Bayesian Spatial Analysis of Archaeological Finds and Radiocarbon Dates: An Example from Finland 4000-3500 cal BC

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Abstract:
Typologically dated archaeological finds together with radiocarbon (^{14}C) dates can be used as proxies for ancient human activity and occupation. We carried out a Bayesian spatial analysis of a selected set of radiocarbon dates and archaeological finds from the area of Finland and ceded Karelia, specifically focusing on the time period of 4000-3500 cal BC. The spatial posterior distributions were produced by a spatio-temporal model known as Besag-York-Mollie (BYM). In general, the resulting maps comply with the pre-existing archaeological understanding. The methodology presented here is one of the first efforts of Bayesian statistical analysis with different types of archaeological data from this area. Moreover, our approach easily allows for utilizing different types of data, be it archaeological, geographical or palaeoclimatologic.

Key Words: *Bayesian, Spatial Analysis, Typical Combed Ware, Radiocarbon Dating, Finland*

Introduction

Summed probability distributions of radiocarbon (^{14}C) or even tree-ring dates of archaeological finds have been used as proxies for population history events in recent studies (e.g. Gamble et al. 2005; Oinonen et al. 2010; Ortman et al. 2007; Shennan and Edinborough 2007; Tallavaara et al. 2010). This approach is especially suitable for studies on a regional scale rather than global scale. Here, we apply a Bayesian method, which enables us to combine different classes of information and can be expanded by additional data. The same method is also applied by Onkamo et al. (in press).

This study aims to construct a spatial distribution of archaeological finds in Finland and ceded Karelia (Fig. 1). Ceded Karelia refers to the region southeast of the current borders of Finland, which was part of the country before the Moscow Armistice signed between Finland and the Soviet Union in 1944. More generally, we develop a method to visualize and process different types of data: locations of radiocarbon dates and typologically dated archaeological finds. We concentrate on the period of 4000-3500 cal BC, as it represents the most prominent era of Typical Combed Ware (TCW) ceramics in the prehistory of eastern Fennoscandia. Moreover, the population reached a peak at that time (Tallavaara et al. 2010). The climate was at its temperature maximum, which probably contributed positively to the environmental

Figure 1. Finland (black) and ceded Karelia (dark grey), Northern Europe.

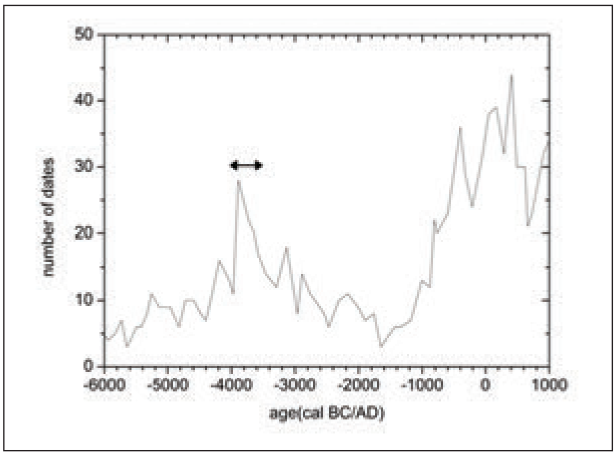

Figure 2. Time distribution of the radiocarbon-dated archaeological charcoal dates from eastern Fennoscandia (6000 cal BC-1000 cal AD).

productivity and thereby to the resource availability for the hunter-gatherers living in the area (e.g. Tallavaara and Seppä in press). Substantial changes in the economy and society of the tribes living in the area are characteristic to the archaeology of this period; together with a new style in ceramics, there is a notable rise in the prevalence of novel materials such as flint and amber (e.g. Carpelan 1999; Edgren 2007; Halinen 1999; Meinander 1984; Pesonen 2002; Vuorinen 1982).

Radiocarbon dating gives significant information of the period when artefacts and features were deposited. In addition to ^{14}C data, the distributions of some typologically dated artefacts are presented in this context. This includes Typical Combed Ware ceramics (Fig. 3) and bifacial, leaf-shaped arrowheads (Fig. 4), made of various stones (e.g. flint, quartzite and quartz). Typical Combed Ware is traditionally dated to ca. 4000-3500 cal BC (e.g. Carpelan 1999; Pesonen 1999; 2004). Leaf-shaped arrowheads are often found in the same archaeological contexts as Typical Combed Ware (Manninen et al. 2003).

Materials and Methods

The archaeological records from all of the excavations in Finland have been documented in the Registry of Ancient Monuments, a national database of the National Board of Antiquities. The database currently contains detailed information on approximately 33,000 heritage sites. The database is being updated by our project (Argeopop: http://www.helsinki.fi/bioscience/argeopop). The analyses performed at the Dating Laboratory (Finnish Museum of Natural History / University of Helsinki) form the backbone (80%) of the radiocarbon dataset and 2,588 items have been radiocarbon-dated. The dataset is extended to cover - as thoroughly as possible - the other published archaeological radiocarbon dates from eastern Fennoscandian territory measured elsewhere. In addition, the data contains also those unpublished dates that have been kindly released for our use by most of the Dating Laboratory customers.

To illustrate the role of the selected time period in eastern Fennoscandian prehistory, the time distribution of the performed archaeological radiocarbon dates on charcoal samples has been plotted in figure 2. The local maximum of dates at around 4000-3500 cal BC overlaps with the Holocene climatic optimum (Tallavaara et al. 2010).

For the present study we used three types of data falling into the time period of 4000-3500 cal BC: 1) 187 radiocarbon dates, 2) 676 sites with Typical Combed Ware ceramics, and 3) 347 finds of leaf-shaped arrowheads, the latter two classes typologically dated to the same period. Several dates, ceramics and arrowheads derive from the same find context, yielding 728 separate locations in total. The total number of finds incorporated in this study was 1210 (Fig. 5).

The spatial posterior distributions were produced by a spatio-temporal model known as Besag-York-Mollie (BYM), based on the Bayesian hierarchical methodology for small area analysis. The basic assumption of this approach is related to image analysis: in an arbitrary image, with respect to a single image pixel, the neighbouring pixels tend to have a more similar colour than pixels positioned farther away (Besag et al. 1991). The BYM-model is appropriate for this study since the same kind of dynamics can be assumed for geographically located areas of, for example, cultural influences, regardless of apparent variations in spatial and temporal scale in this analogy. The methodology has since found use in epidemiological studies (e.g. Best et al. 2005; Held et al. 2005; Moltchanova et al. 2004).

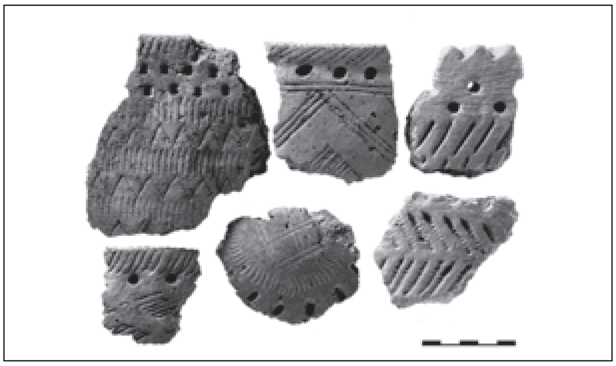

Figure 3. Typical Combed Ware sherds from settlement sites in Vantaa, South Finland. Photo by István Bolgár, National Board of Antiquities, 2008.

Figure 4. Leaf-shaped flint and slate arrowheads from settlement sites in Vantaa, South Finland and an arrow reconstruction. Photo by István Bolgár, National Board of Antiquities, 2008.

Finland and ceded Karelia were first divided into a contiguous grid of 10km by 10km square cells. The division resulted in a total of 3,997 cells. Each cell was given an integer value 0 if there were no archaeological finds in the cell and 1 if there were one or more archaeological finds. The data was processed using R-software (http://cran.r-project.org). Based on the basic assumption of the BYM-model, neighbouring cells were assumed to be more alike than cells located farther away. The local probabilities of a find were given a conditional autoregressive (CAR) prior distribution with a weighting coefficient of 1. This means that *a priori* these local conditional probabilities of a find in a cell depend on the number, or proportion, among its neighbouring cells that contained a find. An excellent discussion of the CAR-prior is given in McColl 2008. The model was estimated using the WinBUGS software (Lunn et al. 2000). WinBUGS utilizes Markov chain Monte Carlo (MCMC) sampling to estimate user-defined model parameters. The three datasets were analysed separately. In each run we used a single Markov chain with a burn-in of 5,000 iterations and a further 15,000 iterations for monitoring. The convergence of the chain was visually inspected, especially for the precision parameter. Finally, posterior means for the probability of making at least one find in a cell were plotted on a map of Finland and ceded Karelia. Pitney Bowes Business Insight's

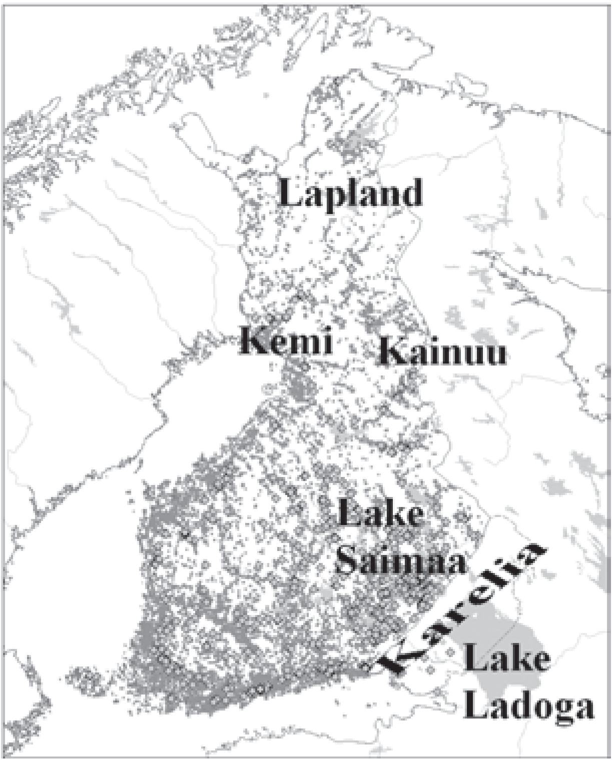

Figure 5. Locations of radiocarbon dated archaeological finds, Typical Combed Ware ceramics and leaf-shaped arrowhead finds falling in the period of ca. 4000-3500 cal BC from Finland and ceded Karelia (green diamonds, N= 1,210 items on 728 separate locations) superimposed on locations of archaeological activity data (red dots, approximately 33,000 events) in present Finland excluding Åland. A few territory names are provided for reference. Some find locations overlap, thus far less than 728 locations are shown. Archaeological activity data (red dots) are provided only for reference and were not used in the analyses presented in this paper (for full colour image please see the online version of this paper).

(http://www.pbinsight.com) MapInfo 10.0 was used for visualization. To verify whether our approach was affected by the modifiable areal unit problem (MAUP), a test was run for the same data with a 20km by 20km grid of the same area and is discussed in the following section.

Results and Discussion

With our relatively sparse data we have used a binary response model in which the responses take values of 0 or 1 as described above. Considering the statistical methods used there is an infinite number of Bayesian statistical models available for spatial analysis. The BYM-model (originally conceived as an application in image analysis, Besag 1986) has been developed into a tool for disease mapping (Besag et al. 1991) and has been used widely and imaginatively ever since. Its use in archaeology is becoming more general. The model easily allows for utilizing different types of data, were it archaeological, geographical or palaeoclimatological.

The BYM-model also fits the general context of this study well: the presence of an archaeological find in a grid cell results in a spatial signal in the cell. The similarity assumption of neighbouring areas inherent in the model propagates this effect into neighbouring cells. This is apparent from the distribution of posterior means for the probability of making at least one archaeological find in a cell (green-yellow-red colouring in Fig. 6a-c, for full colour image please see the online version of this paper). In our opinion the resulting distribution could be interpreted as a statistical prediction of the range of the spatial effects. In our forthcoming study we aim to utilize the national archaeological database which is being updated at the moment. The database of stone tools will become more comprehensive and distributions of several stone tool types associated with certain periods of prehistory will become available. We acknowledge that the model applied is not exhaustive. Water systems (e.g. rivers, lakes and sea shore) and other geographical formations (e.g. hills and ridges) are planned to be included in future versions of the model. Although none of the abovementioned should be considered as obstacles for population movement, they are all possible geographical factors affecting the drift of cultural influences. With larger datasets, it becomes feasible to model the probability of the actual number of finds per cell instead of the strictly binary approach used in this study.

In general, the resulting maps (Fig. 6a-c) comply with the pre-existing archaeological understanding. Most of the radiocarbon dates for the period 4000-3500 cal BC are concentrated in southwestern coastal areas and in the Saimaa Lake district and the Kemi region in the North (Fig. 6a). Additionally, the TCW finds and leaf-shaped arrowhead finds (Fig. 6b and 6c) show a clear signal in the Kainuu region in the East. Concerning the TCW ceramics, the distribution of finds and the posterior distribution (Fig. 6b) corresponds with the diffusion of the ceramics – and possibly people – from the southeast, where the origins of this type are found in the Valdai region and along the upper reaches of the River Volga in Russia (e.g. Carpelan 1999). This comb- and pit-decorated ceramic style along with many new material and cultural manifestations eventually spread as far as the Arctic Circle but did not reach northern Lapland. Again, the apparent gap between the northernmost reach of the spread of TCW and the distinct signal of radiocarbon dates (Fig. 6a) in the extreme North may be indicative of an indigenous population in northern Lapland at 4000-3500 cal BC. Leaf-shaped arrowheads also highlight the southern coastal areas and the Saimaa Lake district (Fig. 6c).

Also of interest is the actual population size in eastern Fennoscandia around 4000-3500 cal BC which, based on the density of archaeological finds, has been considered a local population maximum (Tallavaara et al. 2010, Fig. 2). When measuring population size the principal assumption is that the stronger the archaeological signal, the larger the population that left the signal. Interestingly, the weaker archaeological signal following the population peak at 4000-3500 cal BC implies a subsequent decline of the population. This has been seen as proof of an eventual Neolithic population bottleneck (Lavento 2001, Sundell et al. 2010). The radiocarbon dates suggest that the demographic fluctuations have been more significant in the eastern part of Finland (Tallavaara et al. 2010; Pesonen and Tallavaara 2008). Furthermore, the known reduced genetic diversity in the present day Finnish population and the specific Finnish Disease Heritage (FDH, http://www.findis.org) could well be explained by a population bottleneck and/or a founder effect (De la Chapelle 1999; Nevanlinna 1972; Sajantila et al. 1996). Population bottlenecks can occur rapidly or they can be slower events taking place over centuries or millennia. Slowly developing bottlenecks may be caused by gradually deteriorating climate conditions, for example, whereas other causes such as famine, epidemics and war can be accountable for a sudden population bottleneck. The evidence, although still fragmentary, for such a hypothesis motivates further investigations of the issue within the Argeopop project. The methodology presented in this paper could be a valuable tool for testing this hypothesis, especially when expanded to cover multiple datasets and time intervals. For a more elaborate discussion of population bottlenecks, see Sundell et al. 2010.

In order to study how our results depend on the areal units (Modifiable Areal Unit problem MAUP), we ran a test for the three datasets with a larger grid cell size. In the test we kept the study area, Finland and ceded Karelia, the same but made the length of a grid cell side twofold so that each cell covers an area of 20km by 20km. Consequently, the number of cells on the grid was reduced from 3997 to 1004. This modification is similar to that performed in a recent study concerning the spatio-temporal analysis of archaeological data with a major portion of modern Europe as the study area (McColl 2008). The resulting posterior density maps of the test run are provided in figures 7a, 7b and 7c for the radiocarbon dates, TCW finds and leaf-shaped arrowheads respectively. Evidently, somewhat rougher posterior density maps arise from the larger grid cell size (Figs. 7a-c). In general, larger areas show an elevated posterior density and detailed spatial resolution is lost in many areas when compared to the maps with 10km by 10km cells (Figs. 6a-c). Nevertheless, southern areas

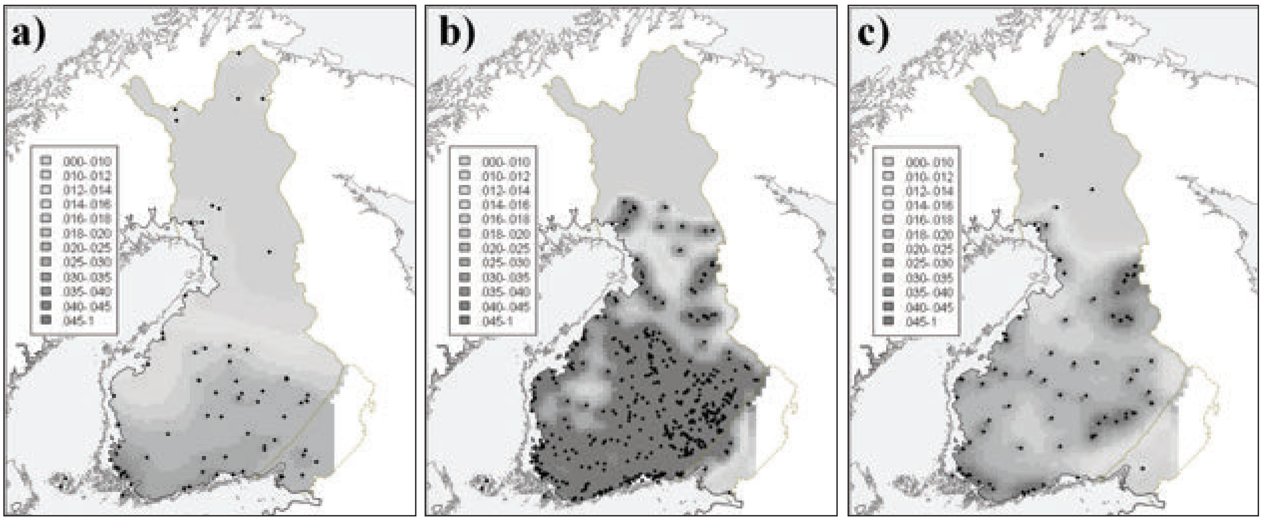

Figure 6. Posterior density (green-yellow-red colour scale) of a) radiocarbon dates (N=187), b) Typical Combed Ware (TCW) ceramics (N=676) and c) leaf-shaped arrowheads (N=347). The finding locations are represented by black diamonds. The shoreline of the central lakes area corresponds to that of ca. 4000 cal BC estimated by Jouko Vanne / Geological Survey of Finland (GTK), whereas the shoreline of the Baltic Sea corresponds to that of 3500 cal BC estimated by Johan Daniels / Geological Survey of Sweden (SGU) (for full colour image please see the online version of this paper).

are still highlighted in the case of radiocarbon dates with higher posterior means in northern Lapland as well (Fig. 7a). TCW finds still show the distinct northernmost extent around the Arctic Circle (Fig. 7b) and posterior density of leaf-shaped arrowheads (Fig. 7c) is higher in the same areas as with the smaller grid size (Fig. 6c) despite the fact that the Kainuu region is no longer highlighted. A change from 10km by 10km to 20km by 20km cells can be considered drastic as it quadruples the area that a single cell covers. Thus, loss of detailed resolution is

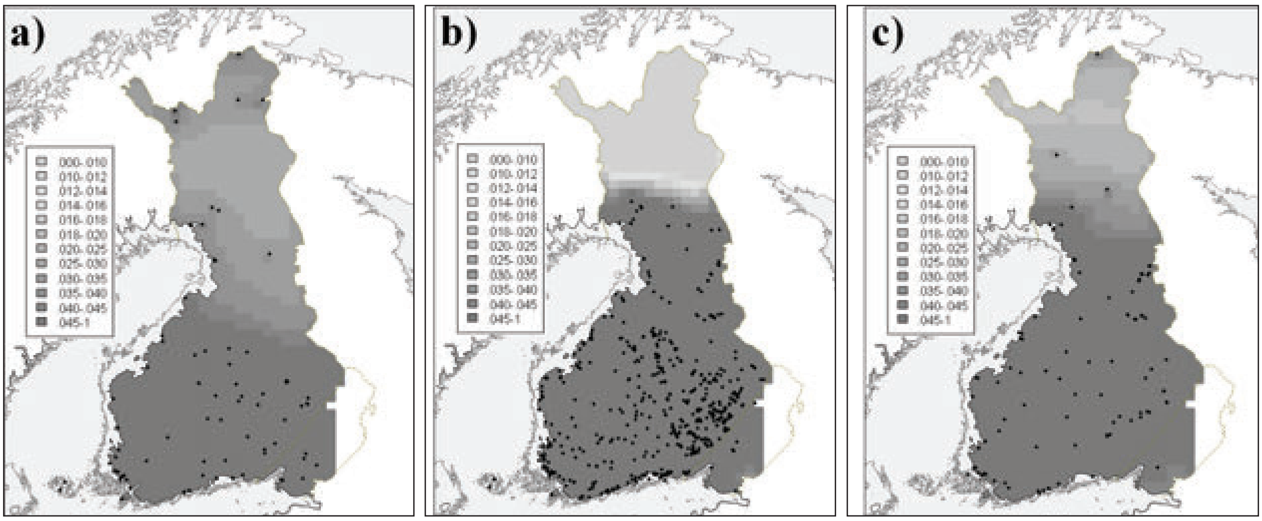

Figure 7. Posterior density (green-yellow-red colour scale) of a) radiocarbon dates, b) Typical Combed Ware (TCW) ceramics and c) leaf-shaped arrowheads on a grid of 20km by 20km cells (for full colour image please see the online version of this paper).

inevitable. Still, the main interpretations from the viewpoint of archaeological understanding appear to hold for our three sets of data.

Conclusions and Outlook

This study shows the results of preliminary Bayesian modelling of the spatial distributions of various archaeological findings within the most active period of the eastern Fennoscandian Stone Age. The methodology presented here can be considered as one of the first efforts of Bayesian statistical analysis with different types of archaeological data from Finland and ceded Karelia. Concerning the modifiable areal unit problem (MAUP), our conclusion is that although some spatial resolution may be lost in the results, the model itself is relatively robust to at least a significant increase in areal unit size. In our opinion, the methodology is worthy of further development. In the future we will expand the analyses to span multiple time periods and utilize recently updated archaeological records. It is also possible to include geographical or palaeoclimatological data into the Bayesian approach and study plausible reasons for the spread of human activity across time and space.

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