stone *et al.*, 2014; Hirst, Yamashiro and Coman, 2018). From the historical perspective, however, it is likely that collective memory and its effect on real-life decisions plays a greater role than the memory of an individual.

Human behaviour after natural disasters (e.g. great floods) is a good model for a study of the collective memory of a community. On the one hand, humans tend to live near the water, because the vicinity of a stable source of the water offers numerous benefits. On the other hand, there is a trade-off between these benefits and a constant threat of flooding. This poses the question – are settlements newly established after floods located in safer sites, or will they preferably be established in close proximity to a water source?

When a flood or a wet climatic period occurred in the past, people often moved their settlements to higher and safer locations, or built new settlements there, or they at least stopped building new houses in dangerous flood zones. This process has been documented in various parts of the world: in Central Europe (Kotyza and Smetana, 1992; Vaishar and Munzar, 2002; Klápště, 2012a; Raška and Zábranský, 2014; Pinke *et al.*, 2016), in Great Britain (Ravensdale, 1974; Galloway and Potts, 2007; Gerrard and Petley, 2013), in Scandinavia (Balbo, Persson and Roberts, 2010), in both Americas (Polyak and Asmerom, 2001; Dillehay and Kolata, 2004; Kalicki, Kalicki and Kittel, 2014; Collenteur *et al.*, 2015) and in China (Zeng *et al.*, 2016). The earliest evidence of this process comes from approximately 4 000 BP (Balbo, Persson and Roberts, 2010; Zeng *et al.*, 2016). Many settlement relocations are reported from the middle ages (Dillehay and Kolata, 2004; Pinke *et al.*, 2016). Similarly, Collenteur *et al.* (2015) proved that the post-flood population growth in areas affected by the 1993 Mississippi flood in the USA was significantly lower than in unaffected neighbouring areas. They also presented a hypothesis, which was however not tested, that the flood memory would decay over time. On the basis of papers dealing with the persistence of human memory (Squire, 1989; Ellis, Semb and Cole, 1998; Eysenck and Keane, 2000; Hirst *et al.*, 2015), we think that flood memory should not start to decay earlier than approximately 5 years after the flood event.

Previous research on these topics was done predominantly by archaeologists/geographers and by psychologists, mostly presented on the basis of case studies and fragmentary stories. Archaeological/geographical studies have described the relocation of settlements after floods, but have not delved into the duration of flood memory. Psychologists have studied the persistence of human memory, usually by testing how long people could remember information. However, papers studying very long-term memory are rather rare (Squire, 1989). Extreme floods that occur once in approximately 100–200 years provide a good opportunity for a natural experiment that can reveal the persistence of historical memory through the behaviour of a community in real situations over several generations.

The aim of our study is to answer the following questions: First, have new settlements been established in the period after major floods in safer sites than before the flood? Second, if so, does this apprehension effect fade away over time, and do new settlements begin to be established closer to the watercourses? Is it possible to determine the length of the flood memory period? Third, can a historical memory effect be observed, i.e., are warnings about rarely occurring great floods passed from generation to generation? Our results indicate that for a period of one generation after each flood, new settlements appeared in safer places. However, respect for floods waned in the second generation and new settlements were established closer to the river. We interpret these results as a consequence of the collective memory, which depends on living witnesses and fades away already within two generations.

2.2.2 Methods

We selected the Vltava river basin in Central Europe as the research area for our study. People have settled there since the early middle ages; the historical floods are well documented; and the river has a big catchment area. We acquired 3 types of data: data about historical floods, data about the history of settlements, and data allowing us to measure the relation between settlements and the watercourse. All geographic calculations were done in ArcGIS 10.5.1 (www.esri.com/en-us/arcgis) and QGIS 2.18.15 software (www.qgis.org) (ESRI, 2017; QGIS Development Team, 2017).

2.2.2.1 Historical floods

Many historical floods have been recorded in various sources at various sites across the Czech Republic (Brázdil *et al.*, 2005), but probably the best data are available for the Vltava river in Prague. We therefore decided to use the Vltava river catchment (T. G. Masaryk Water Research Institute, 2017b) as a test area, and the rest of the Czech Republic (Arcdata Praha, 2016) as a control area (Fig. 2.2.S1). We assumed that if a huge historical flood was recorded in Prague (which lies in the lower part of the catchment), it will also have influenced places situated higher and lower within the catchment area.

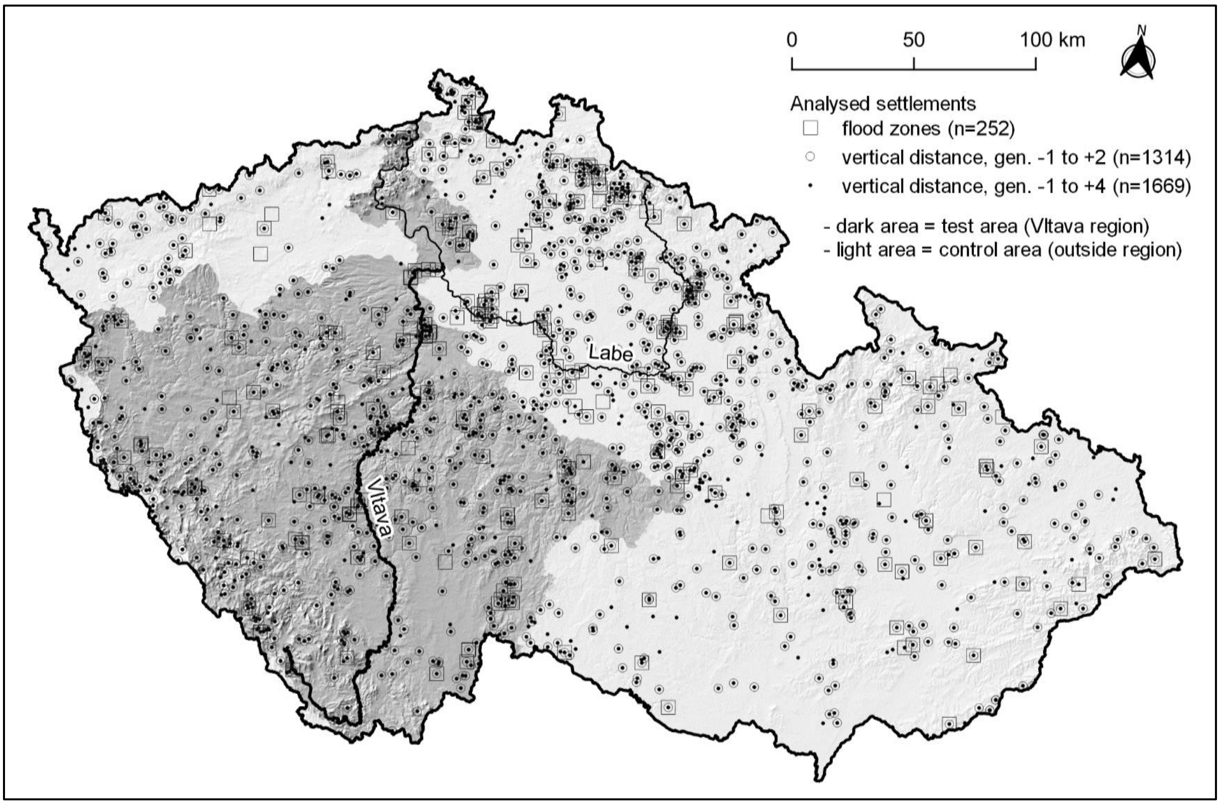

Fig. 2.2.S1. Distribution of the analysed settlements within the Czech Republic. *The test area (Vltava region) and the control area (outside region) within the Czech Republic. The border of the test area has been delimited as the Vltava river catchment plus a few smaller drainage areas below the confluence of the Vltava (Moldau) and the Labe (Elbe). The geographical data were downloaded from T. G. Masaryk Water Research Institute (2012, 2017b), Arcdata Praha (2016), Land Survey Office (2017)*

The next step was to define the most disastrous floods between 1118 (when the earliest flood recorded in historical documents occurred) and the end of the 19th century (almost no new settlements have been established in the Czech lands since the late 19th century). Extreme floods were chosen for our study because they probably have a greater influence on settlement evolution than small floods. The literature provides various lists of extreme floods in Prague during the second millennium. For our study, we selected 7 major floods: 1118, 1342, 1432, 1501, 1655, 1784 and 1845. The criteria for selection were: first, floods greater than a 100-year flood [according to Elleder (2010)]; second, floods with runoff greater than 4000 $m^3 \cdot s^{-1}$ [according to Elleder (2010); the normal runoff of the Vltava in Prague is approximately 145 $m^3 \cdot s^{-1}$ (Elleder, 2015)]; third, floods recognized as extreme floods by the scientific community (Brázdil *et al.*, 2005; Elleder, 2015). All but one of the selected floods were listed as greater than a 100-year flood (Elleder, 2010). We added the flood of 1501 on the basis of its estimated extreme runoff.

2.2.2.2 History of settlements

There are basically two ways to obtain the date when a settlement was established. The first is historical dating, where there is a record in historical written documents (chronicles, correspondence, narrative sources, official papers, etc.). This type of dating is available for every village or town in the country, but may be unreliable: A settlement may not have been recorded in written sources until many years after its real origin – but the period of the time lag is unknown. The other way is archaeological dating – dating of objects found during archaeological excavations (using various methods, e.g. ^{14}C, dendrochronology, ceramics, etc.). There is a high probability that the real founding date is captured, but this way of dating is available only for a limited number of places. Another disadvantage of archaeological dating lies in its inaccuracy – e.g. when dating ceramics, we usually know just the century and not the exact year.

In this study, we combined these two approaches. We selected all towns and villages where archaeological research has been performed and where archaeological dating is available with accuracy of a century or better. We then compared the archaeological dating with the historical dating: if the datings coincided (e.g. if the archaeological dating states 13th century and the historical dating states 1258), we used the historical dating. If the archaeological dating was earlier than the historical dating, we used the mid-point of the archaeological dating interval for the calculation (e.g. for "first half of 14th century" we used year 1325). If the historical dating was earlier, it means that the archaeological dating was insufficiently accurate (artefacts from the oldest phase have not been found); settlements in this category were excluded from our dataset. Moreover, to increase the accuracy of archaeological dating, we worked only with settlements dated with reliable methods (e.g. excavation, profile, trench, field survey). Settlements dated with inaccurate methods (e.g. undocumented research) were excluded from the dataset (we thank archaeologists Jaromír Beneš and Jiří Bumerl for their help with data filtering).

In the 17th century, the state authorities completed the first tax registers (valid for the whole country), in which even small hamlets were described (Doskočil, 1953, 1954). In modern times, written sources usually record the establishment of a village in the same year as it really was established. We therefore assume that historical dating, for the period since 1600, is accurate enough to be used in our study.

We obtained the historical dating data from the Historical Lexicon of Municipalities (Růžková *et al.*, 2006) and the archaeological dating data from the Archaeological Database of Bohemia (Institute of Archaeology of the Czech Academy of Sciences Prague, 2013). For each flood, we compared the settlements from the test area and from the control area that were established during two time intervals: one generation (25 years) before the flood as a reference, and two to four generations (2-4x 25 years according to sub-analysis) after the flood to evaluate the response within the first 25-year period (equivalent to one generation) immediately following the flood, and also the response in the subsequent two to four generations (Table 2.2.S1). Our analysis (1x 25 years before floods plus 2x 25 years after floods) contains a total of 1314 cases (1293 individual towns and villages). The extended dataset (1x 25 years before floods plus 4x 25 years after floods) contains a total of 1669 cases (1637 individual towns and villages). The total numbers of cases are listed in Table 2.2.S1.

Table 2.2.S1. Numbers of settlements selected for the analysis. *In one case, the before/after intervals of adjacent floods overlapped each other (the study periods between the floods in 1784 and in 1845 overlapped in years 1820 – 1833). The settlements in the overlap (n = 21) were included in both intervals*

Flood no.	**Flood [year]**	**Generation no.**	**25-year intervals before and after the flood**	**Historical dating controlled by archaeological dating [No.]**		**Archaeological dating [No.]**		**Historical dating after 1600 [No.]**		**Sum [No.]**		**Total (generations -1, 1 and 2 only) [No.]**	**Total [No.]**
				test	**control**	**test**	**control**	**test**	**control**	**test**	**control**		
1	**1118**	-1	1093-1118	2	0	0	2			2	2	**62**	**87**
		1	1118-1143	1	4	0	0			1	4		
		2	1143-1168	3	2	28	20			31	22		
		3	1168-1193	3	0	3	1			6	1		
		4	1193-1218	3	4	7	4			10	8		
2	**1342**	-1	1317-1342	5	8	0	2			5	10	**62**	**69**
		1	1342-1367	5	16	7	9			12	25		
		2	1367-1392	2	3	4	1			6	4		
		3	1392-1407	4	3	0	0			4	3		
3	**1432**	-1	1407-1432	1	2	0	0			1	2	**25**	**25**
		1	1432-1457	1	0	4	10			5	10		
		2	1457-1476	3	2	1	1			4	3		
4	**1501**	-1	1476-1501	1	2	0	0			1	2	**17**	**34**
		1	1501-1526	0	2	0	1			0	3		
		2	1526-1551	0	7	3	1			3	8		
		3	1551-1576	1	1	0	1			1	2		
		4	1576-1601	0	1	0	0	6	7	6	8		
5	**1655**	-1	1630-1655	1	0	0	2	92	120	93	122	**363**	**658**
		1	1655-1680	0	0	0	0	12	51	12	51		
		2	1680-1705	0	0	0	0	20	65	20	65		
		3	1705-1730	0	0	0	0	70	122	70	122		
		4	1730-1755	0	0	0	0	30	73	30	73		
6	**1784**	-1	1759-1784	0	0	0	0	22	89	22	89	**591**	**602**
		1	1784-1809	1	0	0	0	174	276	175	276		
		2	1809-1834	0	0	0	0	6	23	6	23		
		3	1834-1845	0	0	0	0	1	10	1	10		
7	**1845**	-1	1820-1845	0	0	0	0	77	60	77	60	**194**	**194**
		1	1845-1870	1	0	0	0	24	26	25	26		
		2	1870-1895	0	0	0	0	4	2	4	2		
			Sum [No.]	40	58	58	56	538	924	636	1038		
			Total [No.]	**98**		**114**		**1462**				**1314**	**1669**

Generation -1 [No.]	492
Generation 1 [No.]	626
Generation 2 [No.]	201
Generation 3 [No.]	220
Generation 4 [No.]	135

2.2.2.3 The relation between the settlements and the rivers

We used two indicators for each settlement: First, vertical distance, which is defined as the height of the settlement above the normal water level of the nearest watercourse (to see how people reflected the normal water level) and second, the proportion of settlements established within flood zones, which expresses whether the settlements were situated inside the flood zones of 100-year floods (to show how aware the local community was of extreme situations, primarily on the basis of empirical experience being handed down about the extent of the flood zones of extreme floods). First, we defined the nearest point on a watercourse from each settlement, using the Near tool in ArcGIS software (ESRI, 2017). We then calculated the elevation of the nearest point and of the settlement itself. The settlements were represented by points placed in the middle of the historical centre of the settlement (for the medieval period, it is not possible to find exact borders of towns/villages, because the oldest available maps with sufficient quality were drawn at the end of the 18th century; we think that a point placed in the middle of the settlement is a good representation). We used elevation data from the DMR 5G digital elevation model (raster data in a 2 m grid) provided by the Czech Land Survey

Office (2017) and watercourse vector data provided by the T. G. Masaryk Water Research Institute (2012). The Extract Values to Points tool in ArcGIS software was used for the calculation. Finally, we simply subtracted the elevation of the nearest point on the watercourse from the elevation of the settlement. For the second indicator, we used the "flood zones of a 100-year flood" vector dataset, which was provided by T. G. Masaryk Water Research Institute (2017a). This dataset is based on current and recent observations. There are two ways in which differences between the current situation and the historical situation could have arisen: horizontal changes (the occurrence of new channels and clogging of old channels) and vertical changes (incision and sedimentation) of the rivers. Horizontal changes have occurred in history [e.g. (Stacke, Pánek and Sedláček, 2014; Brown *et al.*, 2018)], but the rivers have usually remained in the current floodplain area during the last millennium. Thus, we assume that the horizontal changes did not affect the extent of the flooded area. The vertical differences between the current position and the early-medieval position of the riverbed could have risen by up to 2 or 3 m in narrow channels (Kadlec *et al.*, 2009; Wistuba, Sady and Poręba, 2018) [sedimentation caused by deforestation (Pokorný, 2011; Wistuba, Sady and Poręba, 2018), sometimes followed by incision caused by lower intensity of human activities in the last century (Wistuba, Sady and Poręba, 2018)]. As most of the sedimentation occurred during the middle ages (Pokorný, 2011; Wistuba, Sady and Poręba, 2018), we think that our data are not much affected, because most of our data comes from settlements established in the 17th to 19th centuries (Table 2.2.S1). For settlements established during the middle ages, distortion of the extent of the flood zones is theoretically possible. However, we think that the extent of a 100-year flood is much bigger than any changes in the vertical position of the riverbed. To conclude, we assume that the changes from past situations are negligible. Unfortunately, the "flood zones of a 100-year flood" dataset covers just the main watercourses in the Czech Republic. We therefore had to limit the calculation of the second indicator to towns and villages located in valleys with a defined flood zone (252 settlements met these requirements).

To discover whether people were generally attracted by the proximity of watercourses, we also prepared datasets of random points ('virtual settlements') for both indicators. For each period (i.e. 25 years before the flood and 50 years after the flood, 7 floods were investigated, so there was a total of 14 periods), we repeatedly (99 times) generated random points simulating centres of 'virtual settlements', taking into account the area occupied in previous periods (4-km buffer zones surrounding all settlements established in previous periods were excluded from the area in which the random points were placed). The aim of this step was to generate a range of randomly distributed values in each situation (including the elimination of already populated places), which could be compared with the distribution of real data (Fortin and Dale, 2005). We then calculated both indicators (the vertical distance above the normal water level of a watercourse, and the presence of the settlement in a flood zone) for each random point, in order to obtain a range of randomly distributed values in each situation.

2.2.2.4 Statistical analysis

In order to compare real vertical distances with the distances expected by chance (virtual settlements) and to show the general trends across centuries in sums of generations, we analysed the median vertical distances of settlements above a watercourse in the following four situations: (a) within the Vltava region before flood disasters, (b) within the Vltava region after flood disasters, (c) outside the Vltava region before flood disasters and (d) outside the Vltava region after flood disasters (Fig. 2.2.1). In this analysis, we compared the real median vertical distances with the medians for randomly generated points in the areas for particular situations and periods. In this way, we obtained separate results for each (a) to (d) situation. We then tested the temporal trends of the real medians in time-aligned flood disasters (through the centuries), using Spearman's correlation coefficients (r_s).

In order to evaluate the general effect of generations in sum of all floods, we selected sets of settlements established one human generation (up to 25 years) before the flood disaster and four generations (4x 25 years) after the flood, in order to obtain two sets of comparable periods, i.e. one reference period (the first) before the flood and two periods after the flood (for model A) and one reference period (the third period) after the flood and the two following (third and fourth) periods after the flood (for model B). In these models, we tested the significance of the linearity and the unimodality of the response (vertical distances above the nearest watercourses) during the two sets of three-generation periods. In the first model (A), we hypothesized that people could have learned from the flood (in the first and second generations after the disaster) and therefore established settlements more safely, i.e. at a greater distance above the watercourses. In this case, we would detect a simple linear response from the reference period to the next two generations. However, if people lost the long-term memory after one generation and initiated a return towards the watercourses (in the second generation), we would detect a more complex unimodal pattern. This pattern would have the greatest distance in the first generation after the flood disaster in comparison with the previous (reference) generation, and also in comparison with the second ('grandchild') generation. This pattern may have differed between the higher-risk Vltava region and the other areas. We applied similar treatment to the another model (B), including a set of three successive generations after flood disasters (second, third and fourth) in which we did not expect any significant pattern.

We analysed the predictions using a mixed-effect model (in the *lme4* package) with the response variable representing the vertical distance of the settlement above the water level of the nearest watercourse. Prior to the analysis, the values of the response variable were centred relative to the mean of the respective flood (i.e. first to seventh), in order to obtain comparable values across periods, and the values were then log-transformed to approach normality. In the models, we tested the fixed effect of three consecutive generations (a three-category predictor, the reference generation prior to a flood and two generations after the flood in model A, and the second, third and fourth generations after a flood in model B). This predictor variable was nested within the region (the Vltava region is compared with the other areas). In both cases (model A: generations -1, 1, 2 as well as model B: generations 3, 4, 5), we compared a model referring to the generations in a linear predictor form (numeric variable 'generation') with a more complex model referring to the generations in a unimodal arrangement [numeric variable 'poly(generation,2)']. In order to select the better candidate model (with a linear effect or with a unimodal effect of the generations), we checked the parsimony of the models, using the Akaike Information Criterion (AIC), and we selected the more parsimonious model with AIC < 2 (Murtaugh, 2014). The results were controlled for longitude and latitude (included as first predictors in the models) to reduce the effect of spatial autocorrelation. The flood event was included as a random factor in order to allow comparisons between particular floods which may vary in average vertical distances.

Finally, we examined how people perceived extreme flood situations, as reflected in the proportions of new settlements established in the flood zones defined by T. G. Masaryk Water Research Institute (2017a) within the selected valleys (regardless of their position in the test area or in the control area) before and after extreme flood disasters. These real proportions were then compared with the proportions calculated from randomly distributed 'virtual settlements' for the respective areas and periods. We applied the generalized linear model (GLM) to test fixed effects of the period (before or after the flood), the numerical order of the flood (1 to 7), and the interaction of these effects, on the proportion of settlements established inside flood zones. We hypothesized that the proportion of newly-established settlements would be lower after the flood event than before it, and that this disproportion would increase over the centuries, due to learning from past experience, at least in the periods after the floods (interaction term). The binary response variable included 1 (present in flood zone) or 0 (outside flood zone). In this model with a binomial error term, we checked for overdispersion by dividing the residual deviance by the residual degrees of freedom. For the purposes of graphic presentation, the proportion (Fig. 2.2.3) associated a number of newly established settlements inside the flood zones and outside the flood zones within the selected valleys.

Partial correlations were performed using the Spearman rank correlation coefficient (r_s). The presented values indicate the mean ± standard error (*se*), unless stated otherwise. The models were analysed in R software ver. 3.4.0 (R Core Team, 2015). The significances are based on likelihood ratio tests, and the level of statistical significance was set at $p = 0.05$.

2.2.3 Results

2.2.3.1 Vertical distances

In all four situations (within and outside the Vltava region, one generation before and two generations after flood disasters), the real median vertical distances of new settlements were always less far above the local watercourse than the randomly generated points (virtual settlements), with only two exceptions that will be discussed below (Fig. 2.2.1). This confirms that people have historically tended to establish new settlements significantly closer to watercourses than settlements randomly located throughout the landscape would be. The median vertical distance has not changed systematically over the centuries (represented by the sequence of seven flood disasters investigated here) in situations (a), (c) and (d) (all Spearman's correlation coefficients $r_s < 0.53$ and $p > 0.13$), whereas in situation (b), i.e. after flood disasters in the Vltava region, we detected the median vertical distance increasing significantly over the course of the centuries (Spearman's correlation coefficients $r_s = 0.77$ and $p = 0.041$; Fig. 2.2.1B). This latter pattern indicates that in the Vltava region, where there is an increased risk of repeated floods, people were well aware of this risk, and took it into account, setting up settlements further above the watercourses in later centuries. An increase in the median distance above watercourses was especially evident in the Vltava region after the 4th flood, in 1501. Indeed, after the flood in 1845, i.e. the last flood in our study, this distance was at the upper limit of the randomly generated 'virtual settlements'.

A comparison of two mixed-effect models analysing the importance of floods as predictors of the decisions of humans on the vertical distance above a watercourse at which new settlements would be set up across generations and through the centuries showed that they provided significantly different results ($\chi^2_2 = 8.42$, $p = 0.015$). The generation was either a linear predictor or a polynomial predictor. As the AIC was lower (ΔAIC = 4.5) in the model with the polynomial expression of the generation predictor ($\mathrm{AIC}_{\mathrm{pol}} = 5151.3$) than in the model with the linear expression ($\mathrm{AIC}_{\mathrm{lin}} = 5155.8$), we selected for interpretation the model with the unimodal response (Table 2.2.1A). We therefore suggest that people established new settlements on higher ground in response to flood disasters in the generation immediately following the flood, but later the collective memory faded to some extent in the subsequent ('grandson') generation (Fig. 2.2.2). This result supports our hypothesis, and indicates that communal memory plays its part, but that it fades away in the second generation. The significant interaction that we observed suggests that the pattern for the Vltava region differed from the pattern for the control region. There was a clear increase in the vertical distance after the disaster, both in the Vltava region and in the control area. In fact, there was a much greater increase in the control area than in the Vltava region, as the vertical distance even before flood was much lower in the control area. It is also evident that in the second generation after the flood, the vertical distance fell to values comparable with those in the period before the flood.

Similarly, we compared two mixed-effect models with the generation stated either as a linear predictor or as a polynomial predictor for the vertical distance above a watercourse from the reference ‘grandson’ generation to the two subsequent generations (i.e. the third and fourth generations after extreme floods, model B). The models provided similar results (ΔAIC = 2.9, $\chi^2_2 = 1.10$, $p = 0.57$) without any significant effects (all $p > 0.22$), suggesting no other significant trend or deflection in the period between the second and fourth generations after the flood (Table 2.2.1B; Fig. 2.2.2).

Table 2.2.1. Vertical distances. *Results of the mixed-effect models that analyse the effects A) of the first and second generations and B) the third and fourth generations after flood disasters on the vertical distance of newly-established settlements above the nearest watercourse. The reference values are the vertical distances in the period of A) one generation before the flood event and B) the second generation after the flood, i.e. one generation before the third and fourth floods. The numeric generation factor (stated in the 2nd order polynomial form) was nested within the Vltava region (within or outside it). Vltava (1) refers to the test area, while Vltava (0) refers to the control area (A)*

(A)

Predictor	estimate	se	df	χ^2	*p*
Intercept	1.446	0.1127			
Longitude	-0.041	0.0608	1	0.459	0.498
Latitude	-0.004	0.0557	1	0.011	0.916
Vltava (yes *vs* no)	0.132	0.1348	1	1.012	0.314
Vltava (0) : Generation (1)	3.41	2.212	4	11.29	0.024
Vltava (1) : Generation (1)	2.88	2.865			
Vltava (0) : Generation (2)	-4.41	2.316			
Vltava (1) : Generation (2)	-7.23	3.04			

(B)

Predictor	estimate	se	df	χ^2	*p*
Intercept	1.571	0.1068			
Longitude	-0.086	0.0948	1	0.747	0.387
Latitude	0.064	0.0788	1	0.837	0.360
Vltava (yes *vs* no)	-0.029	0.2063	1	0.231	0.631
Vltava : Generation	3.523	2.1642	2	3.015	0.222

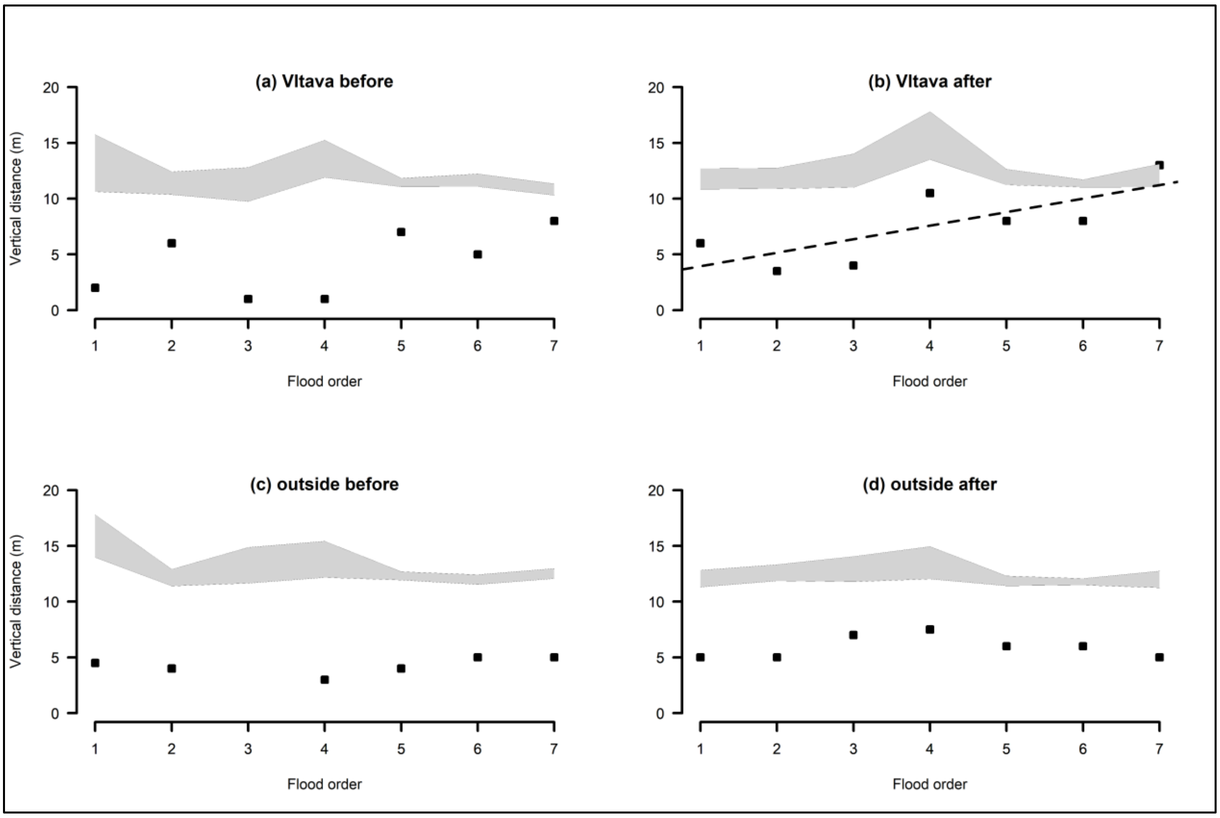

Fig. 2.2.1. Median vertical distances to the nearest watercourses throughout 9 centuries. *A comparison between the median vertical distances of newly-established settlements (black squares) in the four situations (within and outside the Vltava region up to 25 years before and up to 50 years after flood disasters) and the range of randomly generated points (shaded areas) in the same areas and periods shows that people were strongly attracted towards watercourses. A dashed line refers to a statistically significant trend (see Results). The value before the third flood outside the Vltava was 34 m and lies beyond the presented limit. The variance in vertical distances of randomly generated points may be affected by the different sample size used for the simulation (see Methods section and Table S1)*

Table 2.2.2. Flood zones. *Results of the GLM analysis of the effects of the periods (before or after the flood), the order in which floods occurred (1 to 7), and the interaction of these factors on the proportion of real settlements established in the flood zones of the Vltava region and the reference area*

	estimate	se	df	χ^2	*p*
Intercept	-3.766	3.0619			
Longitude	0.050	0.0267	1	3.685	0.055
Latitude	0.063	0.0567	1	0.460	0.498
Vltava	0.075	0.0751	1	0.949	0.330
Order	-0.013	0.0163	1	0.087	0.768
Period	-0.327	0.1846	1	0.444	0.505
Order : Period	0.069	0.0335	1	5.391	0.020

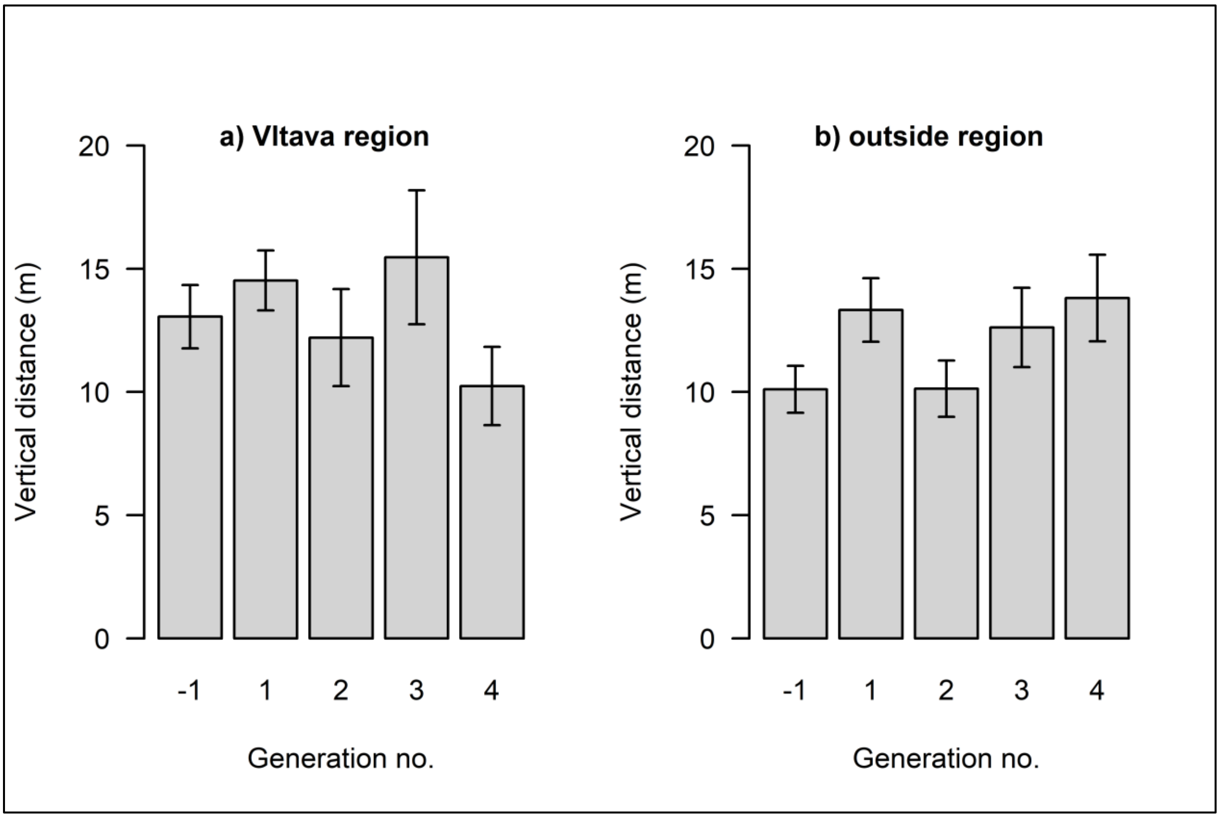

Fig. 2.2.2. Generations before and after the floods. *Mean (± standard error) vertical distances of settlements above the water level of the nearest watercourse within (a) and outside (b) the Vltava region in five consecutive generations (25-year periods): -1: before the flood; 1-4: first to fourth generation after the flood*

2.2.3.2 Flood zones

In the analysis of the human perception of extreme flood situations (which is reflected in the proportions of new settlements established in flood zones), we show that the proportion was almost always lower than the proportion of new settlements in randomly simulated 'virtual settlements' (Fig. 2.2.3). The only exception is the situation before flood 6 (AD 1784), when the real proportion was within the range of randomness.

The results of the GLM analysis of the fixed effects of the periods (before or after the flood), the order in which the floods occurred (1 to 7) and the interaction of these two predictors on the proportion of real settlements established in the flood zones showed that the proportions of settlements established in the flood zones was not significantly predicted by the period (before *versus* after the floods; Table 2.2.2). However, we detected a significant interaction between the periods and the order in which the floods occurred, indicating that there were different trends in this proportion over the centuries. The proportion of settlements established inside flood zones increased before the floods from the period after the third flood disaster (Spearman rank correlation, $r_s = 0.88$, $p = 0.021$), exemplified by a building boom in high-risk areas particularly in the period since the fifth flood disaster in 1655 (Fig. 2.2.3A). In the period after the floods, however, there was no change or only a moderate decline in the proportion of settlements established inside flood zones over the centuries (Spearman rank correlation, $r_s = -0.56$, $p = 0.195$; Fig. 2.2.3B). These findings indicate that people continued to be aware of the risks associated with establishing settlements in flood zones for a period of one to two generations after a flood, even during the building boom after 1655. However, it also indicates that population growth in the later centuries (between floods 5 and 7), and the consequent shortage of available low-risk space, led to a need to occupy new areas. This pushed the population into high-risk flood zones.

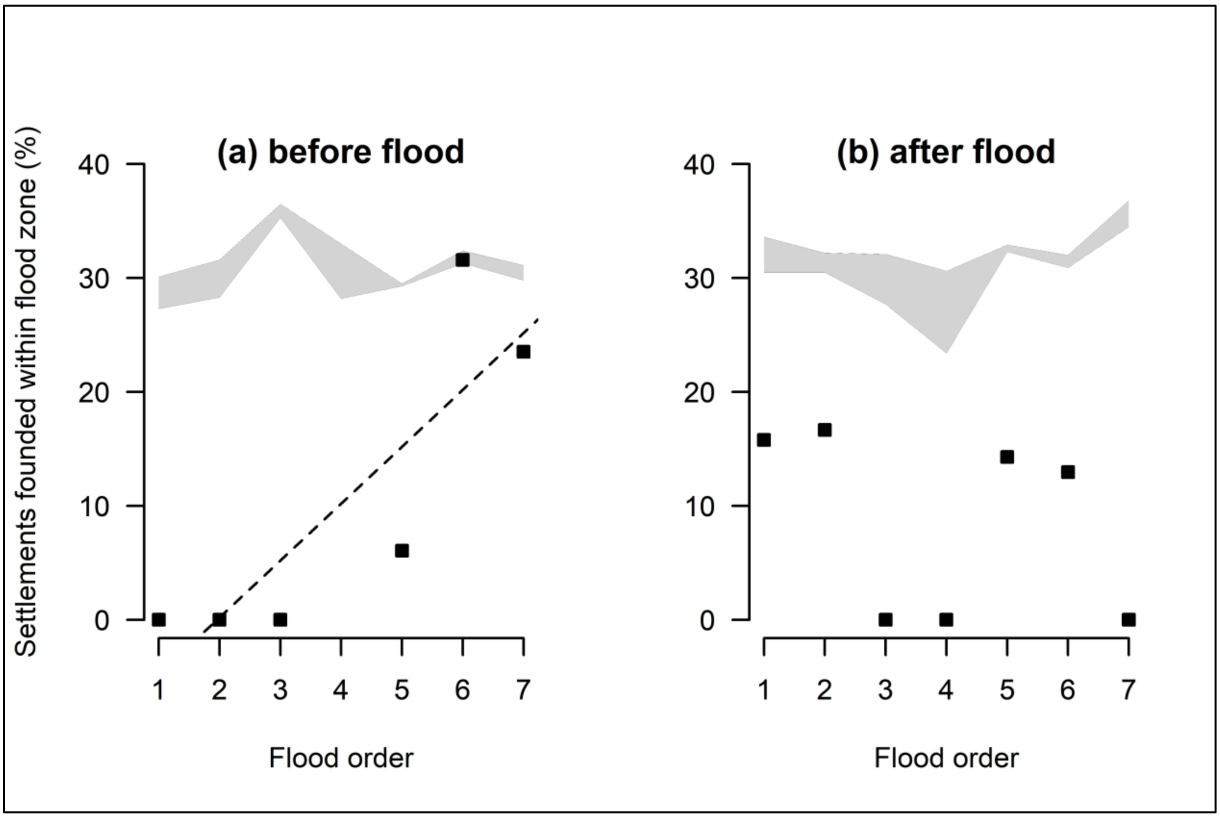

Fig. 2.2.3. Living in the flood zones. *A comparison between the proportions (frequencies, %) of new settlements actually established inside flood zones before and after seven historical extreme flood disasters and a range of virtual flood events based on randomized simulations (grey area). The dashed line indicates a statistically significant trend (see Results). No data were available before the 4th flood event*

2.2.4 Discussion

With just two exceptions, the medians of the real newly-established settlements were always located closer to the actual watercourses than the randomly generated settlements (Fig. 2.2.1). This may prove that people were always attracted by the presence of water (probably because of their everyday needs), despite the potential risk of floods. It could also explain an issue in interpreting the results. On the one hand, it is clear that floods are feared (Fig. 2.2.2), but on the other hand, construction continued in the flood zones despite the flood risk (Fig. 2.2.3). Nevertheless, there is a pattern that bears witness to flood memory, which however fades where great floods are concerned:

In the post-flood periods, there is a retreat to safer locations (Fig. 2.2.2, Table 2.2.2). After several decades (1 – 2 generations), however, settlement activity returns to the watercourses (Fig. 2.2.2). (All these results were controlled for spatial effect of settlements across the country and were comparable across flood events which were stated as random effect in the models.) This suggests that there is a limited period of collective memory [a similar result was presented by Colten and Sumpter

(2009), Egner, Schorch and Voss (2016), Hirst, Yamashiro and Coman (2018), Candia *et al.* (2019) and Coman (2019)]. We hypothesize that the persistence of flood memory is dependent on the presence in the population of eye-witnesses of the event. After these eye-witnesses die out, the historical memory disappears (Vansina, 1985; Pfister, 2016). The loss of historical memory of extreme events leads in the later centuries to an increase in the proportion of newly-established settlements that are located in the flood zones (Fig. 2.2.3A). This settlement growth may have been linked, among other things, to the onset of the industrial revolution, and to the resulting increased need for water for industrial processes. This, along with the fading memory of previous extreme floods, may have led the founders of settlements to make a new cost/benefit analysis, and to consider the vicinity of a water source to be more important than the risk of new floods (in the 17th to 19th centuries, approximately 10-15 % of new settlements were established in flood zones, even after major flood events, Fig. 2.2.3B). On the other hand, the vertical distance of settlements established in the test area in the after-flood periods was significantly increasing though centuries (Fig. 2.2.1B). This result may suggest that the flood memory was passed on to younger generations – which contrasts with our previous findings about the limited duration of flood memory (Fig. 2.2.2). Alternatively, newer settlements were established in higher locations (Fig. 2.2.1B), but they still remained in the flood zones (Fig. 2.2.3B); i.e. the increase in vertical distances does not necessarily indicate the existence of generation memory. Another possible explanation of the increasing vertical distance in time may be the that in the modern period, new settlements were established especially in the uplands and highlands (i.e. in regions with rugged terrain and big vertical differences).

People probably understood the need to build higher above the water level, but lacked information on the precise delineation of the flood zone. Information about the borders of the flood zone that had been acquired empirically in the past was clearly not passed on to future generations. Systematic recording and transmission of detailed flood data only arrived with systematic territorial planning. This developed only in the course of the 20th century, with only sporadic examples in the 19th century (Olschowy, 1976; Fainstein *et al.*, 2016).

Of course, people's resulting behaviour may not have been due to loss of memory alone. For example, the advantages associated with the vicinity of a water source may have played an important role (Changnon, 1998; Bird, O'Grady and Ulm, 2016). People may still have remembered the floods and may recognized the associated dangers, but the final decision may have stemmed from the need for a compromise, or for the choice of the lesser of two evils (e.g. safety from floods versus the danger of a potential drought; or the danger of flooding versus the advantages of an adequate supply of water). The decision may have been the result of a trade-off of this kind. The trade-off may have been influenced by the disproportionate probability of favourable and unfavourable impacts – an everyday need for water versus major flooding once in several generations. Apprehension of floods originating from information passed on by earlier generations may not weigh heavily enough against clear present-day advantages, especially if the knowledge has been passed down only verbally, and if disastrous floods occur only once in several generations (cf. Mauelshagen, 2009; Pfister, 2016).

The relatively short duration of historical memory can be due to several factors: First, the memory of eye-witnesses from the old generation may have weakened by the time they pass information on to their descendants (Squire, 1989; Ellis, Semb and Cole, 1998; Hirst *et al.*, 2015), or they pass it on imperfectly (Lübken, 2016) – because many years have passed since the event. Indeed, the memory is not passed on at all (the old generation has forgotten about it entirely). It has also been observed that repeated (preferably annual) experiences are necessary for proper remembrance (Mauelshagen, 2009; Pfister, 2016). Obviously, this requirement was not fulfilled in the case of extreme floods. Second, the younger generations may not heed the warnings of the ancients, because they seem to them to be ridiculous (Státníková, 2017), or the younger generation is not interested in the memories of the older generation. Third, new generations receive the information only by word of mouth, and this weakens the message, and detaches it from the emotions that they would have felt if they had experienced it for themselves (Dolcos and Cabeza, 2002). As psychological studies (Cocenas-Silva, Bueno and Droit-Volet, 2013) and also neuroscientific studies (LaBar and Cabeza, 2006) have pointed out, strong emotions can even strengthen the memory traces via complex biological and chemical processes in the brain. Thus, memories connected with strong emotions (such as personal – living – memories of a dramatic environmental event) are more likely to be remembered, and vice versa: memories received only by listening (i.e. less emotional) are likely to be weaker. The emotional experiences are also more likely to be shared (Luminet *et al.*, 2000; Rimé, 2009). Although it would be advantageous from the evolutional point of view to have a better historical memory, our physiology (the decay of memory traces) is a counteracting factor. However, a more detailed analysis of this matter would require a separate study. Social learning, or the ability to acquire information from earlier generations, can also be affected by the cultural environment or by the life (subsistence) strategy of individuals of this type (Talhelm *et al.*, 2014; Mesoudi *et al.*, 2015; Glowacki and Molleman, 2017; Mesoudi, 2017).

This type of explanation for the duration of historical memory resembles the difference between so-called communicative/lived memory and cultural/distant memory (Vansina, 1985; Assmann, 1995, 2008). Living memory is the memory of witnesses who are still alive in the population. Their life stories are known and can still be communicated to the descendants of the witnesses. Memories recorded in living memory also have an emotional charge (Muller, Bermejo and Hirst, 2018). Distant memory, on the other hand, is memory transferred through history textbooks or academic works (the eye-witnesses are no longer alive, and current generations are not emotionally involved). Vansina (Vansina, 1985) estimates the line between living memory and distant memory to be not more than three generations, which is somewhat longer than the period indicated in our results (1 – 2 generations); this difference may be associated with differences in research methods, but the principle remains unchanged. After the death of eye-witnesses, the flood fades from living memory and moves into chronicles and into historical documents. As Pfister (2016) noted and as our results have indicated, information written in chronicles and in documents does not affect the real behaviour of ordinary people and communities.

The way of transmission of the flood memory to younger generations can also be an interesting issue. The memory could have been transmitted via personal or written communication (Hübner, 2012; Čapský, 2013), cultural artefacts, water marks on the walls of public buildings, religious traditions (Pfister, 2016) or in other ways. But this was not the aim of our study and we cede this question to future researchers.

The factors that determine the choice of sites for new settlements may have been affected by local considerations, e.g. by a political decision that failed to take the flood hazard into account, by ownership rights (which in the past often directly affected these sites), or by other natural conditions (for example, in a rugged terrain with narrow valleys, it is impossible to establish a settlement close to a watercourse). We also have to consider that the study presented here is based on current environmental conditions, not on those valid at the time of establishment of the studied settlements; the conditions may have changed somewhat over time in a way that had an effect on decisions about new sites (Pavel Raška, personal communication, 23 June 2017 and 12 April 2018). However, changes in environmental conditions are rarely great enough to have had a significant effect on the results of our study and on the way in which they are interpreted. Other uncertainties in our study may have arisen from the founding dates of settlements: although we compared historical dating with archaeological dating, some unavoidable errors may have remained in the database, and these may have affected the results (e.g. in some examples, the archaeological dating may have been less accurate than expected). However, since most of our data comes from the modern period with more precise dating (17th century – 19th century, see Table 2.2.S1), we think that any errors arising from uncertain dating should be very small.

The lack of statistically significant differences between the test area and the control area (Table 2.2.1) was most likely because many of the major floods assessed in this study affected not only the Vltava basin also other areas of Central Europe as a whole, including major parts of the control area, where there were and still are numerous watercourses with a risk of flooding (Brázdil *et al.*, 2005).

Although floods have accompanied humankind since ancient times (Glaser and Stangl, 2003; Brázdil *et al.*, 2005; Glaser *et al.*, 2010; Benito *et al.*, 2015), we still often lack sufficient respect for them. It is therefore important to keep reminding ourselves of the risks posed by natural and other disasters, including the causal chain that can lead to the occurrence of floods. Our study overlaps into the fields of social sciences and history: people keep forgetting the danger of natural disasters, and also of social disasters.

To conclude, our study has confirmed the effect of seven well-documented major historical floods on the real behaviour of the communities directly affected by the floods, with reference to the location of new settlements that have been established. We investigated major floods that occurred between the 11th century and the 19th century, in order to find out whether these extreme events influenced the height of newly-established settlements relative to the normal water level of the nearest watercourse, and the proportion of new settlements that were established in flood zones. The significant effect of the great floods on both indicators was confirmed on a robust sample of high quality empirical data (1293 settlements established over a period of 8 centuries) reflecting the real behaviour of the community.

The results indicate that for approximately 25 years after a great flood, new settlements are preferentially established higher above the average nearest watercourse level than before the flood. After that, the locations of new settlements begin to get closer to the watercourses again. A similar effect was revealed through an analysis of the proportion of newly-established settlements that were located in the flood zones. The results of the analysis also indicate that the proportion of new settlements that were located within the flood zones grew over the centuries, while this proportion remained roughly constant after the floods.

We interpret our results as a consequence of the collective historical memory. So-called living memory is passed down by living eye-witnesses, and the duration of living memory is apparently conditioned by the life span of the eye-witnesses. The effect of living memory leads to the establishment of new settlements, for a period of one to two generations after the flood, higher up above the watercourses and, to a greater extent, outside the flood zones. However, once the eye-witnesses die out, i.e., after "living memory" is lost, the community forgets the consequences of such a disaster, and new settlements are established closer to the water again.

People are therefore able to understand complicated processes and situations (which in many cases happened to someone else) and to apply them to new situations. However, this is true only for a limited period of time. The concept of "knowledge passed down from generation to generation", especially knowledge of an event in the distant past, is therefore a myth – real data indicate that this is not how we behave, and that information that is not repeated often enough (about once in each generation), fades away from the memory.

Our results imply some important practical considerations. Since it is not safe to rely on folk memory to protect communities from extreme floods, it is all the more important to document extreme floods, and also to bring to people’s attention the extreme adverse effects of major flood events. It is essential to keep reminding people of the extent of these events, and to maintain awareness of floods and respect for their impact for a period of decades after the event, especially when no living eye-witnesses remain in the population. It is necessary to teach people about the occurrence of major floods, and about the increasing frequency of these events as a result of climate change. Although flood zones are nowadays relatively well predictable, the exact delineation of flood zones for the purposes of territorial planning are still not universally available. In addition, the risks associated with great floods may be downplayed or simply ignored. The sad result of such attitudes is the sad reality that history keeps repeating itself, even now when reliable knowledge about flood events and about flood prevention is widely available.

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Competing interests: The Authors declare no conflict of interests.

Data availability: We have not performed any investigation on humans or animals. There are no restrictions on data availability. All data is available in the tables or in the supplementary materials (Dataset S1, see the links below)

https://static-content.springer.com/esm/art%3A10.1038%2Fs41467-019-09102-3/MediaObjects/41467_2019_9102_MOESM3_ESM.pdf

https://static-content.springer.com/esm/art%3A10.1038%2Fs41467-019-09102-3/MediaObjects/41467_2019_9102_MOESM4_ESM.xlsx

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https://static-content.springer.com/esm/art%3A10.1038%2Fs41467-019-09102-3/MediaObjects/41467_2019_9102_MOESM7_ESM.xlsx

https://static-content.springer.com/esm/art%3A10.1038%2Fs41467-019-09102-3/MediaObjects/41467_2019_9102_MOESM8_ESM.xlsx

Code availability: The code is available from the authors on request.

2.3 Paper III: How old are the towns and villages in Central Europe? Archaeological data reveal the size of bias in dating obtained from traditional historic sources

Authors:

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Abstract:

In various research fields, from archaeology to landscape history and ecology, it is important to know the date of the origin of historical settlements (i.e. towns, villages, hamlets, isolated farms) as precisely as possible. In Central Europe, there are two primary ways to obtain the date when a settlement was founded: "historical dating" (based on historical written sources) and "archaeological dating" (based on archaeological findings). Historical dating usually does not reflect the real time of origin, since the first reference to a settlement in written sources can be recorded many years after its real origin. However, the time lag is unknown. Until now, no study has attempted to show exactly how the time lag differs in different centuries, or whether the time lag has been affected by any geographical factors.

This paper compares the dates of origin from archaeological and written sources of medieval and early modern settlements (n = 524, AD 850 – 1600) in the present-day Czech Republic. We also tested the role of local environmental conditions on the time lag. Comparison shows that the time lag has been decreasing with the passing of calendar years. Towns and places close to major towns were also have a shorter time lag in their historical dating. The historical dating of medieval towns and villages is too unreliable to be trustworthy, especially due to data dispersion. At least in central Europe, it makes no sense to use historical dating for statistical and other precise works with "big data", since it is burdened with huge errors (especially in the medieval period). Our results identify a severe upward bias in the current chronology of landscape transformation.

Key words:

time lag, dating, archaeology, written sources, middle ages, historical settlement

Authors' contributions:

V. F., J. Z. and P. S. designed the research, V. F. collected the data, J. Bumerl and J. Beneš checked the data quality, J. Z. performed the data analyses, and V. F., J. Z., P. S., J. Bumerl and J. Beneš wrote the paper.

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2.3.1 Introduction

In various fields, from archaeology to landscape ecology (e.g. Beneš and Brůna, 1994a; Lehr and McGregor, 2008; Pokorný, 2011; van Doesburg and Groenewoudt, 2014; Szabó, Šipoš and Müllerová, 2017), it is critical to know the date of the origin of historical settlements (i.e. towns, villages, hamlets, isolated farms) as precisely as possible, or at least to be aware of the level of accuracy of the dating methods that are used. In this paper, we make a comparison between dates of origin from archaeological sources and from written sources of medieval and early modern settlements in Central Europe (to the north of the ancient *Limes romanus*). The medieval settlements in our study region of Bohemia (Czech Republic), with their land division and field systems, are one of the oldest visible layers in the cultural landscape of Central Europe to the north of the historical frontiers of the Roman Empire (Beneš and Zvelebil, 1999; Löw and Míchal, 2003); most of the local towns and villages were founded during the medieval period (Semotanová, 2006; Klápště, 2012b; Poschlod, 2015a). This topic impacts not just the historical and social sciences but also the environmental sciences, since historical settlements were significantly affected by the properties and the limitations of the surrounding environments (e.g. Lukezic, 1990; Fanta *et al.*, 2018), and also because the people actively changed the landscape in their neighbourhood (by deforestation, agriculture, soil erosion etc.) (e.g. Bork *et al.*, 1998; Pokorný, 2011; Maděra *et al.*, 2014). The formation of a cultural landscape makes the study of settlement history an important field of science (Poschlod, 2015b). Among other things, settlement history research uncovers the forces that formed the landscape we live in.

For systematic research on the settlement history, a key question is the dates when the settlements were founded. There are two primary ways to obtain this date, “historical dating” and “archaeological dating”. In historical dating, a date has been recorded in a historical written document (a chronicle, correspondence, narrative sources or official papers). Every village or town in the Czech Republic has recorded date of this kind (e.g. Růžková *et al.*, 2006). However, these dates may be misleading: a settlement can be first recorded in written sources many years after its real origin – but the time lag is unknown (Žemlička, 2014).

Archaeological dating involves dating objects, features or layers found during archaeological excavations or during a survey. The methods of archaeological dating differ according to the nature of the data that is used. The most frequent method works with chrono-typological dating transformed into a time interval with a uniform probability distribution by assigning calendar dates to the beginning and end of the interval, on the basis of external evidence (Lyman and O’Brien, 2006). The second approach comprises exact methods (radiocarbon, dendrochronology etc.) where dates are represented by probability (Aitken, 1990; Demján and Dreslerová, 2016). The widely-used archaeological chrono-typological method is very approximate, usually only assigning a date within a centennial interval for the medieval period. By contrast, chrono-typological models based on current multivariable approaches to medieval ceramics can offer a considerable amount of precise chronology (Čapek, 2010a; Macháček, 2010). Nevertheless, chronological systems of this type do not cross time interval of half a century.

While archaeological dating is very reliable (there is high probability that the real date of origin has been captured), not every settlement has been excavated. A further disadvantage of this method is its inaccuracy. The archaeological dating reliably anchors human activity and behaviour into a settlement space, but only into a centennial interval, and in lucky cases into a part of a century (Kuna *et al.*, 2004). For example, in ceramics dating, we usually only know the century and not the exact year in which an item was being produced. The differences between historical dating and archaeological dating are well known in the archaeological community (Černý, 1992; Kuna *et al.*, 2004; Blain *et al.*, 2011;

Klápště, 2012b; van Beek, Groenewoudt and Keunen, 2014; Sadravetzová, 2015; Szabó, Šipoš and Müllerová, 2017).

However, neither an extensive literature search nor discussions with relevant experts have pointed us toward any studies that have investigated the exact relation between these two types of dating. Two exceptions are a paper by van Beek, Groenewoudt and Keunen (2014), which however has a sample consisting of just 10 villages/farms, and an unpublished master thesis about the early medieval settlement development in Northwest Bohemia (Kraus, 2017). There is a lack of studies dealing with the high medieval transformation. Other studies have dealt with this topic as a secondary objective, but mostly on the basis of either local data, or pure speculation only (Černý, 1992; Sadravetzová, 2015). Černý (1992) performed a local study of 61 deserted medieval villages in the eastern part of the present-day Czech Republic, and claims that the time lag in historical dating is usually 50 years, and in exception cases 100 years. Other studies have shown that the time lag for a medieval village or building can be almost 150 years (Houfková *et al.*, 2015) or even two centuries (Blain *et al.*, 2011; Parkman, Šálková and Beneš, 2015). Examples from the Netherlands suggest that the time lag may vary between 50 and 300 years (van Beek, Groenewoudt and Keunen, 2014). Žemlička (2014) associates a long lag in historical dating with villages located outside monasterial territories or far away from the intersections of major communications, and also with small hamlets or villages owned by indigent lesser nobility. He also claims that most of the settlements were captured in written sources as late as at the end of the 14th century. This is in accord with Boháč (1987), who identifies the 13th and 14th centuries as a period with a rapid increase in the number of written documents in the Czech lands. The time lag may have been influenced by the fact that that it was not usual to make written records about the organization of ordinary communities and communications in the 12th and 13th centuries (Bartlett, 1994). Klápště and Smetánka (1998) underline that the “need to register transfers of landed property” did not emerge until the mid-14th century. Cases when the written sources pinpoint the real foundation date of a settlement are quite rare (e.g. Profous and Svoboda, 1957; Měřínský, 2014).

A comparison between historical and archaeological dating of historical settlements could help us to answer the following questions: To what extent is historical dating accurate/reliable (or: What is the typical time lag of a settlement’s historical dating)? How much has this time lag varied through the centuries? Is it possible to specify a time point at which historical dating becomes a reliable measure? Has the time lag been affected by any geographical factors (e.g. altitude, or distance from the capital city or from a monastery) or by settlement status (towns vs. villages)? Based on the known time lag for different centuries, will it be possible to derive a relation which could be used for estimating the real date of origin for places with no archaeological data?

2.3.2 Materials and Methods

2.3.2.1 Data collection

The area selected for an analysis of this type should fulfil the following stratification requirements: (1) historical and archaeological dating must be available in sufficient quality, (2) the settlement structure in the analysed area should be strongly affected by medieval transformation and also by (early) modern transformation, and (3) there should be various environmental or geographical gradients to indicate the expected effect of environmental conditions. Within Central Europe, the region of Bohemia in the Czech Republic provided a suitable setting for a case study.

For historical dating, we mostly used data from *The Historical Lexicon of Municipalities* (Růžková *et al.*, 2006); in a few cases, we used data from other historical lexicons and encyclopaedias (Profous, 1947, 1949, 1951; Profous and Svoboda, 1957; Kuča, 1997, 1998, 2000, 2002, 2004, 2008, 2011). (These lexicons and encyclopaedias are editions of historical sources; the primary sources are original historical documents, usually from the medieval age or the early modern age.)

The archaeological data were obtained from *The Archaeological Database of Bohemia* (Institute of Archaeology of the Czech Academy of Sciences Prague, 2013), which provided us with 53 953 records from archaeological researches carried out in the Czech Republic with findings from the medieval age and modern age. The archaeological dating is not expressed in exact years, but in centuries or other intervals. We selected only settlements dated to a specific century or more precisely (more extensive information about the archaeological data – including type of human activity, type of archaeological research and links to original records in the database – is available in Supplementary Information). We excluded settlements dated by inaccurate methods (e.g. building archaeology and undocumented research), and only data supported by accurate and trustworthy research methods (e.g. excavation, profile, trench, field survey) were used for further analysis. The selection resulted in 524 settlements with archaeological dating between AD 850–1600 (there are very few archaeological data after AD 1600). Although the careful restriction of the dataset has much improved its reliability, it is worth noting that some systemic errors may have remained, resulting from different authors, different types of research, absence of context, etc.

For each settlement, we combined its historical and archaeological dating to derive the expected date of the true origin and the time lag in historical dating, which will be referred to as the *derived date* and the *time lag*, respectively. These characteristics were obtained by applying the following rules:

(1) If the historical date was outside the archaeological dating interval, the *derived date* was established as the middle of the archaeological interval, and the *time lag* was the difference between the historical dating and the *derived date*.

(2) If the historical date was inside the archaeological dating interval, the historical date is considered correct; in this case, the *time lag* is zero and the *derived date* agrees with the historical date.

Formally, we define

$$\text{derived date} = \begin{cases} \text{archaeological}_{\text{middle}} & \text{if historical date} > \text{archaeological}_{\text{max}}, \\ \text{historical date} & \text{otherwise,} \end{cases} \qquad (1)$$

where *archaeological*$_{\text{middle}}$ and *archaeological*$_{\text{max}}$ denote the middle and the upper bound of the archaeological dating interval, respectively. The *time lag* variable is defined as *time lag* = *historical dating – derived date*.

To test the role of local conditions, we examined several environmental/geographical predictors. The *altitude* and *terrain undulation* (the average slope in a circle with a radius of 4 km) were extracted from the SRTM digital elevation model (GISAT, 2007). The *landscape typology* was adapted from a classification by Chuman and Romportl (2010), coarsened to five landscape types (Table 2.3.1). The extent of the *"old settlement area"* (i.e. the area inhabited almost continuously since the Neolithic) was taken from Löw and Novák (2008). We measured *distance from the capital* (Prague), *distance from the nearest major town* and *distance from the nearest monastery* at the time of the settlement foundation (*derived date*). The major towns in different periods were obtained from Müller (1720), Purš (1965), Hoffman (2009) and Hrnčiarová, Mackovčin and Zvara (2009). The data about monasteries were compiled from Purš (1965) and Hrnčiarová, Mackovčin and Zvara (2009). We also measured the *distance from the nearest major road*; for this purpose, we used the map of historical roads by Žemlička (2007). Similarly, we measured the *distance to the nearest major river*; the following rivers are classified as "major": the Vltava, Labe, Ohře, Berounka, Sázava, Dyje, Morava and Svratka. River data were obtained from the T. G. Masaryk Water Research Institute (2012). For distinguishing the *settlement status* (towns versus villages), we used the encyclopaedia of Czech towns by Kuča (1996, 1997, 1998, 2000, 2002, 2004, 2008, 2011); settlements promoted to towns after the start of the industrial revolution (roughly 1800 AD) have been marked as "villages" in our database (because they really were villages during the period under study). The data were processed in *QGIS 2.18.15* and *ArcGIS 10.5.1* Geographical information system softwares (ESRI, 2017; QGIS Development Team, 2017).

Table 2.3.1. *Landscape types used in the analysis. Classification by Chuman and Romportl (2010)*

Categories of landscape type	**Category**	***N***	**Landscape description**
Moderately warm to warm downs predominantly up to 500 m a. s. l.	8	202	Elevation: 450–500 m, mean annual temperature: 7–8°C, current land use/cover: mixed forest
Moderately warm downs and hilly lands extending between 250 and 750 m a. s. l.	6 and 7	194	Elevation: 450–500 m, slope: 0–2°, mean annual temperature: 7–8°C, reconstructed natural vegetation: acidophilous oak forest, current land use/cover: non-irrigated arable land
Warm to very warm flat to gently sloping lowlands and downs up to 500 m a. s. l.	9, 10 and 11	121	Elevation: less than 450 m, mean annual temperature: 9–10°C, soil type: chernozems
Cold to moderately warm uplands, hills and mountains	4 and 5	7	Elevation: 500–1000 m, mean annual temperature: 4–6°C, soil type: cambisols or entic podzols, reconstructed natural vegetation: herb-rich beech forest or mountain acidophilous beech forest

2.3.2.2 Data analysis

The focal point of our analyses is the relationship between the *historical date* of a settlement and its actual origin, proxied by the *derived dat*e in our analyses. Two different aspects of this relationship are addressed: the probability that a time lag occurs, and if it does, an estimate of its length. The outcome variables in our statistical analyses are thus either a *time lag*, or a *time lag indicator* (1 = accurate historical dating, 0 = non-zero time lag).

A preliminary analysis confirmed the intuitive expectation that both the occurrence and the length of the time lag evolved rapidly over time. Therefore, the first part of our quantitative analysis was devoted to a detailed inspection of how the time lag varied with the foundation date of the settlements (as indicated by the *derived date*). The nature of the relationship between these variables was assessed using a series of scatterplots with smoothed trend lines. In the next stage, we used regression analysis to identify the settlement characteristics that can help predict the occurrence and size of the time lag. First, we studied the determinants of the *time lag indicator* using logistic regression. Then we restricted the sample to observations with nonzero time lag, and explained the magnitude of the time lag in a linear regression setting.

We obtained Moran's *I* to detect spatial correlation in both dependent variables. While no spatial pattern was found in *time lag indicator* ($I = 0.00046$, $p = 0.307$), there was some evidence of spatial dependence in *time lag* ($I = 0.011$, $p = 0.032$). Therefore, in the analysis of *time lag*, we estimated the spatial lag and spatial error models along with standard linear regression. In neither of the spatial models, however, the parameters related to spatial correlation were significant, and both models were outperformed by their simpler (linear-regression) counterpart in terms of the information criteria AIC and BIC. Therefore, we do not report results of these spatial regressions.

Several variables exhibited considerable positive skewness (*time lag*, *distance from the nearest major town*, *distance from the nearest major road*); these variables were logarithmically transformed before all statistical analyses. The variable *distance from the nearest monastery* was the only one that contained missing values, in app. 13 per cent of the observations. In regressions that contained this variable, we applied the procedure of multiple imputation procedure in order to both (i) increase efficiency of the estimates and (ii) avoid potential adverse effect of non-random assignment of missingness. One hundred regression-based imputations were used for this purpose, with all other variables included in the conditional distribution of *distance from the nearest monastery*.

The regression analyses were performed in *Stata 14.2*; spatial regressions were estimated using the user-written command *spatreg* (Pisati, 2001). All scatterplots with smoothed trends were created in *R 3.5.0* using the *ggplot2* package, version 3.0.0 (Wickham, 2016).

2.3.3 Results

Table 2.3.2 shows the summary statistics of all variables except the categorical predictor *landscape type*. Pairwise correlations confirmed the importance of *derived date* as a strong predictor of *time lag*, and identified as other potential predictors the variables *settlement status* and *distance from the nearest major town*. These preliminary results were confirmed by the regression analyses, presented in Table 2.3.3. Due to excessive multicollinearity, we dropped the variable *altitude* from the list of predictors, as it scored the highest variance inflation factor (VIF) among all numeric predictors (max. VIF = 5.65, mean VIF = 2.21 in an analogue to Model 1 from Table 2.3.3 that also contained *altitude*), mainly because of its correlation with *terrain undulation* (r = 0.51, slopes were usually large in highlands) and *old settlement area* (r = −0.67, older settlements were typically found in lowlands). Dropping *altitude* reduced the VIFs to tolerable values (Table 2.3.3). Moreover, due to the issue of missing values in *distance from the nearest monastery*, we ran all regressions both with and without this variable.

Beside *derived date*, the only significant predictors of time lag occurrence and length (Table 2.3.3) were: (i) the *distance from the nearest major town* (positive effect, i.e. greater distance leads to a longer lag), (ii) *settlement status* (villages have a longer lag than towns) and (iii) *landscape type* (a longer lag in uplands and mountains). None of the other predictors affected the time lag significantly.

Settlements founded in early medieval times (10th to 12th centuries) have a time lag of 150 to 300 years (Fig. 2.3.1B). The time lag decreases with increasing calendar year (but the dependence is not linear). When the high medieval and modern ages are reached (13th to 16th centuries), the time lag becomes more stable (75 to 150 years). This pattern is observed especially for villages; while the time lag for towns decreased almost linearly with increasing calendar year (Fig. 2.3.2). The predicted probability of no time lag in historical dating grew steadily throughout the study period (Fig. 2.3.1A). It reached 50 % around AD 1325 (AD 1200 for towns, and AD 1400 for villages). Towards the end of our study period (cca AD 1600), the probability of a time lag decreased to approximately 25 % (cca 3 % for towns and 25 % for villages, though the confidence interval for villages is very wide, due to the sparseness of the observations). Throughout the study period, the data exhibit considerable unexplained variance (Fig. 2.3.4).

Similar results are shown in Fig. 2.3.4: many places are dated back to the 13th century by written sources, indicating that a proportion of them were in fact established in earlier centuries than that. The 13th century is, generally speaking, characterized by a boom in first mentions of settlements in written records. However, the real situation was different, as Fig. 2.3.4 shows. Later, in the 14th century to 16th century, written sources became increasingly reliable for settlement dating.

Fig. 2.3.5 shows the spatial pattern of the *derived date* (map A) and of the *time lag* (map B); the interpolation was calculated by the *Kriging interpolation* tool in ArcGIS software (ESRI, 2017). The spatial correlation in *time lag*, confirmed by the significant Moran's *I* statistic (section Data analysis), is manifested by large continuous regions in either red or green color. The comparison of such regions in maps A and B documents the relationship between *derived date* and *time lag*. Relatedly, map C indicates areas where *time lag* cannot be explained solely by the age of the settlement: it shows the residuals from a regression of *time lag* on a natural cubic spline of *derived date* with a knot in 1250.

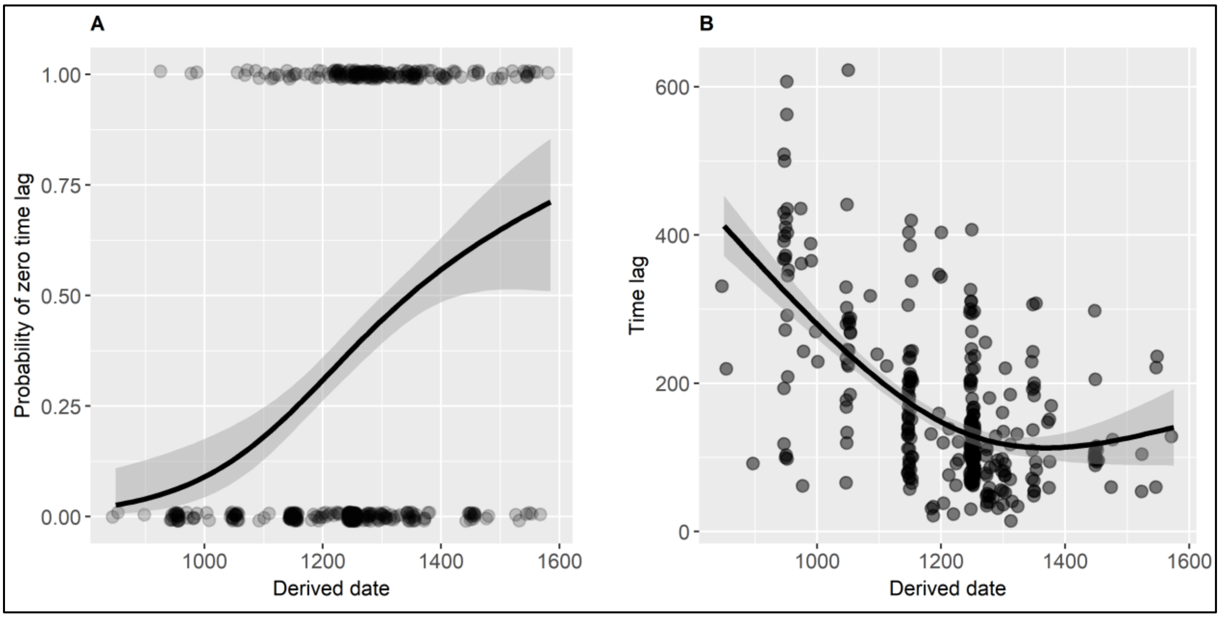

Fig. 2.3.1. *(**A**) Scatterplot of the* time lag *indicator (0 = positive lag, 1 = no lag in historical dating) against the* derived date*; the points are jittered to enhance readability. The curve shows the probability that a historical date is accurate for a settlement founded at the corresponding* derived date*, predicted by logistic regression of the* time lag indicator *on a natural cubic spline of the* derived date *with a knot in year 1250, the median of* derived date*. The shaded area shows the 95% confidence interval for the predicted probability. (**B**) Scatterplot of* time lag *against* derived date*; only settlements with a non-zero* time lag *have been retained in this plot. The curve (and the shaded area) shows a least-squares fit of the relationship (and its 95% confidence region), again using a natural cubic spline of the* derived date *with a knot in year 1250*

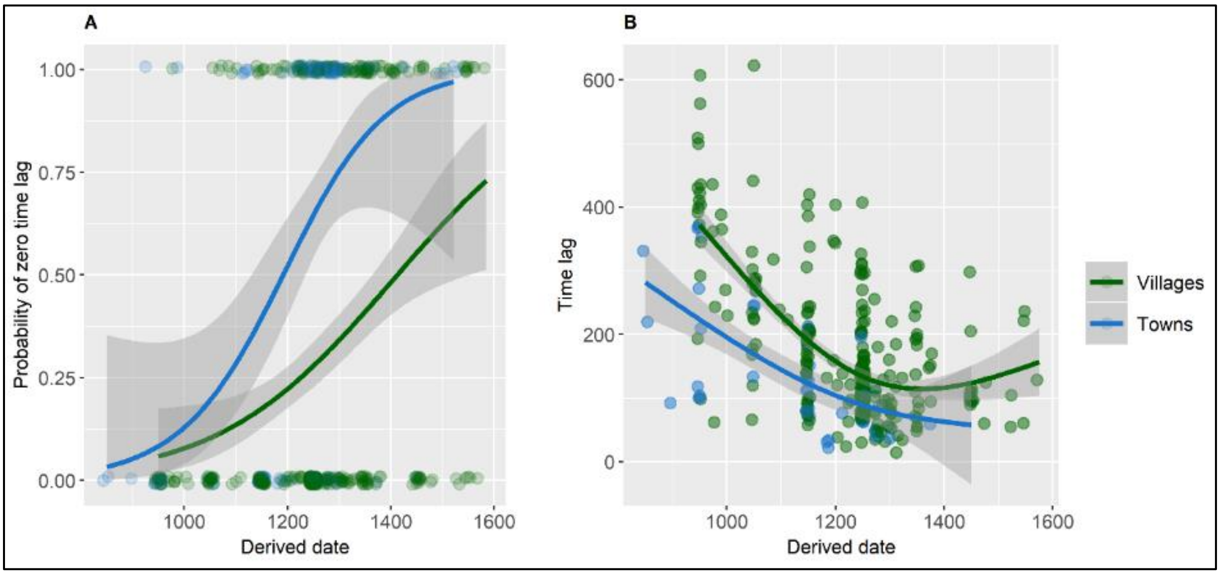

Fig. 2.3.2. *The effect of* settlement status *(towns versus villages) on the relationship between* time lag *and* derived date*. The two plots are analogous to those in Fig. 2.3.1, only that villages and towns are now separated, and are shown in different colours (see the caption of Fig. 2.3.1 for more details)*

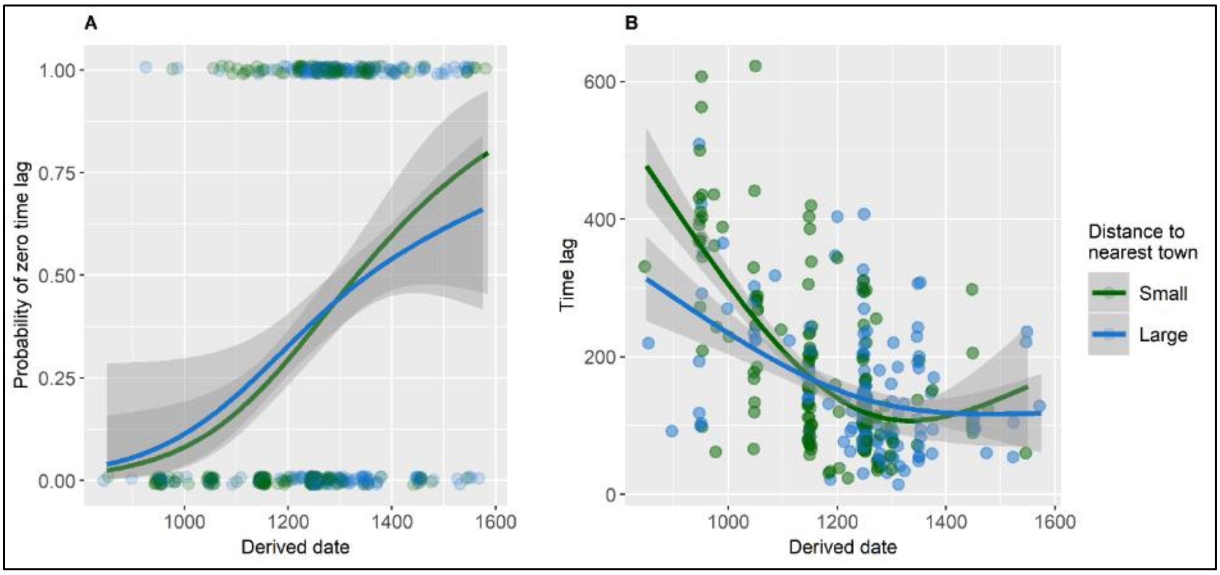

Fig. 2.3.3. *The effect of* distance from the nearest major town *on the relationship between* time lag *and* derived date*. The two plots are analogous to those in Fig. 2.3.1, only that settlements with a small distance (1st and 2nd quartile) and with a large distance (3rd and 4th quartile) are now separated, and are shown in different colours (see the caption of Fig. 2.3.1 for more details)*

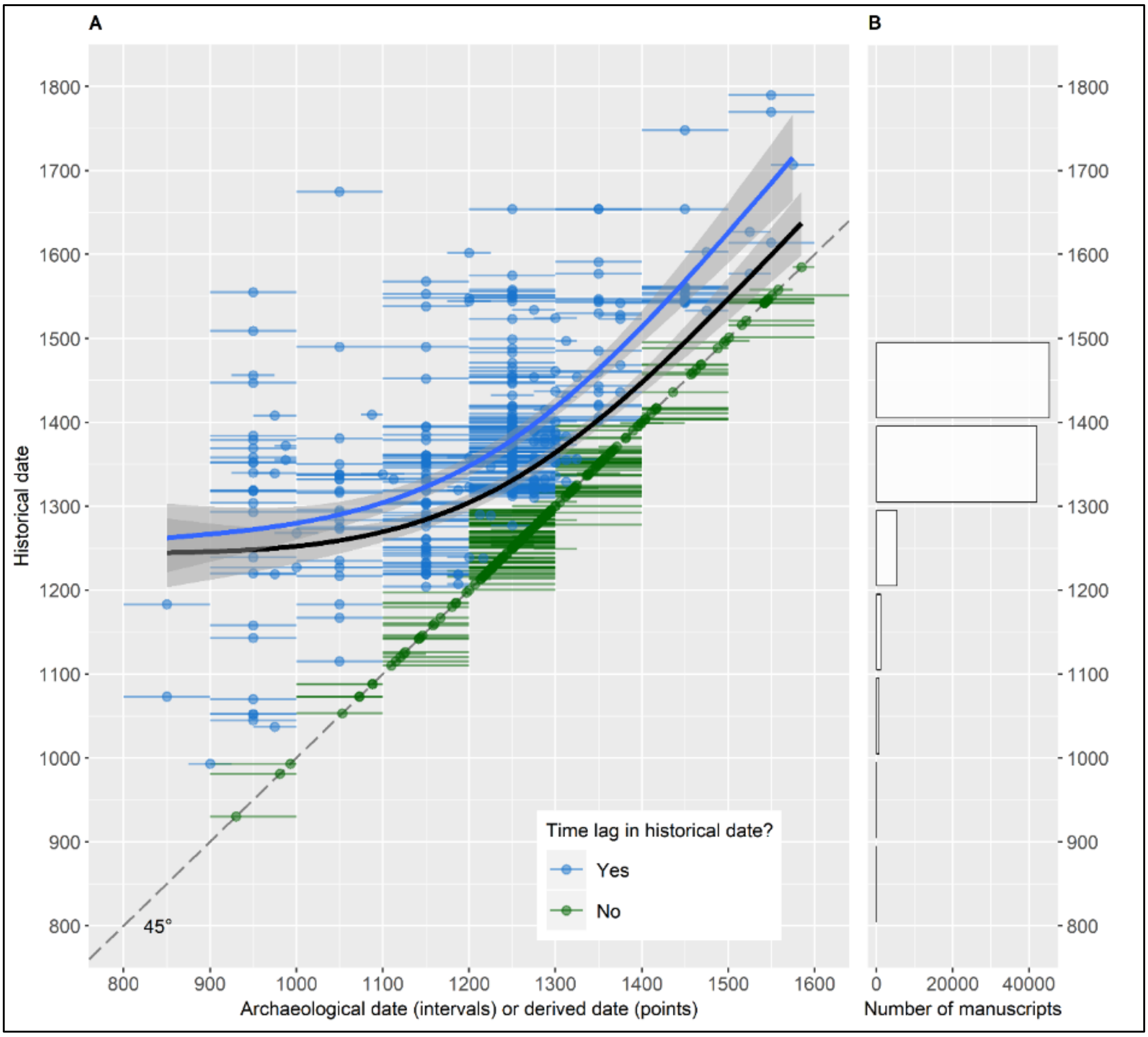

***Fig. 2.3.4.** (**A**) Scatterplot of the* historical date *against the* derived date *of all settlements in the sample. Intervals of archaeological dating are indicated by horizontal line segments around the scatterplot markers. According to the definition of the* derived date *(Eq. 1), whenever the line segment intersects the 45° line, historical dating of the given settlement is regarded as accurate,* derived date = historical date *and* time lag *= 0; such cases are distinguished by green colour. For blue points, the* time lag *is equal to the distance (horizontal or vertical) from the 45° line. The black curve shows a least-squares fit of the historical-versus-derived relationship, using a natural cubic spline of the* derived date *with a knot in year 1250 (sample median). The blue curve is analogous, but with a sample restricted to "blue points" only, i.e. to observations with a nonzero time lag. Shaded areas show the 95% confidence intervals. (**B**) Manuscript production in Bohemia, 9th–15th century AD. Source: Buringh and van Zanden (2009)*

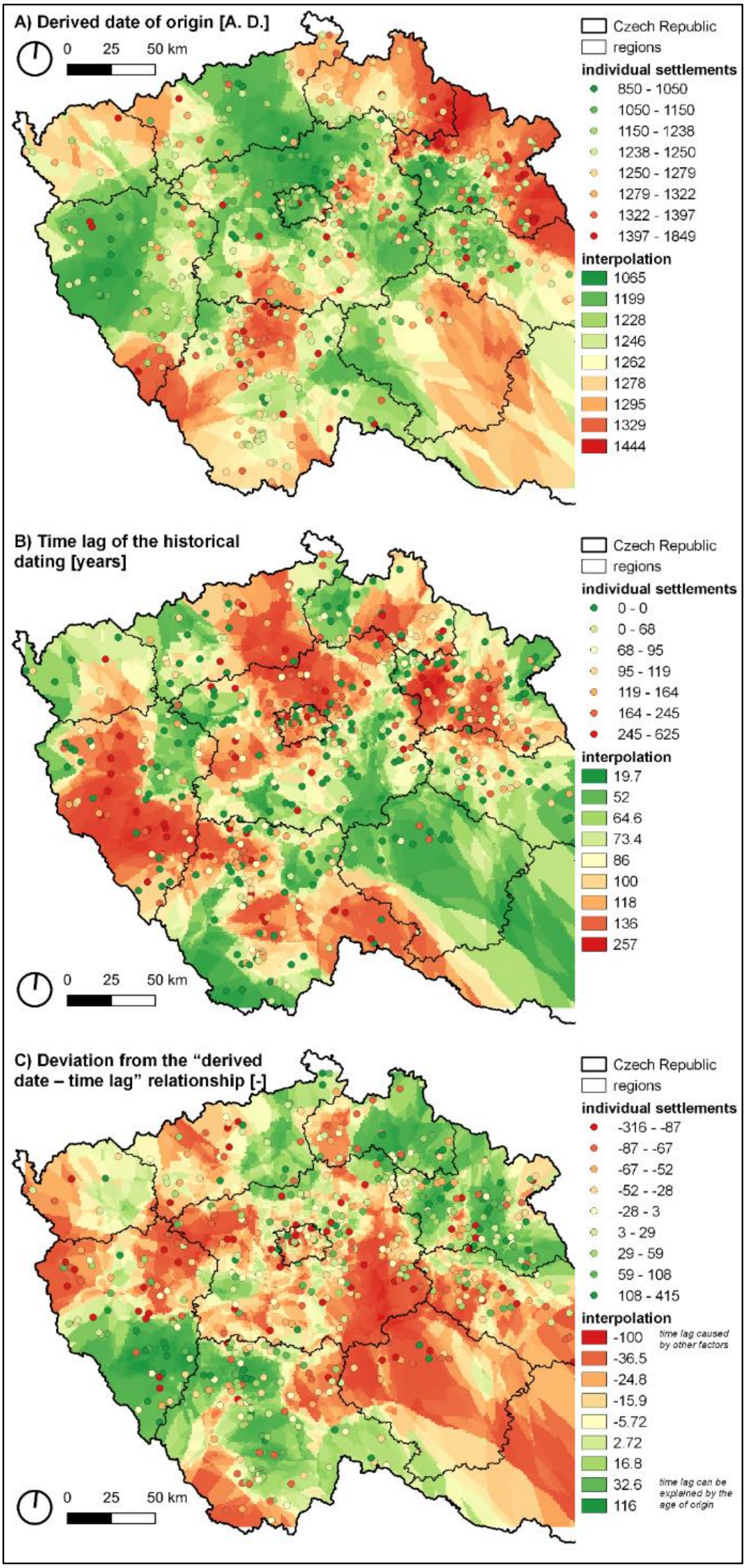
A) Derived date of origin [A. D.]
0
25
50 km
Czech Republic
regions
individual settlements
850 - 1050
1050 - 1150
1150 - 1238
1238 - 1250
1250 - 1279
1279 - 1322
1322 - 1397
1397 - 1849
interpolation
1065
1199
1228
1246
1262
1278
1295
1329
1444
B) Time lag of the historical dating [years]
Czech Republic
regions
individual settlements
0 - 0
0 - 68
68 - 95
95 - 119
119 - 164
164 - 245
245 - 625
interpolation
19.7
52
64.6
73.4
86
100
118
136
257
0
25
50 km
C) Deviation from the "derived date – time lag" relationship [-]
Czech Republic
regions
individual settlements
-316 - -87
-87 - -67
-67 - -52
-52 - -28
-28 - 3
3 - 29
29 - 59
59 - 108
108 - 415
interpolation
-100
time lag caused by other factors
-36.5
-24.8
-15.9
-5.72
2.72
16.8
32.6
116
time lag can be explained by the age of origin
0
25
50 km

Fig. 2.3.5 (on the previous page). *Maps showing the spatial pattern of (A) the* derived date *of origin, (B) the* time lag *of the historical dating and (C) the deviation from the “*derived date – time lag*” relationship. In map (C), the green colour indicates that the time lag can be explained by the age of origin (early medieval period → longer time lag, modern ages → shorter time lag), while the red colour indicates that there was some other cause of the length of the time lag*

Table 2.3.2. *Descriptive statistics and selected pairwise correlations*

						Pairwise correlation	
	N	**Mean**	**SD**	**Min**	**Max**	***Time lag***	***Time lag indicator***
***Time lag* [year]**	524	102.5	116.6	0	625		
***Time lag indicator* [1 = no time lag, 0 = time lag]**	524	0.37	0.48	0	1		
***Derived date* [year]**	524	1244.1	131.3	850	1585	−0.517***	0.307***
***Settlement status* [1 = town, 0 = village]**	524	0.25	0.43	0	1	−0.230***	0.242***
***Distance from the nearest major town* [m, logged]**	524	8.98	1.55	0.78	11.3	0.203***	−0.227***
***Terrain undulation* [°, logged]**	524	1.12	0.55	−0.66	2.47	−0.110*	0.106*
***Old settlement area* [1 = yes, 0 = no]**	524	0.33	0.47	0	1	0.085	−0.079
***Distance from the capital* [100 km]**	524	0.83	0.37	0.021	1.72	−0.067	0.037
***Altitude* [m]**	524	369.1	126.3	133	1068	−0.064	0.047
***Distance from the nearest monastery* [100 km]**	457	0.18	0.10	0.00019	0.57	0.062	0.017
***Distance to the nearest major river* [100 km]**	524	0.15	0.12	0.0017	0.56	0.051	−0.014
***Longitude* [100 km in Křovák’s projection]**	524	−7.26	0.68	−8.97	−5.85	−0.041	0.002
***Latitude* [100 km in Křovák’s projection]**	524	−10.6	0.54	−12.1	−9.48	0.050	−0.035
***Distance from the nearest major road* [m, logged]**	524	8.66	1.24	2.94	10.6	−0.034	−0.003

Notes: (i) Explanatory variables are sorted by their correlation with time lag (descending order). (ii) * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.3.3. *The effects of environmental and geographical predictors on the occurrence and length of the time lag in historical dating (regression results)*

Dependent variable: **Regression model:**	***Time lag indicator*** **[0 = time lag]** **Logistic regression**		***Time lag*** **[years, logged]** **Linear regression**	
	Model 1	**Model 2**	**Model 3**	**Model 4**
Settlement status [1 = town, 0 = village]	3.931*** (0.981)	3.930*** (0.981)	−0.461*** (0.0791)	−0.450*** (0.0789)
Distance from the nearest major town [m, logged]	0.776*** (0.0524)	0.775*** (0.0523)	0.0574 (0.0400)	0.0546 (0.0405)
Terrain undulation [°, logged]	1.264 (0.352)	1.257 (0.355)	0.0296 (0.0794)	0.0482 (0.0819)
Old settlement area [1 = yes, 0 = no]	0.850 (0.319)	0.841 (0.327)	−0.161 (0.118)	−0.123 (0.120)
Distance from the capital [100 km]	0.599 (0.229)	0.602 (0.231)	0.127 (0.101)	0.114 (0.102)
Distance from the nearest monastery [100 km]		0.847 (0.994)		0.518 (0.330)
Distance from the nearest major river [100 km]	0.583 (0.560)	0.587 (0.570)	0.00698 (0.277)	−0.0201 (0.280)
Longitude [100 km in Křovák's projection]	0.906 (0.188)	0.904 (0.188)	0.00939 (0.0525)	0.0173 (0.0533)
Latitude [100 km in Křovák's projection]	0.867 (0.219)	0.877 (0.229)	0.0771 (0.0743)	0.0461 (0.0789)
Distance from the nearest major road [m, logged]	0.930 (0.0883)	0.931 (0.0893)	−0.0410 (0.0249)	−0.0474 (0.0256)
Landscape type				
• Moderately warm to warm downs predominantly up to 500 m a. s. l.	ref.	ref.	ref.	ref.
• Moderately warm downs and hilly lands extending between 250 and 750 m a. s. l.	0.768 (0.222)	0.767 (0.222)	−0.0400 (0.0813)	−0.0416 (0.0815)
• Warm to very warm flat to gently sloping lowlands and downs up to 500 m a. s. l.	0.979 (0.387)	0.975 (0.384)	0.0650 (0.125)	0.0687 (0.125)
• Cold to moderately warm uplands, hills and mountains	1.731 (1.496)	1.757 (1.524)	0.853*** (0.213)	0.756*** (0.217)
N	524	524	330	330
No. of imputations (no. of imputed values)		100 (67)		100 (59)
p(*derived date*)	<0.0001	<0.0001	<0.0001	<0.0001
p(*landscape type*)	0.398	0.380	0.00013	0.00072
R^2	0.175		0.364	
Max. VIF	4.171		4.721	
Mean VIF	1.761		1.921	

Notes: (i) For logistic regression (Model 1 and 2), exponentiated coefficients (odds ratios) are reported. (ii) Standard errors are shown in parentheses; for linear regression (Models 3 and 4), the "HC3" heteroskedasticity-robust version of standard errors was obtained (MacKinnon and White, 1985). (iii) All regressions contained among the explanatory variables a natural cubic spline of *derived date* with a knot in 1250; only a *p*-value indicating a joint significance of all terms related to is *derived date* presented, in row *p*(*derived date*). (iv) Similarly, *p*(*landscape type*) indicates joint significance of all landscape dummies. (v) * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

2.3.4 Discussion

The growth of historically dated settlements in the 13th and 14th centuries corresponds well with the increase in manuscript production in Bohemia (Fig. 2.3.4). The increased manuscript production could also be responsible for the decrease in the time lag in the 12th to 14th centuries (Fig. 2.3.4B), as has been suggested by Boháč (1987). Szabó, Šipoš and Müllerová (2017) wrote that the growth in the number of written documents throughout the middle ages reflects a rise in literacy.

Our results correspond with Bartlett's (1994) findings about “no written records being made” in the 12th and 13th centuries. The growth in the time lag in the 15th and 16th centuries apparently reflects lower availability of data for that period. The length of the time lag observed in our data is similar to the results of van Beek, Groenewoudt and Keunen (2014). However, the time lag is much longer than that predicted by Černý (1992). In contrast with Žemlička's findings (2014), the time lag did not disappear at the end of the 14th century. Towns and villages close to major towns have a slightly shorter time lag than villages and settlements in remote areas (Fig. 2.3.2, Fig. 2.3.3, Table 2.3.3). Similarly, settlements in marginal areas (*landscape type* “cold uplands and mountains”) have significantly longer time lag (Table 2.3.3). In high medieval period, the mean time lag was approximately 75 to 100 years for towns, and 120 to 150 years for villages (Fig. 2.3.2). This is in accord with Žemlička (2014), who expected small settlements and settlements in distant or marginal areas to have a greater time lag. This could be due to the lower importance of such places for the ruling class, or for other people who were responsible for the written records, or due to a lower intensity of written communication in more remote and less important areas.

For more recent historical periods, historical dating is definitely more reliable than for the early medieval period, but there is still a considerable risk of a time lag. When working with historical dating from the middle ages, researchers should take its inaccuracy into account. Historical dating is an important historical source of knowledge about the date of settlement origins, but due to its unreliability each case should be considered individually. It should be compared with other geographical factors (as was suggested by van Beek, Groenewoudt and Keunen, 2014) and above all with direct archaeological dating (Bellanger and Husi, 2012). We cannot recommend the use of historical dating as a sufficiently reliable source for “big data” computations, at least for the middle ages. However, the more recent the centuries that we look at, the more precise and the more reliable data is available, and the greater the opportunities are to use this data in various fields of science.

The dispersion of the prediction interval covers extremely long periods: from almost 400 years for the 16th century to 250 years for the 12th century (the horizontal distance in Fig. 2.3.4). Unfortunately, this does not help us to date a settlement more precisely.

Historical dating is characterized by good availability but high irregularity. Even the growth in the quantity of written documents in early modern times (Buringh and van Zanden, 2009) does not guarantee the reliability of this source. There are examples of settlements from the 15th century that were not captured by written sources until 100 years later (Fig. 2.3.4). Unfortunately, even if the time lag probability, e.g. for the 16th century, is “just” 30 % (Fig. 2.3.1A), this does not give us the right to believe that a written source from the 16th century is reliable for dating a settlement. Conversely, many settlements captured in written sources in the 16th century were really founded between the 13th century and the 15th century, and only some of them were really founded in the 16th century (Fig. 2.3.4). The situation is much worse for older times.

The problems with archaeological dating are substantially different. Archaeological dating can involve either exact dating or chrono-typology, nowadays in sophisticated forms using developments in statistics (Bellanger and Husi, 2012). In historical settlements, dendrochronology is mostly associated with younger historical buildings, which have limited applicability for entire historical settlements. Radiocarbon dating offers reliable data, but the intervals can be almost as long as in chrono-typology. Other methods are rarely used in archaeology. Despite the problems with archaeological dating, the results are usually reliable. The large bias in the quality of archaeological dating is probably caused by the uneven quality and quantity of particular regions (Klápště, 1989). In regions with a long tradition of archaeological research, archaeological dating is likely to be statistically more reliable than in regions without this tradition. This concerns especially mountainous/upland regions that were colonized in the high medieval period, some of them also in the early modern period like upper parts of Šumava mountains (Beneš, 1996). Other problems with archaeological dating can arise when scientists want to identify the archaeological findings to historical settlements mentioned in written sources (this especially concerns towns).

Some authors (Sadravetzová, 2015; Szabó, Šipoš and Müllerová, 2017) admit the existence of a time lag, but in their work they treat historical dating as if it were a reliable source that can be used for drawing graphs and for statistical computation. That is extremely precise work with (as we are showing in this paper) extremely unprecise data. It is necessary to take all the irregularities and disadvantages of historical dating into account when analysing and interpreting such data – it really does not make sense to use the historical dating for precise computations. Adams (2003) stated that historical dating is often the most precise way of dating settlements, and should be used in preference to archaeological dating. Our findings show that this is not true, at least for medieval and early modern Central Europe (however, the topic of Adams' paper is North America in the 19th century, which might be considered as a different context).

Fig. 2.3.5 indicates that in some areas (e.g. the Labe valley in NW Bohemia and part of SW Bohemia), the time lag can be explained by the early origin of the settlements: the sites in these regions were established in the early medieval period, and it took a long time to log the towns and villages into the written records. However, in many other areas, the time lag (or the absence of a time lag) cannot be explained just by the date when a settlement was established – it must have been caused by other factors. For example, in the Bohemian-Moravian Uplands and in Eastern Bohemia, settlements were founded in early medieval times, but the time lag is (counterintuitively) very short. In such situations, the (low) availability of data, and also historical reasons, may have played a role: zones close to major communications, regions owned by the German Empire, mining areas, monastery activities or the colonization of "virgin" regions in periods when written sources were expanding may have attracted a greater density of written records.

Our results may have also implications for the study of historical landscape development, as archaeological dating of settlements shifts the perceived timing of landscape transformations (e.g. the medieval colonization) to earlier centuries.

2.3.5 Conclusion

The historical dating of towns and villages includes important and unique information about settlement and landscape history. However, historical dating of medieval towns and villages is too unreliable to be trustworthy, especially due to the dispersion of the data. Our study has provided the first exact comparison between historical dating and archaeological dating. It has demonstrated the limits of historical dating or the first mention of the site in written record respectively: In central Europe, the historical dating is surely useful for an rough estimate of the origin of individual settlements with knowledge of the time lag, and perhaps for micro-regional studies; however, it makes no sense to use historical dating for statistical and other precise works with “big data”, since it carries overwhelmingly huge errors (especially in the pre-modern period). The probability of a time lag in historical dating has decreased with increasing calendar year (this corresponds with the increasing production of manuscripts/written sources in the course of history; Fig. 2.3.5), but the probability remained nonzero even at end of the 16th century. Towns and settlements located close to major towns had a shorter time lag, as these places were probably more important for the central and regional lords (the monarch/nobility/clergy) and/or there was greater intensity of written communication. The historical dating of medieval settlements may therefore not so much reflect the colonization of the landscape, but an increase in manuscript production (and indirectly the literacy level, together with the intensity of communication).

Acknowledgements

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Data availability

All data are available in the electronic supplementary material, Dataset S1.

Competing interests statement

The authors have no competing interests.

3 Summary

The original aim of this thesis was to study the influence of environmental conditions on settlement history – more specifically, on selected processes in settlement history. Simultaneously, I wanted to use the aforementioned "ecological" approach, i.e. working with bigger data sets and statistical processing. In total, we investigated three sub-questions of various topics, which examined the usability of the above-mentioned approaches in different fields.

The first paper ("Equilibrium dynamics of European pre-industrial populations: The evidence of carrying capacity in human agricultural societies") describes population dynamics in the period of the Thirty Years' War, and subsequent centuries, in the context of human carrying capacity. We have found that human communities in this period were limited by environmental carrying capacity even in the 17th century, i.e. deep within the modern period. Our paper shows that the main limiting factor for population growth was soil fertility and cadastre size – or, in other words, food availability [this result is in accordance with previous findings regarding human carrying capacity (Seidl and Tisdell, 1999; Hopfenberg, 2003; Zhang *et al.*, 2007)].

The second paper ("How long do floods throughout the millennium remain in the collective memory?") was focused on the influence of big floods on the historical memory of people. The main question was whether people are able to transmit prior catastrophic flood information to younger generations, and whether this passed memory can affect the decision making of younger generations in decisions for settlement locations. The results show that the flood memory really exists, but its effects are limited only up to approximately 25 years (i.e. one generation). We attribute this limitation to population ageing and a loss of eye-witnesses (cf. Vansina, 1985; Pfister, 2016). It could be stated that the younger generations might have heard about floods from generational storytelling, but it obviously had no effect on their behaviour.

The third paper ("How old are the towns and villages in Central Europe? Archaeological data reveal the size of bias in dating obtained from traditional historic sources") studied a more specialized and practically oriented topic: time-lag in the dating of historical sites. While time-lag was quite long (150 to 300 years) in the early and high medieval periods, it became strongly shortened in the late medieval and early modern period. At the end of the 16th century, the probability of time-lag was less than 5 % (towns) or 25 % (villages). Unfortunately, data for the 17th and 18th centuries was not available. However, we expect that time-lag would be permanently decreasing during these centuries.

Below follows more detailed analysis of the particular papers.

3.1 Comments on Paper I (Thirty Years' War and human carrying capacity)

3.1.1 Thirty Years' War

The Thirty Years' War (1618 – 1648) was a tragic conflict in European history. The war started as a religious conflict between the Catholics and the Protestants. However, in the 1630s, political motivation became more important. The originally religious war was turned into a fight for land, goods, properties and power (Hora-Hořejš, 1995; Walker, 2014). Many European nations were involved in this war (namely Czechs, Germans, Austrians, Danes, Swedes, Frenchmen, Spaniards, Dutchmen and other nations). The battles took place mainly in Central Europe (modern Czech Republic and Germany), but partially also in the Netherlands and on French-Spanish borderland (Walker, 2014).

The Thirty Years' War became infamous by soldiers of fortune, who were plundering the villages and towns and killing the civilians (Fig. 3.1) (cf. Hornstein, 2005). This problem mainly arose in the last phase of the war (1630 – 1648), when the armies were in short of supplies and money for the soldiers' pay (Asch, 1997). Soldiers thus learned to "feed themselves" and receive supplies by plundering villages (Hora-Hořejš, 1995). The soldiers also didn't care about being in allied or enemy territory (Klučina, 2004). For example, during a Swedish raid into Bohemia in 1639, several thousand villages were devastated within a timespan of eight months (Hora-Hořejš, 1995). Munck (1990) specifically mentions a German village which was plundered 28 times in two years, including two raids in a single day. The soldiers also quite often destroyed all supplied that could be potentially utilized by their enemy (Asch, 1997). Several cities also experienced multiple plunders' raids (Němečková, 2012). These repeated acts of violence had a naturally catastrophic effect: although it was possible to rebuild the economy in a relatively short time (10 – 12 years) in some areas, repeated invasions pushed down the economy as well as the demographical situation and made the recovery nearly impossible (Asch, 1997).

Fig. 3.1. *Plundering of villages during the war in historical engraving. Source: Callot (1633)*

Steinberg (1966), Asch (1997), Fialová *et al.* (1998) and Lederer (2011) unanimously claim that the most terrible suffering of civilians was not caused by military activities or plundering, but as a result of food shortage and the spread of diseases. Abandonment of fields, wartime destruction and worse climatic conditions caused an increase in food prices (Asch, 1997). High concentration of people in the armies and their movement across Europe gave rise to the spread of epidemics (namely plague, smallpox, typhus fever and venereal diseases) (Steinberg, 1966; Fialová *et al.*, 1998). Fialová *et al.* (1998) points out that the increase in disease spreading was boosted by a long-lasting weakening of humans due to starvation, which was caused by the devastation of settlements and economy. Further, the occurrence of stress amenorrhea (a temporary infertility of women as a result of malnutrition and stress[8]) and a reduction of marriages led to a decreased birth rate (Fialová *et al.*, 1998). The migration of humans during and after the Thirty Years' War took place very often (Steinberg, 1966; Munck, 1990; Fialová *et al.*, 1998). There are records of large movements within one country from strongly disturbed to less disturbed areas (Dokoupil *et al.*, 1999).

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[8] I would like to thank my friend Robert Barkman for this medical explanation.

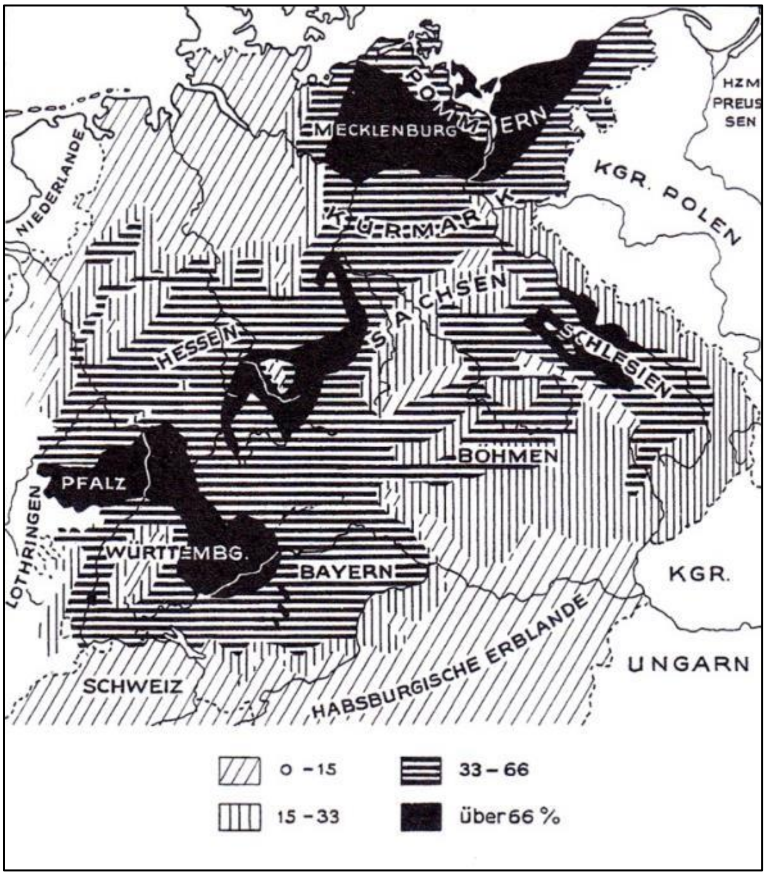

Fig. 3.2. *Population decrease during the Thirty Year's War in Central Europe. Source: Kirsten et al. (1965)*

The Thirty Years' War was the most destructive conflict in European history (Wilson, 2011). The impact of the war on the civilian population was terrible. According to historians' estimates, the population in Central European rural areas decreased by 30 % during this period, in some regions up to 50 % (Fialová *et al.*, 1998; Wilson, 2011; Walker, 2014). The decline was much worse in towns, which lost 50 % to 80 %, and, in some cases, even up to 90 % of their population (Munck, 1990; Čornejová *et al.*, 2008; Wilson, 2011; Němečková, 2012), as the towns were often burned down as a direct result of fighting (Asch, 1997). Walker (2014) estimates that 8 million Europeans died during the war. Five million of them died in the Holy Roman Empire (20 % of the pre-war population; Wilson, 2011). In today's Germany, the total losses rose to ⅓ to ½ of population (Davies, 1997). In some areas, the population decrease (intensified by plague epidemics) started already at the end of the 16th century (Dokoupil *et al.*, 1999). The consequences of this depopulation in the first half of the 17th century are apparent even in lacustrine sediments (Enters, Dorfler and Zolitschka, 2008). However, it is important to note that the aftermaths of the war varied by region (Fig. 3.2); some lands escaped without damage (Rabb, 1962; Kirsten, Buchholz and Köllmann, 1965; Pühringer, 1997; Fialová *et al.*, 1998).

Büntgen *et al.* (2013) and Zhang *et al.* (2007) point out that the Thirty Years' War happened in the coldest era of the modern period. Some historians believe that the humid climate of the 16th and 17th centuries might have resulted in a decrease in agricultural yields, thus worsening the economic situation (Munck, 2005; Schmidt, 2005; Behringer, 2007), which has already been recorded (Pühringer, 1997). Consequently, limited resources and environmental degradation can lead to conflicts (Zhang *et al.*, 2007; Lee, 2014).

The population decrease was (besides violence, starvation and diseases) also generated by migration (both emigration and internal migration), which led to a heterogeneous spatial distribution of the population (Fialová *et al.*, 1998). Steinberg (1966) and Munck (1990) also attribute the observed population decrease to migration and the redistribution of inhabitants. While some towns had recovered from the impact of the war quickly within one decade (Munck, 1990), the countryside was characterized by regression: quality of building practices of rural houses was declining (Frolec, 1992) and uncultivated fields were being registered in some regions even in the beginning of the 18th century (Dohnal, 2006). The pre-war population numbers were not reached until the end of 17th century (Fialová *et al.*, 1998; Dokoupil *et al.*, 1999), respectively in Southern Germany in the first third of the 18th century (McIntosh, 2001).

According to historical population records of individual villages and towns, the after-war regeneration was different in particular places (Doskočil, 1953, 1954; Chalupa *et al.*, 1964, 1966). A similar result was presented in Frolec's (1992) paper about regression of vernacular building activities in the post-war period. Unfortunately, it is not clear why the regeneration was so heterogenous and which factors played an important roles for the regeneration. Historical literature dealing with this problem is limited. Maur (2001) claims that in some submontaneous and montaneous regions, towns grew better due to smaller impact of war damages and the presence of proindustry. The protoindustrial factor was also underlined by Fialová *et al.* (1998). On the other hand, Dokoupil *et al.* (1999) asserts that the largest growth did not occur in the protoindustrial regions, but in the interior regions, which experienced the worst effect of wartime destruction. They think that the growth was stimulated by the availability of uncultivated land in the most affected regions.

With respect to expected appreciable influence of the environmental and cultural factors on the settlement history, we decided to study the after-war regeneration process through statistical methods. Our motivation was primarily historical-geographical, but we also found that our data contributes heavily to the field of population ecology. And, among other things, we have shown that Dokoupil's *et al.* (1999) explanation was right.

3.1.2 Carrying capacity and the human society

The issue of human carrying capacity has been widely discussed throughout the last decades. Many authors concentrated their efforts on the carrying capacity of planet Earth (Fig. 3.3) (e.g. Hardin, 1968; Cohen, 1995b; Townsend, Begon and Harper, 2008; Ehrlich and Ehrlich, 2013), or on the carrying capacity of historical human societies (e.g. Cohen, 1995b; Zhang *et al.*, 2007; Lee, 2014). But such studies were either just theoretical, or, when dealing with historical situations, worked on a coarse spatial scale (e.g. on the level of whole countries). What are we bringing as a new thing is the detailed insight into one particular historical event on a scale of individual villages.

Our findings corresponds with many studies on historical societies, where it has been shown that human carrying capacity is primarily determined by food availability (Hopfenberg, 2003; Zhang *et al.*, 2007; Zhang, Lee, Wang, Li, Pei, *et al.*, 2011; Zhang, Lee, Wang, Li, Zhang, *et al.*, 2011). The same result is also expected by human carrying capacity theories (Cohen, 1995b; Seidl and Tisdell, 1999). Our results also concur with the study by Zhang *et al.* (2007) regarding the importance of population pressure on population growth: in pre-industrial societies, lower population pressure enabled higher population growth (because more food per capita was available) and vice versa. In line with Dokoupil *et al.* and Zhang *et al.* we suggest that one important reason for rapid European population growth in the second half of the 17th century was a huge reserve of uncultivated agricultural land (Dokoupil *et al.*, 1999); or more generally: the population pressure was very low in that period (Zhang *et al.*, 2007). Similarly, Cohen (1995b) claims that the increase of population growth in the 17th century was made possible by a prior extensive period of an increasing carrying capacity of the Earth. The depletion of these reserves due to re-cultivation at the end of the 17th century could have caused an inhibition of population growth at the turn of 17th and 18th centuries (Dokoupil *et al.*, 1999).

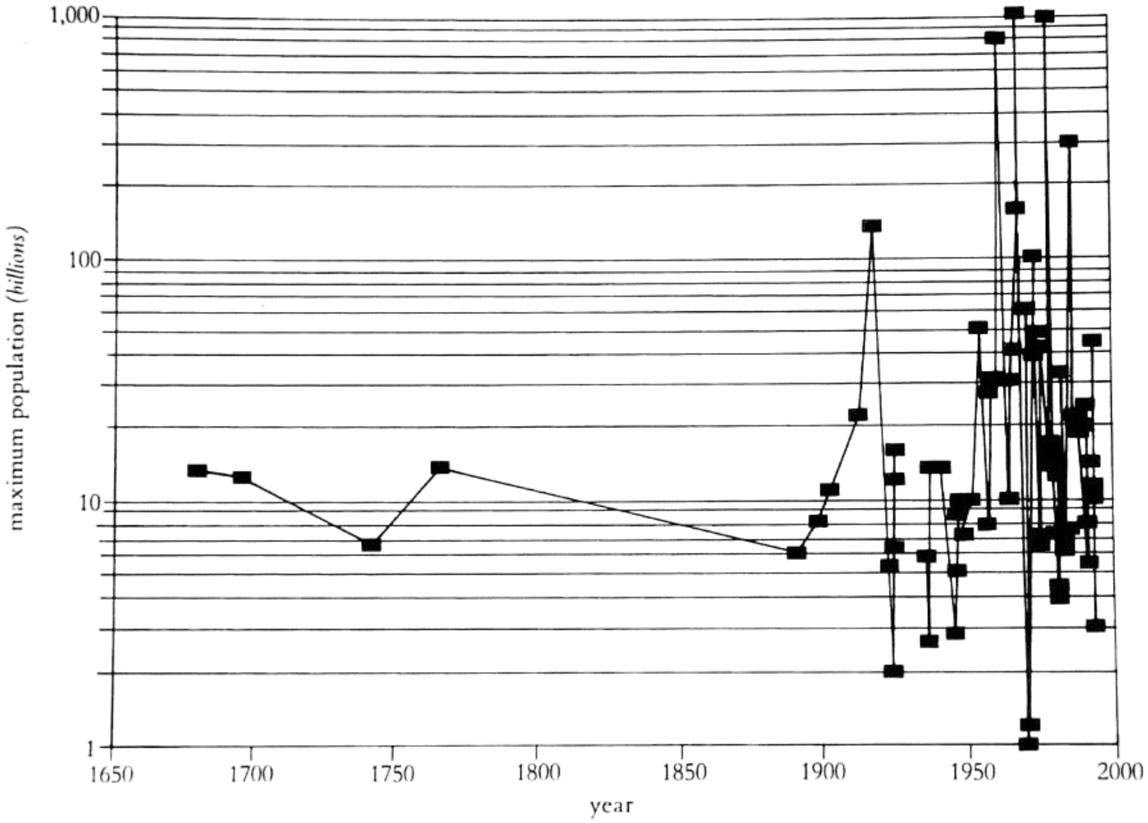

FIGURE 11.1 Estimates of how many people the Earth can support, by the date at which the estimate was made. When an author gave a range of estimates or indicated only an upper bound, the highest number stated is plotted here. The 1964 estimate by J. H. Fremlin would be off the scale and is omitted. SOURCE: Appendix 3

Fig. 3.3. *Development of opinions on the carrying capacity of our planet. Source: Cohen (1995a)*

It is important to underline that the observed process occurred before the beginning of the industrial revolution, which dramatically changed agricultural possibilities and also human carrying capacity. As many authors state, human carrying capacity is dynamic; it depends on a lot of quantities, including food availability, technologies, exploitation strategies, production and consumption patterns, external influences etc. (Arrow *et al.*, 1995; Cohen, 1995b; Seidl and Tisdell, 1999; Hopfenberg, 2003). It could have been expected that humans overcame carrying capacity at some point in distant history (e.g. during the Neolithic or as a result of medieval agricultural innovations); however, our study shows that environmental carrying capacity limited human populations even in the pre-industrial period. Thus, carrying capacity was apparently overcome (or more precisely: shifted to higher level) first by the industrial revolution. Therefore, our work covered perhaps the best study period for research of human carrying capacity in traditional agricultural societies: the 17th and 18th centuries are relatively well-covered by historical population data, and agricultural production in these centuries had not yet been affected by the industrial revolution. The population development in the course of the 18th and 19th centuries, coupled with the expected influence of industrial innovations, is going to be a subject of our next study. Also, since we know that the main factors affecting historical village sizes were soil fertility and cadastre size, it would be possible to derive a "potential of pre-industrial settlement" for every cadastre in the whole country, and compare such potential e.g. with historical subsidence strategies (agriculture / grazing / proto-industry).

Our findings have also been indirectly confirmed by other papers. Tao *et al.* (2017) studied settlement pattern in agricultural regions in China. They predicted that settlement size should positively correlate with territory size and also with energy availability (measured as the potential evapotranspiration). They did not observe the effect of soil fertility, but they studied the current situation, which has been affected by agricultural innovations from the last two centuries. Their findings on factors affecting settlement size concur with ours. Tallavaara, Eronen and Luoto (2017) have shown that the population density of hunter-gathers is mostly affected by net primary productivity (i.e. available energy) and also by biodiversity in low-productivity regions and by pathogen stress in high-productivity regions. Their study points out that environmental factors played an important role in the population density of the pre-agricultural population, which resonates with our findings. Xu *et al.* (2015) studied agricultural populations in China, spanning the last two thousand years, and found that settlement pattern well reflects various factors directly influencing crop yield. To conclude, the papers mentioned here suggest that settlement size was moderated by agricultural yields, i.e. food availability.

3.1.3 Uncertainties, doubts and advantages of our approach

The approach that we used in this study (statistical analysis of a large data set) differs from the habitual attitude of traditional historical studies (deep analysis of a single feature or a microregion). Since our approach was different, it offers some advantages; on the other hand, it bears also some disadvantages. To be fair, I want to mention several possible uncertainties raised from our approach.

One major problem is the work with the historical data itself. In our case, we compared the data from two historical sources – the Tax Register from 1654 and the Theresian Cadastre from 1757, both in editions from 1950s and 1960s (Doskočil, 1953, 1954; Chalupa *et al.*, 1964, 1966). These records were made 260 and 360 years ago for special taxation purposes and we could not exclude that already the original files contain errors or inaccuracies (intentional or unintentional mistakes caused e.g. by indolence of the tax officers or bribery). It also known that some files of the Tax Register from 1654 did not survive until today and were additionally calculated from other sources. Another problem rises from the comparison of two different sources, because each of them was made by different people using different methods. All of these uncertainties were and are hardly avoidable.

Another limitation comes from the big data approach itself: while a careful analysis of historical source(s) with identifications of all their limits is an inseparable part of a "standard" historical study, to perform a similar analysis in a big data approach would require a cooperating historian[9] and extensive time, far more time than a PhD study allows. Therefore, I omitted this work.

During discussions with other colleagues (namely with Dr. Dagmar Dreslerová from the Institute of Archaeology CAS, and with colleagues at the conference about Thirty Years' War in Pilsen during November 2017), I was often alerted that many other factors could appear (especially in the wake of social or economic conditions or political decisions). Such influences were definitely possible. This case

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[9] For a long time, I have been looking for a historian who would agree to cooperate with us. Unfortunately, my search was not successful.

is similar to the previous issue – if we performed a detailed study on a small number of settlements, it would have been necessary to consider such factors. However, large numbers of studied features would require considerably more time than what was available. I think that it may become a task for historians, for whom I ask: why did some villages deflect from the "return to K" pattern, as indicated in the Fig. 2.1.2? In other words, why did some villages overcome their carrying capacity limitation – while others did not?

To conclude: our method definitely has several disadvantages. On the other hand, the main advantage of our approach is the fact that the study was performed on a big dataset. This allows the neglecting of particular items and the study of general trends, e.g. ecological patterns like carrying capacity. Another advantage is an insight into history with an ecological magnifying glass – which means that we can study the ecology of human populations in history and use unique historical data to describe the "natural experiments".

3.2 Comments on Paper II (historical floods and human memory)

3.2.1 Historical floods

Historical floods (Fig. 3.4) have been widely studied in the recent decades. Many authors have compiled detailed flood-chronologies of European rivers (e.g. Brázdil *et al.*, 2002, 2005; Glaser and Stangl, 2003; Glaser *et al.*, 2010; Elleder, 2015; Pfister, 2016), including comparisons of flood histories of individual rivers (Glaser *et al.*, 2010). E.g. Elleder (2010) identified 181 floods in Prague between the years 1118 and 1830. In general, the floods in Central Europe can be caused by four meteorological events: (1) flash floods, (2) long-lasting rainfall, (3) snow-melting and (4) ice-damming (Brázdil *et al.*, 2002). Because reliable instrumental weather records have been only available since the 18th or 19th century (Elleder, 2007), researchers have to rely on other historical sources. Elleder (2007, 2010) distinguishes several possible sources: (1) physical remains in river morphology and artefacts (paleohydrology, geomorphology, archaeology), (2) documentary sources (chronicles, historical registers, newspapers, images, scientific studies, correspondence, old maps), (3) flood marks on old houses or rocks; and, since the 19th century, (4) instrumental records.

The following are short descriptions of floods that were incorporated into our study:

(1) September 1118: A catastrophic flood, also recorded in Austria (Melk) and Germany (Thuringia, Brandenburg) (Brázdil *et al.*, 2005). It was probably caused by intense rainfall (Elleder, 2007). Estimated runoff in Prague was 6000 $m^3 \cdot s^{-1}$ (Elleder, 2010). The chronicler Cosmas described this flood in his famous *Chronica Boemorum* ("The Chronicle of the Czechs"): *"In the year of our Lord 1118 in the month of September there was such a flood as, I think, it has not been on the Earth since the Deluge. This river of ours, the Vltava, suddenly broke out of its bed – how many villages, how many houses in the suburbs, huts and churches did it take away! At other times, although it happens rarely, the water reaches only the floor of the bridge, but this flood rose to a height of ten ells [i.e. approximately 6 m] over the bridge,"* [10] (Brázdil *et al.*, 2002). A flood mark of this flood has

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[10] Latin original: *„Anno dominice incarnationis MCXVIII. Mense Septembri tanta fuit inundatio aquarum, quantam non reor fuisse post diluvium in orbe terrarum. Nam noster iste fl uvius Wlitaua repente preceps erumpens de alveo, ah quot villas, quot in hoc suburbio domus, casas et ecclesias suo impetu rapuit! Aliis namque temporibus tametsi hoc raro evenit, ut unda alluens vix tabulata pontis tangeret, hec autem inundatio altius quam X ulnis super pontem excrevit,"* (Brázdil *et al.*, 2005). Czech translation: *"Léta od vtělení Páně 1118. V měsíci září byla taková povodeň, jaké tuším nebylo od potopy světa na zemi. Neboť řeka naše Vltava, náhle prudce vyrazivši ze svého řečiště, ach, kolik vsí, kolik v našem podhradí domů, chalup a kostelů svým přívalem pobrala! Neboť kdežto*

been identified on a rock in Děčín, but later research has shown that it is younger falsum (counterfeit), probably from the 16th or 17th century (Brázdil *et al.*, 2005).

(2) January and February 1342: A flood recorded at many rivers in Western and Central Europe (Loire, Seine, Rhein, Mein, Neckar, Inn and Elbe) (Brázdil *et al.*, 2005). It was caused by a rapid thaw combined with heavy rainfall (Elleder, 2007). The estimated runoff in Prague was more than 3500 $\text{m}^3 \cdot \text{s}^{-1}$ (Elleder, 2010). The flood destroyed three quarters of the stone Judith's bridge (Brázdil *et al.*, 2005) and also mill and weir (Elleder, 2007). The chronicler Franciscus of Prague left a detailed description of this flood [11] (Brázdil *et al.*, 2005).

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jindy, ač se to málokdy stává, hladina vody sotva dosahovala podlahy mostu, za této povodně vystoupila voda přes deset loktů nad most," (Brázdil et al., 2005).

[11] Latin original: *"Anno Domini MCCCXLII in vigilia Purificacionis sancte Marie Virginis calido vento australi preambulo, quem pluvia quasi vernalis fuit subsecuta, post durissimam hyemem et gravissimam, in qua multitudo hominum in Boemia et in aliis terris nimio frigore fuit extincta, factum est grande diluvium per impetum aque nivealis et pluvialis et propter ingentem molem et spissitudinem glaciei ruptus est pons Pragensis in pluribus locis, quod vix quarta pars de ipso remansit, verumtamen aquarum impetu debilitata. Et omnia molendina et obstacula sunt destructa, pluresque ville circa littora site cum hominibus et ceteris animalibus sunt absorpte et suffocate. In toto quoque mundo tunc temporis fuerunt maxime inundaciones, ita quod in aliis terries pontes lapidei et lignei per aquas nimias sunt destructi. Mare quoque fuit multum augmentatum et in altum elevatum, quod omnes cysternas Weneciis et in aliis civitatibus mari adiacentibus totaliter destruxit. Et in civitate Pragensi aque longe lateque diffuse, maxime in celariis diversum potum humanis usibus preparatum destruentes, dampna plurima intulerunt. Cives quoque Pragenses et Podskalenses strues magnas et multas lignorum ad edificia varia dipositorum propter impetum aquarum perdiderunt. Et quia inopinate et subito factum est hoc diluvium, vise sunt domus cum hominibus et infantes in cunabulis natantes; quibus matres nimium meste succurrere non valuerunt. Visa sunt quoque animalia diversa domestica et varia suppellectilia deferri. Et illa quassacione miserabili mitigata multa corpora hominum submersorum sunt reperta. Et primo homines intellexerunt, quod tam grande et arduum bonum perdiderunt. Nam cum res necessaria perditur, primo eius precium advertitur. Nam quasi corona regni cecidit, cum ille pons famosus corruit, et fit labor magnus et personarum pericula in navigando, merorque pauperum naulo carendo. Pons quoque valentissimus a venerabili in Christo patre domino Johanne IV, Pragensi episcopo XXVII, in Rudnicz efficaciter, firmiter decenterque constructus inviolatus permansit, licet maior ibi concursus fuisset aquarum et grandior de glacie massarum impulsus repentinus, de quo gracias Deo referentes, sui fideles congaudebant. Tunc temporis circa Minorem civitatem Pragensem propter multitudinem arene, que impetu aquarum extitit aggregata, fuit obstructus aque meatus et amplius molendina ibidem haberi non potuerunt,"* (Brázdil et al., 2005). Czech translation: *"Léta Páně 1342, v předvečer Očišťování svaté Panny Marie [1. února], po předchozím teplém jižním větru, po němž přišel déšť jakoby jarní, po velmi kruté a tuhé zimě, za níž silným mrazem zahynulo množství lidu v Čechách i v ostatních zemích, nastala přívalem sněhové a dešťové vody veliká povodeň a obrovskou spoustou a tloušťkou ledu byl na několika místech stržen pražský most, takže z něho zůstala sotva čtvrtina, leč i ta byla přívalem vod poškozena. Byly též strženy všechny mlýny a jezy a četné vesnice ležící u břehů byly i s lidmi a ostatními živočichy pohlceny a zatopeny. Také na celém světě byly tenkrát převeliké povodně, takže i v jiných zemích byly spoustou vod zbořeny mosty kamenné i dřevěné. Také moře se velice vzdulo a vystoupilo do výšek, takže úplně zničilo všechny vodní nádrže v Benátkách i v jiných městech ležících u moře. I v městě pražském vody široko daleko rozlité převelice zničily ve sklepích různé nápoje, připravené k potřebě lidí, a způsobily mnoho škod. Pražští a podskalští měšťané ztratili přívalem vod mnoho ohromných hromad dřeva, určeného k různým stavbám. A protože tato povodeň nastala nečekaně a náhle, bylo vidět plavat domy s lidmi a nemluvňata v kolébkách, jimž matky, nesmírně nešťastné, nemohly pomoci. Bylo též vidět, jak jsou odnášena rozličná domácí zvířata a různé nářadí. A když se ona žalostivá pohroma zmírnila, našlo se mnoho těl utonulých lidí. Tu lidé ponejprv pochopili, jak nebetyčně veliké dobro ztratili, neboť když se ztratí nezbytná věc, tu se teprve pozná její cena. Neboť jako by spadla koruna království, když se zřítil onen proslulý most, a nastala veliká potíž a nebezpečí lidí při převážení a zármutek chudáků nemajících na převoz. Zato velmi pevný most v Roudnici, postavený úspěšně, pevně a krásně ctihodným otcem v Kristu, panem Janem IV., 27. biskupem pražským, zůstal nepoškozen, ačkoli tam byl větší proud a silnější nápor masy ledových ker. Z toho se jeho věřící radovali, vzdávajíce díky Bohu. Tenkrát na Menším Městě pražském množstvím písku, který se tam přívalem vod nahromadil, zatarasen průtok vody a nadále už tam nemohly být používány mlýny,"* (Brázdil et al., 2005).

(3) July 1432: A catastrophic flood, also recorded in Southern Bohemia, Moravia, Austria, Hungary and Saxony (Brázdil *et al.*, 2005). It was caused by extreme rainfall (Brázdil *et al.*, 2005). The estimated runoff in Prague was 6000 $m^3 \cdot s^{-1}$ (Elleder, 2010). Until the flood in 2002, the flood in 1432 was believed to be the most disastrous flood in Prague through the second millennium (Brázdil *et al.*, 2005); however, Elleder (2007) suggests that the flood in 1432 was even more disastrous than the flood in 2002. Historical records claim that, *"the wise men tell that such flood has not come since the deluge,"* [12] (Elleder, 2007). The Charles bridge was damaged (Elleder, 2007).

(4) August 1501: This flood afflicted several catchments in Europe (Bohemia, Moravia, Hungary, Silesia, Austria and Bavaria). It was caused by long lasting rainfall (Elleder, 2007). The estimated runoff in Prague was more than 4000 $m^3 \cdot s^{-1}$ (Elleder, 2010).

(5) February 1655: A flood recorded in many places in Bohemia and in Dresden, it was caused by snow melting after a severe winter (Elleder, 2007). The estimated runoff in Prague was more than 4000 $m^3 \cdot s^{-1}$ (Elleder, 2010). Historical records note that such a flood has not come "since people remember" [13] (Brázdil *et al.*, 2005).

(6) February 1784: This flood affected all of Western Europe (namely Germany), it was caused by rapid snow melting and heavy rainfall after a severe winter (Brázdil *et al.*, 2005; Elleder, 2007). Estimated runoff in Prague was 4400 $m^3 \cdot s^{-1}$ (Elleder, 2010).

(7) March 1845: This flood was also recorded in Moravia (Brázdil *et al.*, 2005). It was caused by a rapid thaw (Elleder, 2007). The estimated runoff in Prague was 4500 $m^3 \cdot s^{-1}$ (Brázdil *et al.*, 2005). Historical records say that 114 streets and almost one third of all houses in Prague were flooded (Brázdil *et al.*, 2005). The state authorities and noblemen organized financial collections for people struck by the flood (Brázdil *et al.*, 2005).

Elleder (2010) noticed that many catastrophic floods were mentioned by contemporary historical sources as "the greatest flood since the deluge", "out of historical memory", "even the elders do not remember such flood" etc. It means that extreme floods had been so rare that even the oldest members of the community did not remember them. Surprisingly, there are no known records of elders telling flood stories experienced by their ancestors – this suggests that the concept of "passing down historical memory to younger generations" really did not work for these communities. These findings put Pfister's (2016) "disaster gap" (a lack of large floods and other natural disasters between 1882 and 1976, which led to the unlearning of flood preparedness) into a very interesting context.

Elleder (2010) carefully mentions that the emergence of large floods may be connected with the so called Solar Inertial Motion cycle (SIM cycle; a 179 year long repeating cycle of the Sun's movement in relation to the barycentre of the Solar system, which could possibly affect the Earth's weather, magnetism, volcanism and other geophysical parameters). Within the first 130 years of a SIM cycle, floods are usually more catastrophic, while during the last 50 years of a cycle, the floods are smaller. The "quiet" period of the last cycle lasted from 1905 to 1955, which nestling well into Pfister's "disaster gap". The current cycle started in 1956 and, according to Elleder, it should be running until 2133.

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[12] Czech original: *"tomu chtie mudrci, že jest od potopy světa tak veliké vody nebylo,"* (Elleder, 2007).

[13] German original: *"Trat plötzlich ein Hochwasser mit starkem Eise ein, wie es seit Menschengedenken nicht gewesen, welches in den an der Elbe liegenden Ortschaft en großen Schaden verursachte. (…)"* (Brázdil *et al.*, 2005). Czech translation: *"Nastoupila náhle povodeň se silným ledem, jaká nebyla od lidské paměti, která způsobila velké škody v obcích ležících při Labi. (…)"* (Brázdil *et al.*, 2005).

Fig. 3.4. *Building a dike. Illustration from Sachsenspiegel ("The Mirror of Saxons"), collection of laws and rules from the high medieval period. Source: Raška and Zábranský (2014)*

3.2.2 Historical memory and society

Our results indicate that the persistence of human memory and its ability to affect real life decision making is decreasing with time. Similar findings have also been proposed by other studies:

Colten and Sumpter (2009) compared the situations in New Orleans after hurricane Betsy in 1965 and after hurricane Katrina in 2005, analysing the following assertion: If people were really able to learn from extreme events, rescue and governmental services should have improved after the hurricane in 1965; these services should have worked much better and more efficiently in 2005. Unfortunately, this paper clearly shows that such a concept hardly works. The immediate reaction after the first event contained (besides other things) extensive flood prevention constructs (dams, levees), which should have protected New Orleans from a 200-year storm. Contradictory, the levee system could also retain water in damaged areas after a storm. This actually happened in 1965 and was forgotten when the 2005 hurricane came. In 2005, the protection system had not yet been finished. However, the general public thought that the protection system had been already completed (the people had a false feeling of safety). Spatial planning in New Orleans also ignored the extent of flood zones and authorities allowed new construction projects there. The evacuation plans from 2004 did not incorporate what had been learned in the previous catastrophic events. The authors concluded: *"the lessons from previous events completely fell by the wayside"*.

In their review paper, Hirst, Yamashiro and Coman (2018) bring attention to the difference between Assmann's (2008) *communicative memory* and *cultural memory*. The former is transmitted from person to person, while the latter is preserved through cultural artefacts (memorials, written records or traditions). Hirst *et al.* underline Assmann's note that communicative memory only serves for a limited period of time. They also underline that the way in which a younger generation interprets inherited information can be very different or even completely opposite from its original meaning (Welzer, 2005).

Vansina (1985) studied how long communicative memory remains present in a traditional communities. He discovered that, in the traditional tribes, people usually remember names of their ancestors for no more than three prior generations. He claims that communicative memory can persist up to 60 – 80 years, what is two or three times longer than our study suggests. This difference may be caused by different methods of study or by simple remembrances in Vansina's study and remembrance combined with its effect on real-life behaviour in our study.

Nearly the same outcomes are presented in book *Learning and Calamities* by editors Egner, Schorch and Voss (2016). In the abstract, they clearly state that *"learning (…) rarely lasts more than one or two generations"*, which is in absolute concordance with our study. Pfister's (2016) chapter describing disaster memory between years 1500 – 2000 is particularly remarkable. Pfister especially stresses the importance of repetition for proper remembrance and learning from environmental threats. E.g. he explains that, in the Alps, people have learned to not build their houses in avalanche zones – because the avalanches were endangering the communities almost every year (Favier and Granet-Abisset, 2009). On my opinion, this is a key point in learning from history: rather than *historia magistra vitae* we should put emphasis on *repetitio mater studiorum*. We do not usually learn from one event, but repetition may strengthen our experiences. Repetition should be performed efficiently, since (as Pfister claims) simple records in chronicles or historical books become quickly forgotten. Pfister tells a story about a small chapel built in the Italian Alps in 1606: The builders dedicated this chapel to Santa Margherita with the hope that the heavens would protect the believers from natural disasters. It actually worked, but in a different way – the annual religious processions to this chapel helped to keep the flood memory intact and thus protecting the people by themselves. For an example of a different process, Pfister brings attention to a situation in Switzerland: between 1882 – 1976, no great floods occurred, which led to the loss of flood memory and to waning of civilian preparedness (Pfister calls that period "the disaster gap"). When the floods appeared in the 1980s and later, property damages were much higher. At last, the author also proposes two processes which may cause the limited duration of disaster memory: (1) some disasters never become part of the "cultural memory", or (2) some memories are more or less intentionally "erased".

A remarkable paper on this topic was recently published by Candia *et al.* (2019). The authors studied the decay of communicative and cultural memory in the online attentions of song and movies and on the citation of academic papers. They found that the persistence of the communicative memory depends on "cultural domains" and varies between 5 years (songs) and 20 – 30 years (biographies of athletes) (Fig. 3.5), which is in accordance with our findings regarding flood memory.

As can be seen, findings of several independent studies which used different data tested by different methods have shown a clear convergence in results: communicative/flood memory is usually considered only for a short amount of time (which does not exceed several tens of years) and is at the risk of misinterpretation. The consequences of this inability to learn from history remind me two situations our society faces in the present days: (1) anti-vaccination movement (we are not aware of dangerous yet preventable diseases which are no longer present in the living memory, Fig. 3.6) and (2) the rise of nationalistic and extremist political activities [today's political extremist dare to say statements similar to what one could hear in Germany in 1930s; as an expert on political extremism stated in a recent newspaper interview, the weakening "family bond" with holocaust survivors leads to rise of antisemitism (Mareš and Kotoučová, 2019)]. In both cases, we have not learned from history (Fig. 3.7). Or, in other words, we have forgotten what our predecessors had learned with great sufferings. Maybe we should consider changing the way in which we teach the modern history. Instead of teaching dates, events and numbers, it might be better to explain the processes and causal links which led to important events.

A noteworthy comment on our paper by Toman (2019) puts our results in the context of cultural evolution. Toman points at the “trade-off” between the advantages and disadvantages of living at water and its dynamics. From the evolutionary point of view, it may be advantageous to ignore the rare danger of flooding and choose a place with better water supply. If no additional floods arrive for a short period after an extreme one, it would not be wise to remain in a place with limited resources (although the place is safe). This is similar to a classical ecological dilemma: the choice between a safe but hungry place and place with enough food but high risk of predation (Fig. 3.8) (Townsend, Begon and Harper, 2008). Toman sums up that, from the long-term perspective, excessive vigilance may not be the best subsistence strategy.

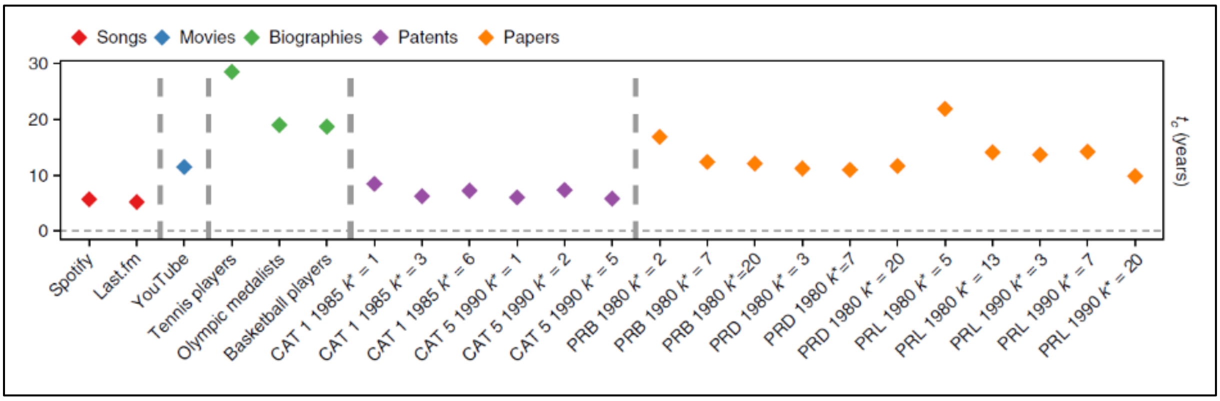

Fig. 3.5. *Critical time (t_c) of communicative memory varies among different cultural domains. After a critical time period, the discussed topic moves from communicative memory into cultural one (i.e. it becomes a record in a library instead of a topic for personal communication). Legend: “CAT” stands for patent citations and “PRB”, “PRD” and “PRL” stand for citations of papers published in academic journals. Source: Candia et al. (2019)*

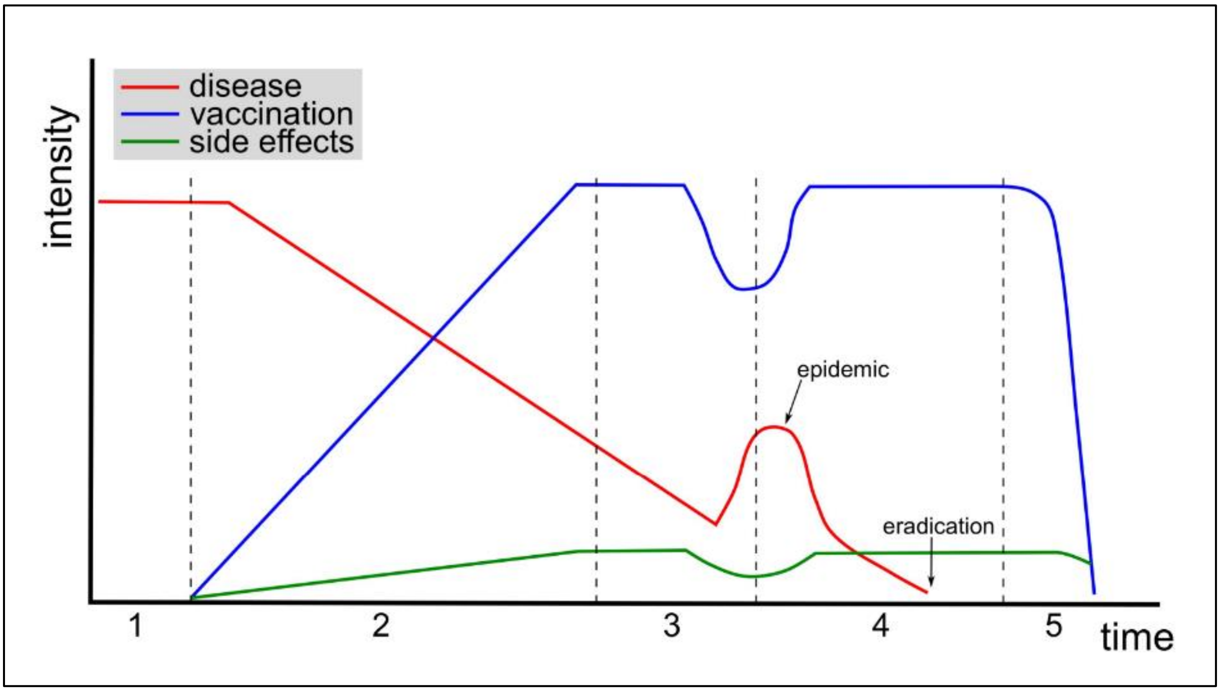

Fig. 3.6 (on the previous page). *The dynamics of trust in vaccination. Legend: (1) pre-vaccination period, (2) increase of vaccination effort and decrease of disease prevalence, (3) decrease of the trust in vaccination, outbreak of disease, (4) restoration of the trust in vaccination, (5) eradication of the disease. Source: Šimurka (2009), redrew. The gap in vaccination between parts 3 and 4 is caused (among other reasons) by the loss of historical memory (the people do not find the vaccination necessary, since they personally have never encountered the disease and thus they are not afraid of it). This is the same principle as we presented in our paper about flood memory*

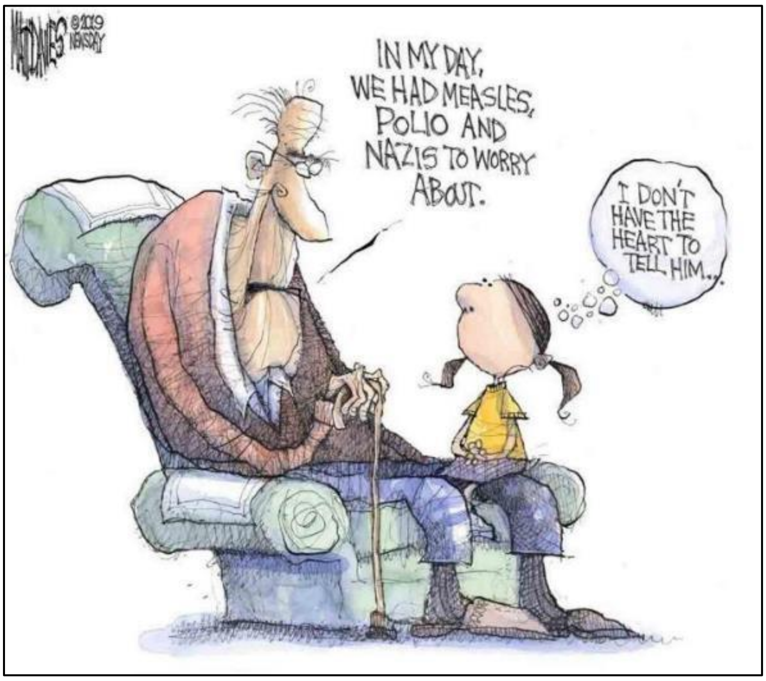

Fig. 3.7. *A magazine cartoon briefly illustrating the loss of historical memory. Source: Davies (2019)*

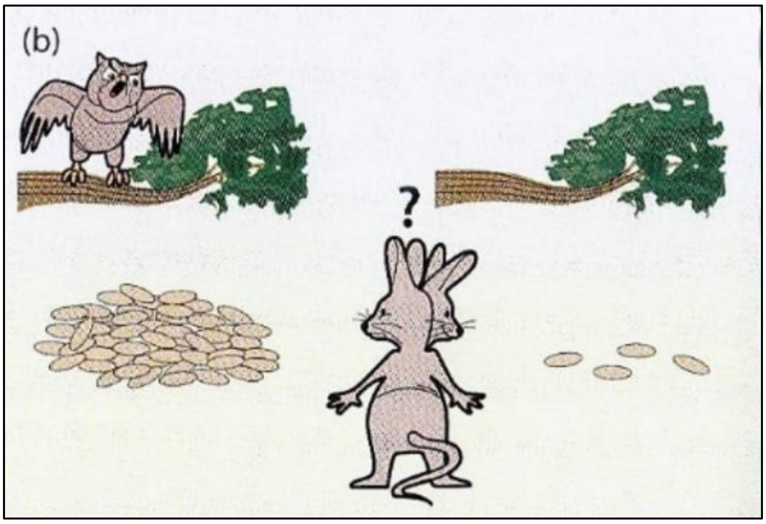

Fig. 3.8. *Ecological dilemma (see text). Source: Townsend, Begon and Harper (2008)*

3.2.3 Uncertainties, doubts and advantages of our approach

To be honest, I must confess that I am aware of several possible issues which could affect the precision of our data. I think that the way we used the data is accurate enough to be believable; however, I want to mention all the problematic points I know. First of all, we have used mostly current data to study a historical topic. The data from the Digital Elevation Model (Land Survey Office, 2017) was collected within the last few years and does not reflect changes of water channels in the previous centuries. As stated in the Methods section of the respective paper, there were many changes of river channels in the last millennium (caused mainly by rapid deforestation), especially during the medieval period. However, as the majority of our data comes from the modern period (1600 and later), we think the fraction of our data which could have been affected by the river channels changes would be very small (yet not zero). To avoid this problem, it would be necessary to perform geomorphological research on every river incorporated in our study, which is impractical.

Another problem raises from the inaccuracy of settlement dating: we obtained data from historical written sources (precise yet unreliable) and from archaeological sources (reliable yet unprecise). For the period prior to 1600, we combined historical and archaeological dating: we used only the historical dates that are confirmed by archaeological dates, and also "pure" archaeological dates. This approach raised two possible problems with archaeological dating: (1) archaeological surveys do not need to find the oldest phase of settlements; thus, its findings may be skewed towards younger periods; and (2) the archaeological dating may not be precise enough to "fit" into the 25-years long "generation periods". The latter problem is more serious (fortunately, only a few tens of sites could be affected by this issue). For the period after 1600, we also used pure historical dating. As we show in our third paper, historical dating is much more trustworthy for the modern period. However, there may still be a time lag. To sum up, all these issues with dating are hardly avoidable. If we want to study historical settlements, there is no other option than to work with the only available data.

If we accept the data as sufficiently accurate, another problematic issue appears from the results: although Fig. 2.2.2 suggests a limited duration of flood memory, Fig. 2.2.1B warns that the median vertical distance between newly established settlements and the nearest river or creek has been growing significantly (p = 0,041) in the test area (Vltava river catchment) in after-flood periods. The latter result indicates that *"people were well aware of the risk, and took it into account, setting up settlements further above watercourses in later centuries,"* as we have explored in the Results section of the respective paper. However, the communities pushed themselves into the flood zones even in the modern period (Fig. 2.2.3), which (again) is in contrary to the existence of the generation memory proposed in Fig. 2.2.1B. We therefore think that the rise of a median vertical distance observed in Fig. 2.2.1B may be explained by the properties of the landscape colonized in the respective periods – in later centuries (especially in the modern age), many settlements were established in higher locations (with probably more rugged terrain) than in the middle ages (Fig. 3.9).

The last possible problem is the delivery of flood information to future settlers. The people who colonized the landscape did not need to live exactly in the Vltava river catchment. Contrarily, many of them came from abroad (especially from today's Austria). Thus, neither the settlers nor their ancestors had to experience the flood themselves. So, how could they be worried about possible floods in the future? The answer is that the floods we worked with were very extreme and usually affected a large part of Central Europe (Brázdil *et al.*, 2005; Glaser *et al.*, 2010). Therefore, it is quite probable that almost everyone in this region experienced these floods.

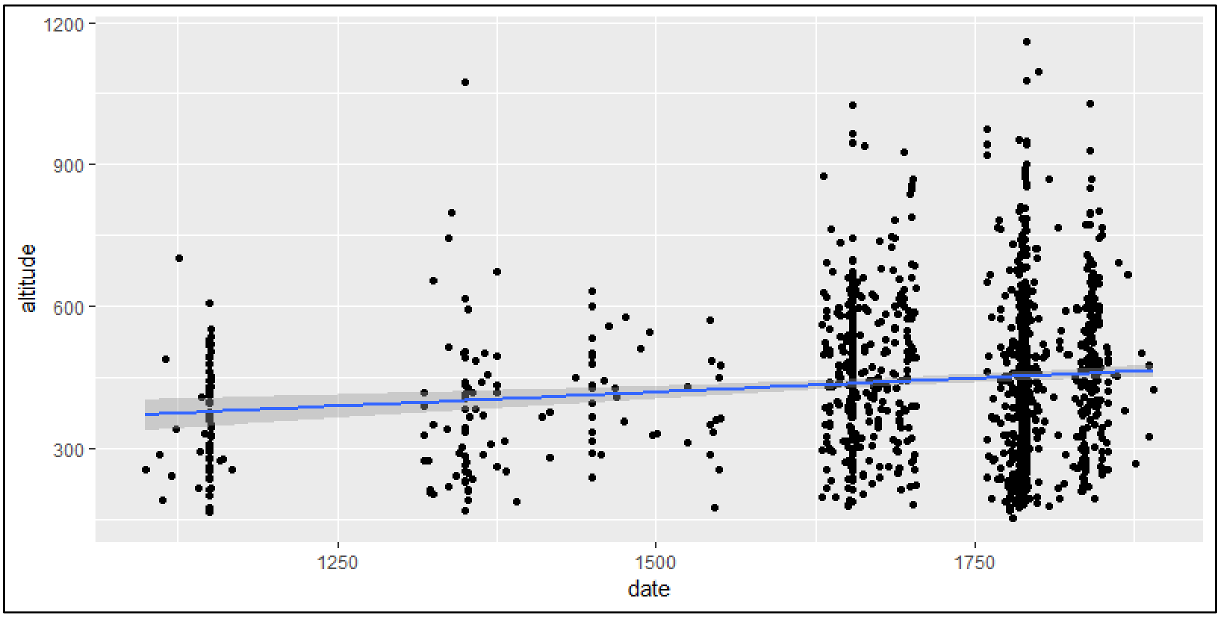

***Fig. 3.9.** The altitude of a settlement significantly depends on the year when the settlement was founded (p < 0,001, linear model, data from the flood study). Calculation and graph: author, 2019*

Despite these uncertainties, our paper brings a new approach into the study of long-term human memory. The persistence of memory has been usually studied on the basis of questionnaires (see Introduction of the respective paper), but we were able to study its influence on real-life decision making (together with necessary trade-off selection). We also dealt more with community or intergenerational memory, which is quite uncommon. Our paper not only proposes the same outcomes as the above-mentioned psychological studies, but it also combines psychological and geographical approaches into one perspective, which is based on statistical evaluation of solid data sample of almost 1300 historical settlements and 7 major floods in the course of 9 centuries. To conclude: our approach (the use of big data instead of researching the history of individual settlements) surely brings new contexts into memory research as well as into flood research and historical geography. On the other hand, several problematic (and hardly avoidable) points have been mentioned. Thus, the results should be interpreted with caution. For example, with respect to the lower accuracy of settlement dating, it would be better to state that flood memory vanishes after "approximately few decades", rather than claim that the turning point is "exactly 25 years" away.

3.3 Comments on Paper III (historical *vs.* archaeological dating)

3.3.1 Settlement establishment and the time-lag

A significant part of settlements in the Czech lands were established during the high medieval colonization. This process probably started in Western Europe as early as in the 6th – 7th centuries AD (Klápště, 2012a); however, Žemlička (2014) puts the beginning into the 12th century in the Netherlands (Žemlička, 2014). Anyway, completely new customs of land and settlement organization arrived into the Czech lands in the 13th century (Klápště, 2012a). This customs, called *ius teutonicum* ("the German law") and recorded in the 13th century legal book *Sachsenspiegel* ("The Mirror of Saxons", Fig. 3.4), set specific rules for village establishment and field pattern organization (Klápště, 2012a; Žemlička, 2014). On the basis of these rules, a lot of new villages were established and many existing villages were translocated or reorganized (Fig. 3.10 and 3.11) (Klápště, 2012a; Žemlička, 2014). It is important to note that the colonization or relocation was a complicated process with many failures (Černý, 1992; Klápště, 2012a). Similarly, the village establishment should not be perceived as an one-time act; reversely, it was a long, complex and difficult process (Klápště, 2012a; Fanta *et al.*, 2014).

Although the existence of time-lag is generally known among scientists dealing with medieval archaeology and history, we have not found any studies focusing directly on this issue. Several comments on this topic were stated in the latest book describing medieval colonization of the Czech lands, Žemlička's (2014) work *Kingdom in Motion*: the author affirms that in the 2nd half of the 14th century, the majority of existing settlements had been captured in written records. However, at other pages he writes that sometimes it took one or two centuries to capture all villages in written sources. Based on research of the colonization in Litoměřice region, Žemlička also underlines that the time-lag was probably strongly dependent on several factors: (1) richness of owners of the villages as well as richness of the villages themselves, (2) distance to major towns and crossroads of important roads, (3) being a subject of trade.

We have also found several additional mentions in various literature: van Beek, Groenewoudt and Keunen (2014) estimated the time-lag between 50 and 300 years (n = 10), Černý (1992) estimated the time-lag between 50 to 100 years (n = 61, regional study). Other studies observed 150 to 200 years, but these studies were based only on a single sample (Blain *et al.*, 2011; Houfková *et al.*, 2015). From this point of view, it seems that our paper may be the first ever exact analysis of this topic. However, we do not exclude the possibility that we missed some papers from older, regional or grey literature or papers not abstracted in the Web of Science and Scopus databases.

Comparing the above-mentioned studies with our results, we can conclude that: (1) In the 14th century, probability of time-lag was around 50 % and time-lag duration was approximately 100 years. This means that as late as at the end of medieval period, the time-lag still played an important role. (2) The findings of the cited studies, expecting length of the time-lag to be cca 100 to 200 years, are mostly right. We can say that various local observations have been confirmed by our results describing general trend. (3) Distance to major infrastructure and settlement status really influenced the length of the time-lag. To conclude: expectations of the mentioned papers and books, which studied this topic on local or regional scales, were right almost in all cases. The novelty of our paper lies in observation and analysis of the time-lag effect on extensive spatial and temporal scale.

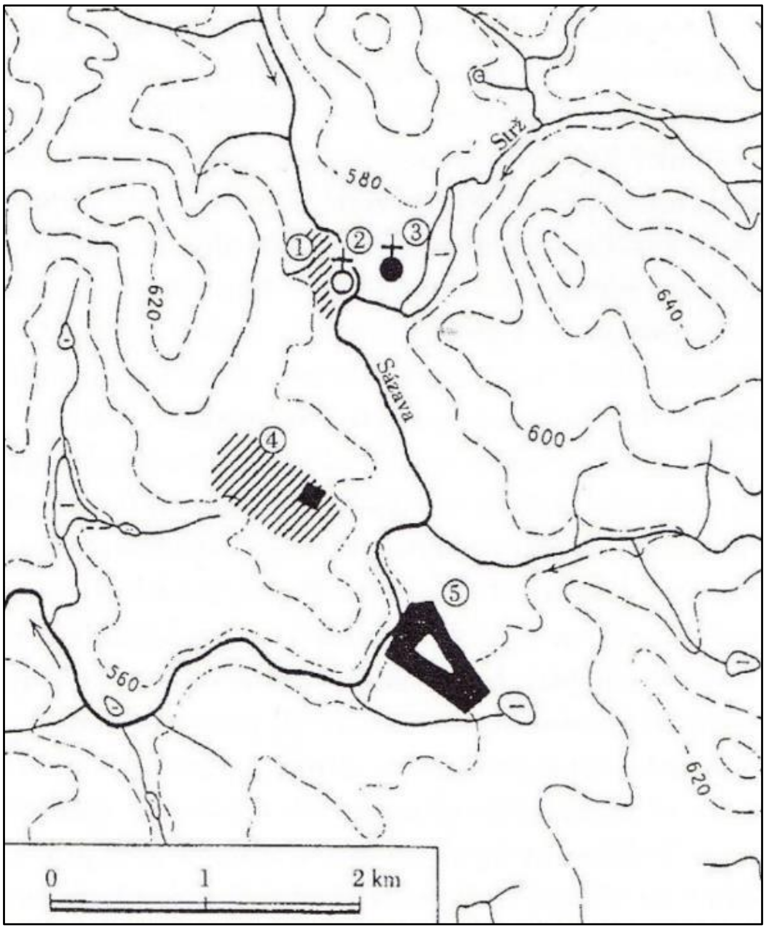

Fig. 3.10. *The establishment of Žďár monastery and relocations of settlements. Legend: (1) older village, (2) provisional monastery, (3) monastery, (4) first market-town, (5) the core of town Žďár. Source: Žemlička (2014), after Richter (1974)*

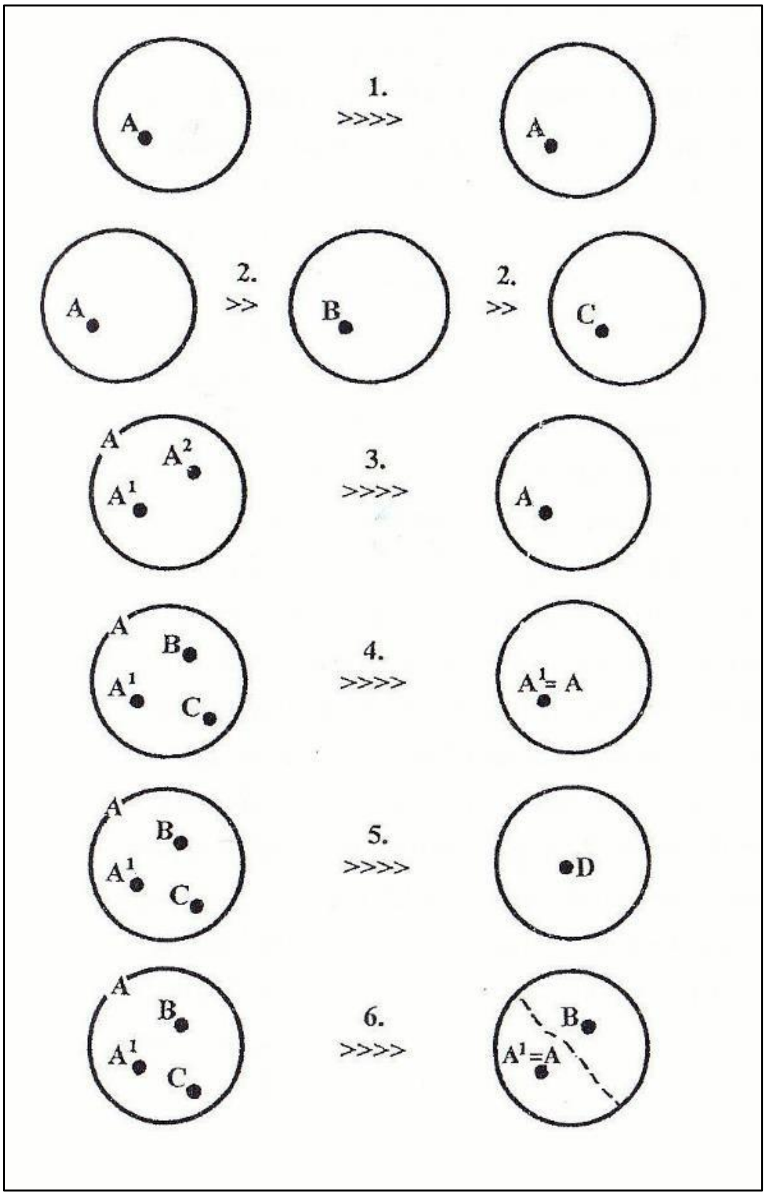

Fig. 3.11. *Schemes of settlement transformations in the 13th century. Left side: before the transformation, right side: after the transformation. Legend: dots = villages, circles = cadastres, letters = village names. (1) No transformations. (2) Changes in village names, no changes in settlement pattern. (3) The name "A" was a joint name for villages A^1 and A^2. During the transformation, the village A^2 was abandoned and the settlement was concentrated into the village A^1. (4) The name "A" was a joint name for villages A^1, B and C. During the transformation, the villages B and C were abandoned, and the settlement was concentrated into the village A^1. (5) The name "A" was a joint name for villages A^1, B and C. During the transformation, all villages were abandoned, and the settlement was concentrated into new village D. (6) The name "A" was a joint name for villages A^1, B and C. During the transformation, the village C was abandoned and A^1 = A and B became independent villages. Source: Žemlička (2014)*

3.3.2 Uncertainties, doubts and advantages of our approach

As in the two previous cases, I want to mention a few problematic issues related to this paper, which may arise from unprecise data. The *Archaeological Database of Bohemia* has been made on the basis of field reports of hundreds of archaeologists gathered for more than 50 years. There can be differences in quality and accuracy in the data among individual researchers (Jiří Bumerl, personal communication, 2018). To improve the reliability of the database, we had to exclude several non-reliable types of archaeological research from our dataset. Nevertheless, some errors or mistakes could have remained in it, but these are hardly avoidable without a detailed, time-expensive individual assessment. The historical dating data was mostly taken from the *Historical Lexicon of Municipalities* and partially from other encyclopaedias and lexicons – this means that the data was not taken from primary sources. A correct approach would require a precise inspection of every single historical source, which would probably exclude a part of the data, but such data-checking would take years. Formally, as I was notified by Dr. Martin Čechura, we did not compare the archaeological dating with the historical dating, but with its *edition* published in historical lexicons. However, from my point of view, we compared data from historical lexicons (which are the most common source of data on landscape and settlement history) with archaeological dating, to show how much or less we can trust the historical lexicons.

Our approach is focused on general trends and not on individual settlements and their histories. Thus, many possible influences on the time lag are almost impossible to catch (local, political, social, ownership issues etc.). Such issues can be identified only by detailed historical research and it would be great if our study would point historians to study some questions that we were not able to answer. On the other hand, I think that our study may be an interesting complement to "traditional" micro-regional studies on settlement history.

It would be possible to object that, while our third paper shows that historical dating is not reliable, our second paper (about historical floods) does not hesitate to rely on it. When we were writing our second paper, we were aware of this issue and we adopted several measures to increase the reliability of our data: (1) For the period before AD 1600, we used only the historical dating, which was confirmed by archaeological dating. (2) As our third paper shows, the probability of time lag in historical dating decreases rapidly during the early modern period. Thus, I think it is possible to use "pure" historical dating for the period after AD 1600. Of course, there can be errors, but there should not be an extensive amount of them.

3.4 General comments

The results of these particular papers have been described in chapter 3, page 71. Below follows a contemplation on the main aims of this thesis, as they were laid down in the introduction: (1) to study settlement history in an environmental context and (2) to use a big data approach for solving this question.

In the introduction, I summarized opinions and findings on the influence of environmental conditions on settlement site preferences. In our studies, we focused on the further settlement development, their interaction with water elements or regeneration after disturbances. Our papers show that the influence of the environment persisted even in the modern period, and that studies focusing on environmental context of settlement development in the second millennium are definitely worth noticing. Moreover, settlement history data can become an engaging proxy description of human behaviour or ecology. Our studies also show that the combination of historical-geographical/archaeological data regarding medieval settlement history and environmental data is extremely interesting, even for the general public (Toman, 2019). Since similar approaches are common in prehistoric archaeology, they are very rare in middle age history research.

The conventional historiographical and archaeological approach is usually focused on the research of single places, eventually regions. This common approach contains an intensive study of historical sources, their analysis and critics of their information value. Results obtained by these methods are as precise as possible, but their validity is limited in space or time. The "statistical" approach differs from the conventional one and has several advantages: using big datasets with a large spatial and temporal extent enables one to deal with trends or gradients. The results also have more general validity, and, as we have shown, they can be also interesting for other scientific disciplines. Last but not least, this approach can use data from "natural experiments" – such as wars or other disasters in history – for the observation of human reactions. Unfortunately, there is limited time and means for a detailed analysis of every single historical source when working with big datasets. Although general measures can help with the data filtering, errors can remain. Other problems may rise from the comparison of different historical sources from different periods, or from a limited reliability of some historical sources (as explored in the third paper). I have also been notified by my colleagues that we may have omitted some important influential factors, such as social, political, local, economic or other issues [a similar warning was also presented by Stone (1996)]. Finally, using current geographical data for the description of a past situation can be problematic. Many of these issues (or similar problems) have already been mentioned in previous studies (Lukezic, 1990; Bubeník, 1991; Dreslerová *et al.*, 2013; Ljungqvist *et al.*, 2018). All of these facts can lower the information value of the results. Thus, a big data approach has several advantages as well as disadvantages. It is imperative that we should be aware of both of them.

To conclude: this big data approach brings *different* type of evidence to conventional historiographical studies. However, I think that neither of these two methods alone can discover all the mysteries of nature and history, that only at combination of different approaches can help us to understand the world. The combination of settlement history and environmental sciences can result in remarkable interdisciplinary studies, the conclusion of which can point to interesting, large-scale trends and the analysis of general processes. I think that this type of research can add a broader perspective into conventional, micro-regional historiographical research and vice versa. I suggest that a cooperation between both approaches ("big datasets" and "single features / micro-regions") should be a subsequent step in settlement and landscape history research.

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