# Natural Hazards

## Exploring representativeness and reliability for late medieval earthquakes in Europe

--Manuscript Draft--

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| **Manuscript Number:** | NHAZ-D-16-00209R2 |
| **Full Title:** | Exploring representativeness and reliability for late medieval earthquakes in Europe |
| **Article Type:** | Manuscript |
| **Keywords:** | earthquakes, historical seismicity, Late Medieval Europe, GIS , Kernel Density Estimation, risk |
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| **Order of Authors Secondary Information:** | |
| **Funding Information:** | |
| **Abstract:** | Seismic catalogues of past earthquakes have compiled a substantial amount of information about historical seismicity for Europe and the Mediterranean. Using two of the most recent European seismic databases (AHEAD and EMEC), this paper employs GIS spatial analysis (Kernel density estimation) to explore the representativeness and reliability of data captured for late medieval earthquakes. We identify those regions where the occurrence of earthquakes is significantly higher or lower than expected values and investigate possible reasons for these discrepancies. The nature of the seismic events themselves, the methodology employed during catalogue compilation and the availability of medieval written records are all briefly explored. |
| **Response to Reviewers:** | Dear Editor in Chief,<br><br>We accepted and integrated the minor corrections suggested by reviewer #2.<br><br>We just added a very minor integration into the conclusions of our work. We integrated archaeoseismology with palaeoseismology as we believe that also this discipline has the tools for improving our knowledge about past earthquakes in those regions that suffer for the lack of written documents.<br><br>We also added a missing reference about the source we used for identifying the largest medieval European cities (Jotischky and Hull 2005) and updated the map crossing KDE of late medieval earthquakes with these urban centres (editing the legend and the colour of the point shape file).<br><br>In our opinion, this paper is now in its final version.<br><br>Yours sincerely,<br><br>Paolo Forlin<br>Christopher Gerrard |

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| | David Petley |

# Exploring representativeness and reliability for late medieval earthquakes in Europe

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Abstract: 150 – 250 words

*Seismic catalogues of past earthquakes have compiled a substantial amount of information about historical seismicity for Europe and the Mediterranean. Using two of the most recent European seismic databases (AHEAD and EMEC), this paper employs GIS spatial analysis (Kernel density estimation) to explore the representativeness and reliability of data captured for late medieval earthquakes. We identify those regions where the occurrence of earthquakes is significantly higher or lower than expected values and investigate possible reasons for these discrepancies. The nature of the seismic events themselves, the methodology employed during catalogue compilation and the availability of medieval written records are all briefly explored.*

Keywords: earthquakes, historical seismicity, Late Medieval Europe, GIS, kernel density estimation, risk

A key initiative in historical seismology in recent years has been the collection of earthquake data at a continental scale, especially for Europe. AHEAD (Archive of Historical Earthquake Data; Locati *et al* 2014; http://www.emidius.eu/ahead/main/) and SHEEC (SHARE European Earthquake Catalogue 1000-1899; Stucchi *et al* 2013; http://www.emidius.eu/SHEEC/sheec_1000_1899.html) have developed systematic catalogues of past seismic events between AD 1000 and 1899, generating and publishing a robust archive of macroseismic information. A third project, EMEC (the European-Mediterranean Earthquake Catalogue; Grünthal and Wahlström 2012), consists of a unified catalogue of earthquakes with an $M_W$ higher than 3.5 in Europe, Mediterranean Africa, Turkey and Cyprus up to 2006. In contrast to the other two catalogues, EMEC is mainly based on instrumental recording of recent seismic events.

These meta-data archives are primarily intended as inputs into the seismic hazard assessments which remain fundamental to the development of strategies for earthquake risk reduction (through, in the case of the SHARE project, Seismic Hazard Harmonization in Europe). The valuable contribution of historical seismology to national and international earthquake catalogues has long been recognised (Ambraseys 1971; Gürpinar 1989; Voght 1991; Caputo and Helly 2008) but these new larger databases now open up fresh possibilities for research. Not only do they add a remarkable volume of data which has been standardised according to published criteria, but both AHEAD (http://www.emidius.eu/ahead/main/) and EMEC (http://emec.gfz-potsdam.de) also operate on open access online platforms and embed useful tools for geographical and chronological interrogation.

For more than a generation research tools have been available to seismologists to help evaluate the completeness of historical earthquake catalogues as time series data (eg. Stepp 1972; Weichert 1980; Woessner, Wiemer 2005; Hakimhashemi, Grünthal 2012; Alamilla et al. 2014) but it is now possible to supply a spatial as well as a chronological assessment of past events. In this paper therefore we explore the use of kernel density estimation (KDE) to investigate the representativeness of the historical seismic activity in Europe in the late Middle Ages (here defined as AD 1000-1550) from a geographical perspective. We identify those European regions where our knowledge of medieval seismicity is especially weak and we ask whether medieval seismicity is sometimes overestimated.

## The earthquake record over time

It is well understood from numerous case studies that the available information for some European regions and periods is better than it is for others (for instance Guidoboni and Comastri 2005 for 11th to 15th Century earthquakes in the Mediterranean region) and this point is quickly underlined by an analysis of the AHEAD dataset for the last 1000 years (Figure 1). As has been noted previously for other datasets (Daniell et al. 2011), the number of recorded earthquakes per year increases through time: there are far more earthquakes known from the modern period of instrumental monitoring than there are from patchy historical records. Thus, the number of recorded earthquakes in the 11th century (n=30), for example, represents less than 2% of the earthquakes catalogued for the 19th century (n=2432). In fact, the number of known earthquakes approximately doubles with each passing century.

The reasons for this disparity are also well rehearsed (Guidoboni and Ebel 2009, for example). They include the comprehensiveness and reliability of any individual account of a historical seismic event, the preservation and transmission of that record (which may be one of a number which provide evidence of a single event) and the capacity of modern compilers and analysts to recognise and catalogue the event. When researchers claim that 'libraries may hide hundreds of treasures that are mostly unknown to seismologists'(Vogt 1991) they concede the degree to which research intensity varies across European regions.  In short, it cannot be assumed that current catalogues, vital though they may be, are homogeneous in their representation of past seismicity. The key question to ask is precisely *where* the strengths and weaknesses of the data might lie.

**KDE analysis**

Point density analysis is a technique that permits the visualization and consideration of clusters in a spatial dataset and facilitates comparison of trends (Conolly and Lake 2006). In this case we have used this approach to undertake an evaluation of earthquake distribution across Europe in the late Middle Ages, matched against later seismic activity. By taking earthquake epicenters and magnitudes as the input point layer, a continuous density surface is created. Applying kernel density estimation (KDE), a non-parametric technique (Illian *et al* 2008; Wand and Jones 1995), the probabilistic density of earthquake epicenters is then calculated within a circular area (the KDE 'search radius'). The density value of each output raster cell is obtained by summing the values of all the kernel surfaces calculated for the population of points, the kernel function being based on the quadratic function described in Silverman (1986, p.76, equation 4.5) and available in Esri ArcGis 10.3. The resultant KDE maps (Figures 2-5) apply a search radius of 200 km to measure densities in point distribution at a regional scale with an output resolution (pixel dimension) of 5km.

In order to obtain a mean to compare earthquake distributions over time, KDE analysis was undertaken for selected datasets showing medieval earthquakes (AD 1000-1550), post-medieval or early modern historical earthquakes (AD 1551-1899), and 20$^{th}$ century (AD 1900-1999) earthquakes. Calculations were applied both to the entire number of the recorded earthquakes collected within each dataset and for the earthquakes with Mw ≥ 5, introducing a threshold which excludes events that cause little damage. The KDE maps are then displayed using a coloured key which defines density trends. To avoid redundancies during comparison, the density values in each case were homogenised to a range of values ranging from 0 to 100. The mean values of density were extracted from the maps using a zonal statistic analysis and assigned to a shape file displaying the provinces (1248 in total) of all European countries. This allows differences in mean value density to be calculated and then displayed.

**Figure 2** is the KDE map of known late medieval earthquakes for the period AD 1000-1550. Some 567 events are shown, displaying a density peak across northern and central Italy. The highest values are concentrated in Umbria, Northern Tuscany and Marche, and the central and the east Po Plain, including the Eastern Alps between Friuli and Slovenia. High values are also identified for the central Apennines and south towards Campania, eastern Sicily (including the area of Reggio Calabria in Calabria) and the Rhine Graben area, which corresponds to the Basel region, Lower Alsace and Baden-Württemberg. Lower values are found in the eastern Pyrenees, Transylvania in central Romania, Central and Southern Dalmatia, around Aachen (Germany) and between Brussels (Belgium) and Cologne (Germany). If a threshold for stronger earthquakes equal to Mw ≥ 5 is applied to this dataset (**Figure 3**), the map shows a marked concentration of high values in central and northern Italy.

**Figure 4** processes the epicentres of post-medieval earthquakes (AD 1551-1899; n=3840) using the same methodology.  Although central Italy and the Strait of Messina are still characterised by high values, higher density values still are visible in both Switzerland and Slovenia. For this period, medium values are found across Transylvania (Romania) and along the western border between Slovakia and Hungary. Again, Greece, Albania and Andalusia show lower values, comparable with those for the Pays de la Loire (France) and Aachen region (Germany). If a threshold of Mw ≥ 5 is applied to this dataset, the post-medieval map changes dramatically (**Figure 5**). Peak values shift to central Italy, Transylvania in Romania, and the Adriatic coast of Albania and Greece. Higher values are also obtained for the Strait of Messina and Calabria (Italy), Slovenia and the Belgrade area in Serbia. Average values are registered for Eastern Bulgaria and southern Andalusia (Spain), and lower ones for Switzerland, the Aachen area, the Pyrenees and southern Portugal.

**Figure 6** presents the KDE for 20$^{th}$ century earthquakes extracted from the EMEC database (n=23,438). Here the picture for the instrumental period is very different from the catalogue of historical earthquakes. The area with the highest peak of density values now focuses on Greece and Albania, extending southward to the Hellenic Arc and including Crete and Rhodes. Transylvania in Romania represents another peak but, taken together, this pronounced clustering makes the visualisation of areas with lower values appear undifferentiated. Fortunately, this can be overcome by introducing a non-linear binning technique, such that the application of breaks in the data have geometric rather than linear break to emphasise the distribution of lower value events. This makes it possible to identify other regions for which seismic activity is noteworthy. This includes the Balkan Peninsula as a whole, Slovenia and the eastern Alpine arch between Italy and Austria, central Italy and the area of the Strait of Messina, Switzerland, and Iceland. Areas characterised by lower seismic activity are the western Pyrenees, the Aachen region, Andalusia and Murcia and around Lisbon.

In this case introducing a magnitude threshold of Mw ≥ 5 does not change the picture significantly (**Figure 7**). The highest values still centre on Greece, Albania and the Hellenic Arc, with a new peak now identifiable in Iceland. Italy, northern Switzerland, and the Rhine Graben are still characterised by high seismicity, though Andalusia, Murcia and Lisbon area are also included in this class. Lower values are assigned to the western Pyrenees, northern Portugal and Galicia, with two smaller zones to the north of Aachen and in western Belgium.

## Discussion

The maps presented in Figures 2 to 6 confirm that there are significant differences in our understanding of seismicity for different periods of our historic past. To draw out these patterns further, **Figure 8** evaluates differences in the spatial distributions in the density of recorded earthquake events from the 20$^{th}$ century and the later medieval period. This map was created through a three-step process. First, given that density maps of different periods have differing value ranges, these values have been normalised to obtain a common value ranging from 0 to 100. Second, zonal statistical analyses facilitate the interrogation of the KDE maps against a vector shape file of the modern day provinces of the European Union and adjoining territories. This generates mean values of epicentre density for each of the 1248 European districts which, in turn, can be exported to produce tables for late medieval, post-medieval and 20$^{th}$ century epicentre densities and then joined with the shape files so as to visualise differences in density trends between the KDE raster maps. Third, for ease of identification, differences in density values between late medieval KDE maps and 20$^{th}$ century KDE maps have been calculated for all the epicentres as well as for epicentres with Mw ≥ 5.

By comparing several datasets, **Figure 8** highlights the extent to which the recorded distribution of 20$^{th}$ century seismic events differs from those that occurred in the Middle Ages. Once more, it is possible to identify where higher and lower than anticipated levels of activity are located. Negative values (in blue on **Figure 8**), which indicate lower than anticipated levels of medieval seismicity, are focused on two areas: eastern Europe and the eastern Mediterranean, including the Balkans, Romania, Greece and Crete, and Iceland. The most under-represented areas lie in the south of Albania, around the Gulf of Corinth and Crete. By contrast, those regions showing a higher than expected level of medieval seismicity (in red on **Figure 8**), when compared to contemporary seismicity, can be found in Western Europe, especially in Andalusia, the eastern Pyrenees, Switzerland, the Aachen region, northern and central Italy, the Strait of Messina, Slovenia and Dalmatia. Peaks in positive values centre on northern and central Italy.

The higher than expected spatial density of earthquakes may in part be explained by the nature of the seismic event itself. While it could be argued that, over a period of a century, the spatial and temporal distribution of small to medium earthquakes on a continental scale might be approximately constant, the recurrence interval of seismic events scales with time, such that the largest earthquakes occur the least frequently; the recurrence period of a large earthquake on a given active fault might be typically in the order of a century to a few millennia. The largest earthquakes, because they have much longer return periods, introduce greater temporal and spatial variability. Once more, there may be a high occurrence of aftershocks after a very large seismic event and, where a large earthquake has occurred, it would be expected that a number of small to medium earthquakes might also strike in the same region.

It is also the case that two earthquakes of the same magnitude may not have the same consequences for above ground structures because of the nature of local geology and geomorphology. For example, variations in rupture speed may affect the frequency of the shaking experienced at ground level, changing the damage potential of the earthquake. In addition, different continental areas have different attenuation characteristics which affect the distribution of ground shaking. In central Greece, for example, strong earthquakes have been described with a Mw between 6.5 and 7.2 but with only very localised impacts (Ambraseys and Jackson 1990; Stiros and Pytharouli 2014). Another important influence on our mapping is the method by which events have been recorded by catalogue compilers. The observed peaks of post-medieval earthquakes in Switzerland and Slovenia, for example, are probably due to the recording of a large number of low impact aftershocks as independent earthquake events in these regions and also to some extent the comprehensive research which has been undertaken by the Swiss Seismological Service (Fäh et al. 2011; Živčić 2009, as reported in Stucchi et al. 2013: 533).

Question marks concerning over- and under-reporting may apply equally to the later medieval period and, to investigate this possibility further, **Figure 9** displays the KDE map of medieval earthquakes but this time including all late medieval cities with a population above 10,000 inhabitants (Jotischky and Hull 2005: 73). What emerges is a positive relationship between the density of recorded seismic events and the distribution of these more significant settlements. Thus, larger numbers of people in medieval urban areas, particularly those in literate institutions such as monasteries and universities, presented not only greater opportunities for damage to occur but also for that damage to be observed and recorded as a seismic episode. Towns and cities which were better connected to national and European trading networks with substantial numbers of visitors, pilgrims and merchants also multiplied many times over the opportunity for comment well outside the affected region. Furthermore, in a risk sensitive society in which earthquakes occurred more frequently and measures of hazard adaptation and mitigation were better understood (e.g. structural assessments, financial relief, reconstruction, etc) there was perhaps a greater propensity to evaluate and record in order to justify a civic or State response (Gerrard and Petley 2013). As an illustration of this, one of the best-documented and most destructive seismic events in the Late Medieval Italy struck the southern Apennines and the Naples region in December 1456 with an estimated Mw = 7±0.30 and a maximum Intensity Io=11 (*total destruction*)(Meletti et al. 1988). Information about this earthquake which was probably composed of three distinct but coincident seismic events (Teramo et al. 1999) is derived from more than 60 different historical sources, including royal privileges given in the aftermath, ambassadors' letters, reports, chronicles, scientific treatises and inscriptions (Figliuolo 1988; Guidoboni and Comastri 2005). Not surprisingly, the number of known affected locations is also remarkably high; 199 different places recorded the event in one form or another. On the other hand, the Xylocastro earthquake, which affected the Gulf of Corinth in June 1402, was one of the strongest earthquakes recorded in the late medieval Greece (Guidoboni and Comastri 2005).This tsunamigenic event had an estimated Mw = 6.6 ± 0.35 and Io=10 (University of Thessaloniki 2003) and yet just eight places are recorded as being affected along the shores of the Gulf, and only two historical sources provide any information at all about the event: one is a letter written by a Venetian merchant, the other a chronicle from the city of Ferrara (in Italy).

If the earthquake data for Italy and Greece is examined over time rather than spatially, further patterns emerge. **Figure 10** shows the 269 known earthquakes in Italy between 1000 and 1550 AD at 50 year intervals, plotted alongside the 48 recorded earthquakes for Greece. Whereas the trend for Italy is quite simple if non-linear, with more earthquakes in more recent centuries, that for Greece is more variable. With the exception of limited numbers of monastic archives (such as those at Monte Athos and island of Patmos), documents for the Middle and the Late Byzantine period are almost completely absent (Tsougarakis and Angelomatis-Tsougarakis 2012). From the $13^{th}$ century, the situation improves as commercial contacts improved with the West, for example with Venice, and the presence of new institutions such as the Military Orders on Rhodes, Cyprus and elsewhere (e.g. during the 1493 earthquake of Kos; Figliuolo 2002). Only from the $15^{th}$ century did archives become richer as a consequence of integration into the Ottoman Empire with a subsequent growth of ecclesiastical and monastic archives (Tsougarakis and Angelomatis-Tsougarakis 2012).

## Conclusion

This paper highlights some of the strengths and weakness of current historic earthquake meta-datasets. While seismologists have long been aware of the incompleteness of their catalogues, we offer this KDE comparison as another tool in the toolbox, one that provides better geographical definition. The results immediately suggests an agenda for further investigation, particularly across eastern Europe and the eastern Mediterranean where our methodology suggests that there were more and more powerful seismic events during the Middle Ages than have hitherto been recorded. For some of these areas archaeoseismological and paleaosesimological projects might shed new light on historical seismic events, otherwise a more detailed assessment is required of the information gap resulting from a scarcity of written documents. Finally, we also highlight here the issue of over-recording, something which may be explained by the nature of the seismic event and the density of human settlement combined with regional cultural and social factors, including the more sophisticated development of risk-sensitive tactics.

**Acknowledgments**

This analysis falls within the ArMedEa project (Archaeology of medieval earthquakes in Europe; Forlin, Gerrard, and Petley 2015), which aims to build upon the dataset published by AHEAD and survey archaeological and palaeoenvironmental evidence related to late medieval seismicity in Europe. ArMedEa was developed in the Department of Archaeology and the Institute of Hazard, Risk and Resilience of Durham University and supported by a Marie Curie Intra European Fellowship within the 7th European Community Framework Programme. Petley's contribution was funded by the NERC/ESRC *Earthquakes Without Frontiers* project, grant reference NE/J01995X/1. The authors would like to thank the anonymous reviewers for their constructive comments.

**Captions**

Figure 1. Numbers of recorded earthquake events across Europe by century (source: AHEAD 2014) .

Figure 2. Distribution of late medieval (1000-1550 AD; source: AHEAD 2014) earthquake epicentres (sx) andthe associated KDE (dx).

Figure 3. Distribution of late medieval (1000-1550 AD; source: AHEAD 2014) earthquake epicentres with Mw ≥ 5 (sx) the associated KDE (dx).

Figure 4. Distribution of post-medieval (1551-1899 AD; source: AHEAD 2014) earthquake epicentres (sx) and the associated KDE (dx).

Figure 5. Distribution of post-medieval (1551-1899 AD; source: AHEAD 2014) earthquake epicentres with Mw ≥ 5 (sx) and the associated KDE (dx).

Figure 6. Distribution of 20th century earthquake epicentres (sx; source: EMEC 2012) and the associated KDE (dx).

Figure 7. Distribution of 20th century earthquake epicentres with Mw ≥ 5 (sx; source: EMEC 2012) the associated KDE (dx).

Figure 8. Calculated difference between the KDEs for medieval and 20th century earthquakes.

Figure 9. Medieval cities with a population higher than 10k inhabitants (in AD 1300 ca.) and the KDE of late medieval earthquakes.

Figure 10. Recorded seismic events in Greece and Italy between 1000 and 1550 AD, here calculated for 50 year intervals

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Figure 1 Click here to download Figure fig.1 diag pre1900 eqs.jpg

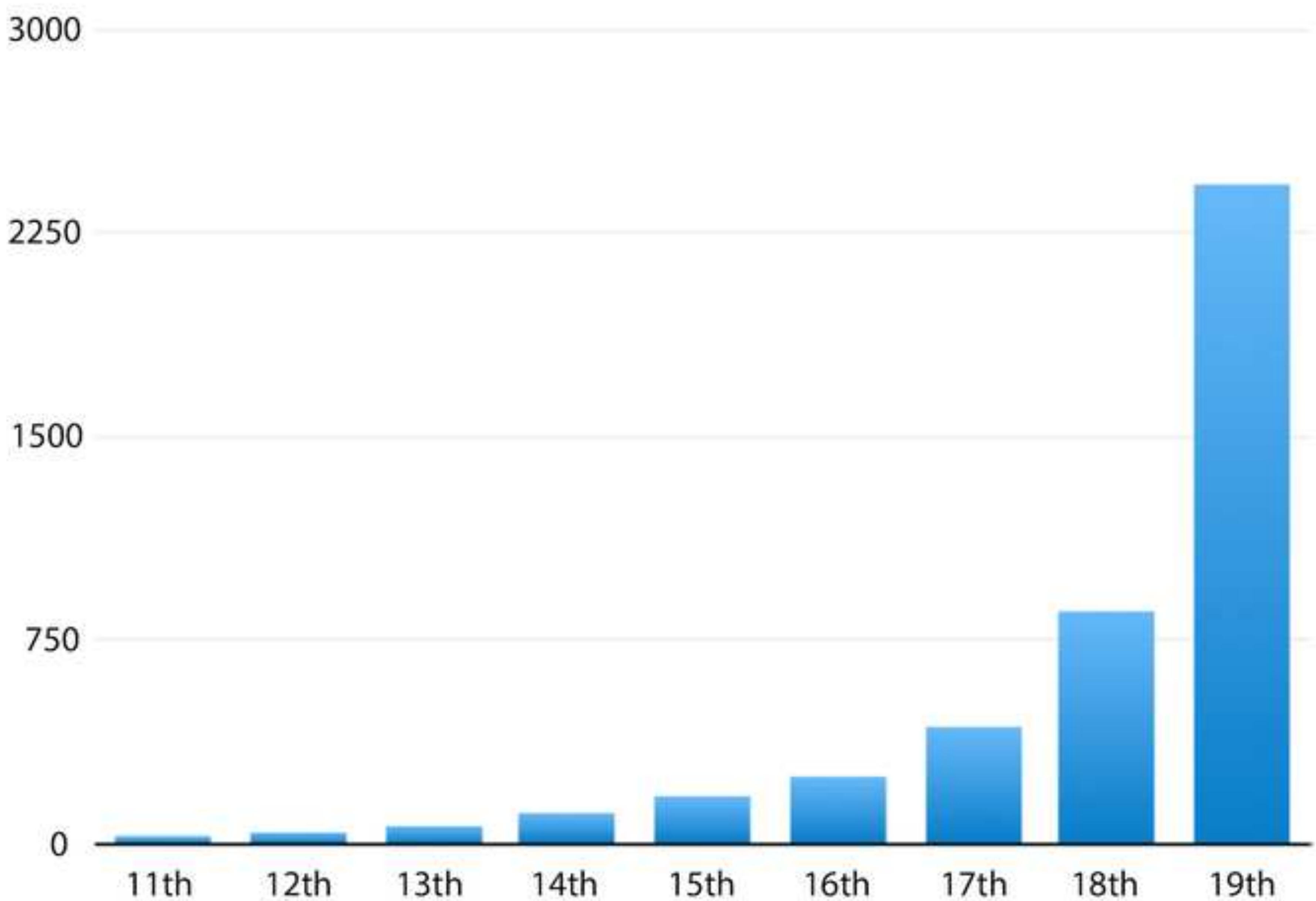
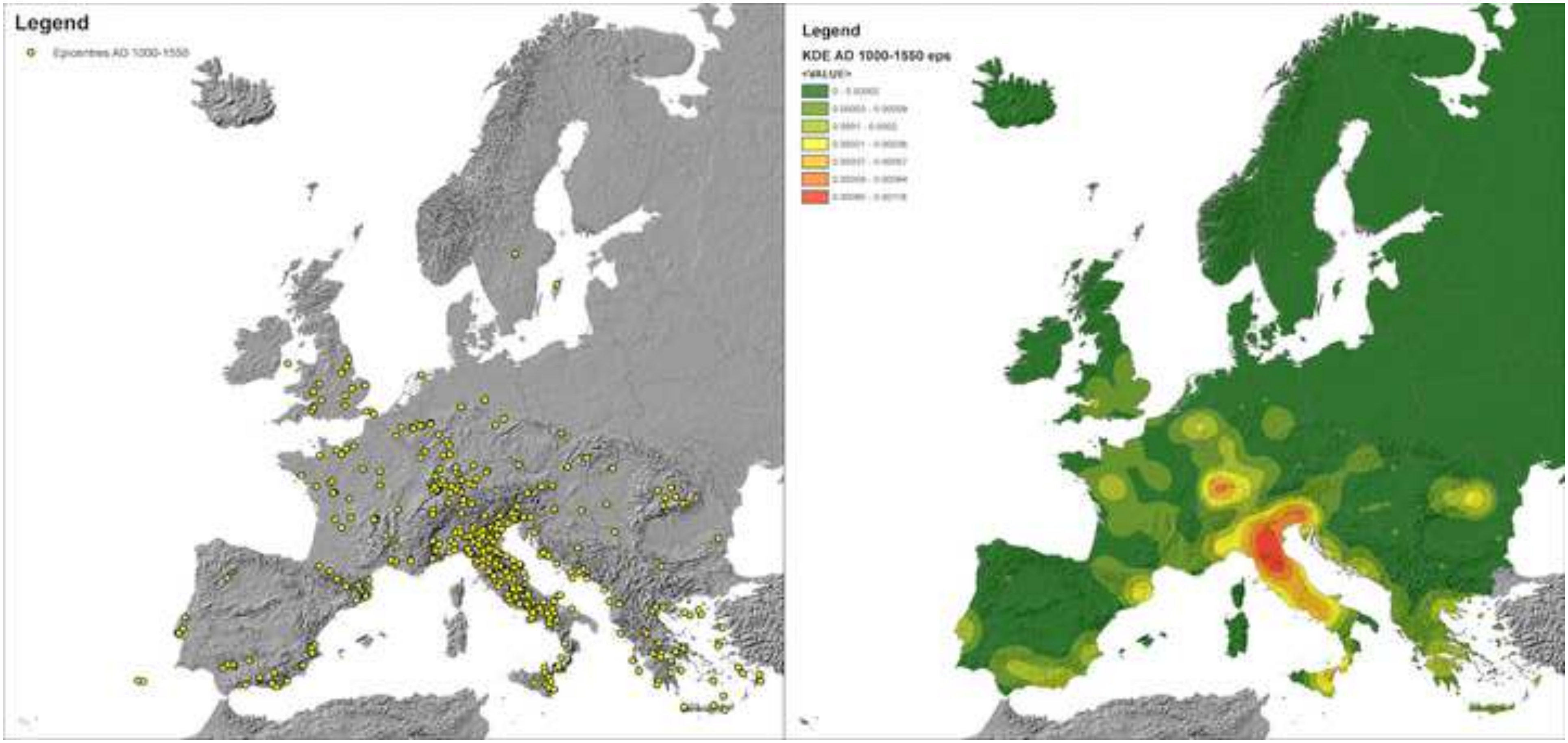


Figure 2

Click here to download Figure fig.2 medieval eqs.jpg



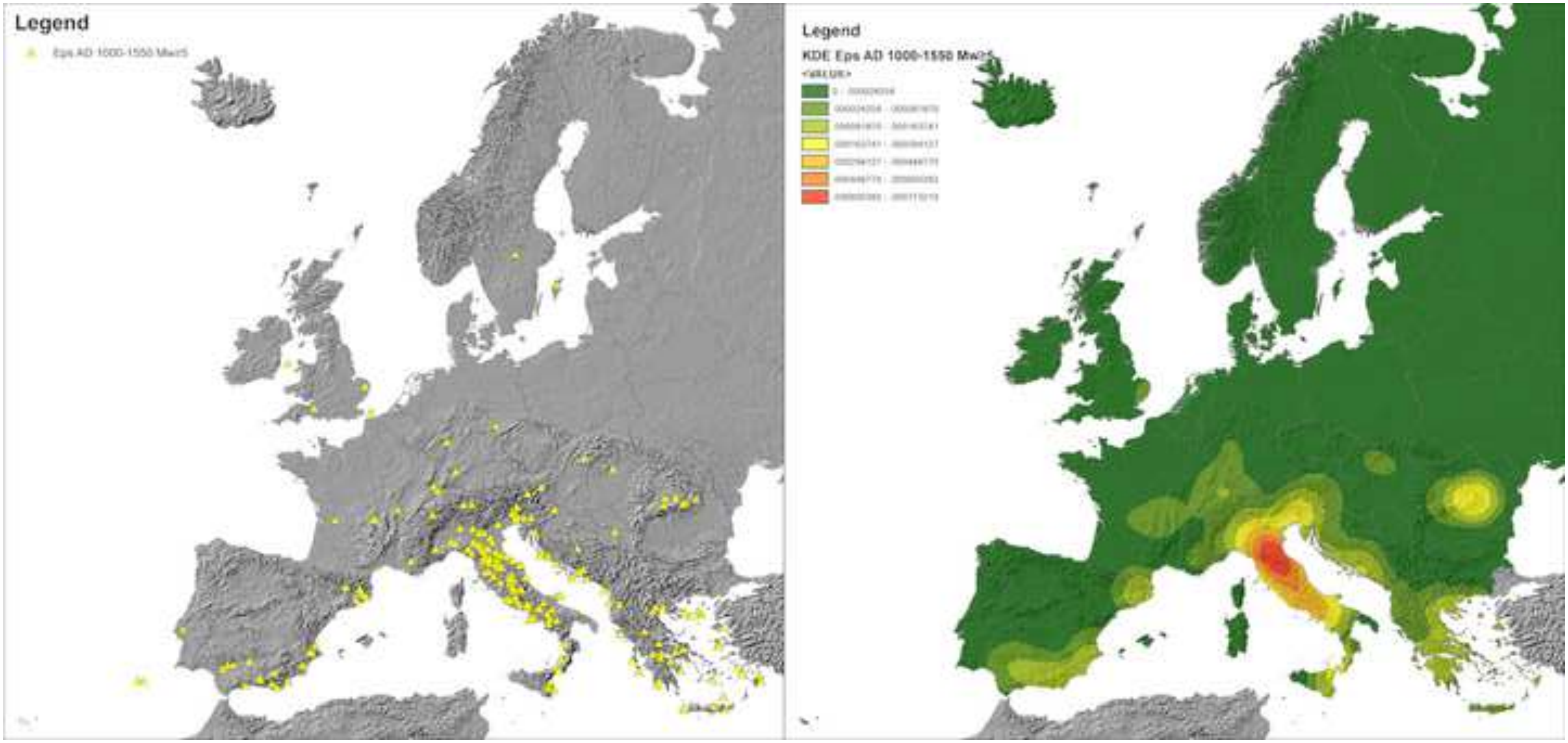

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Figure 4

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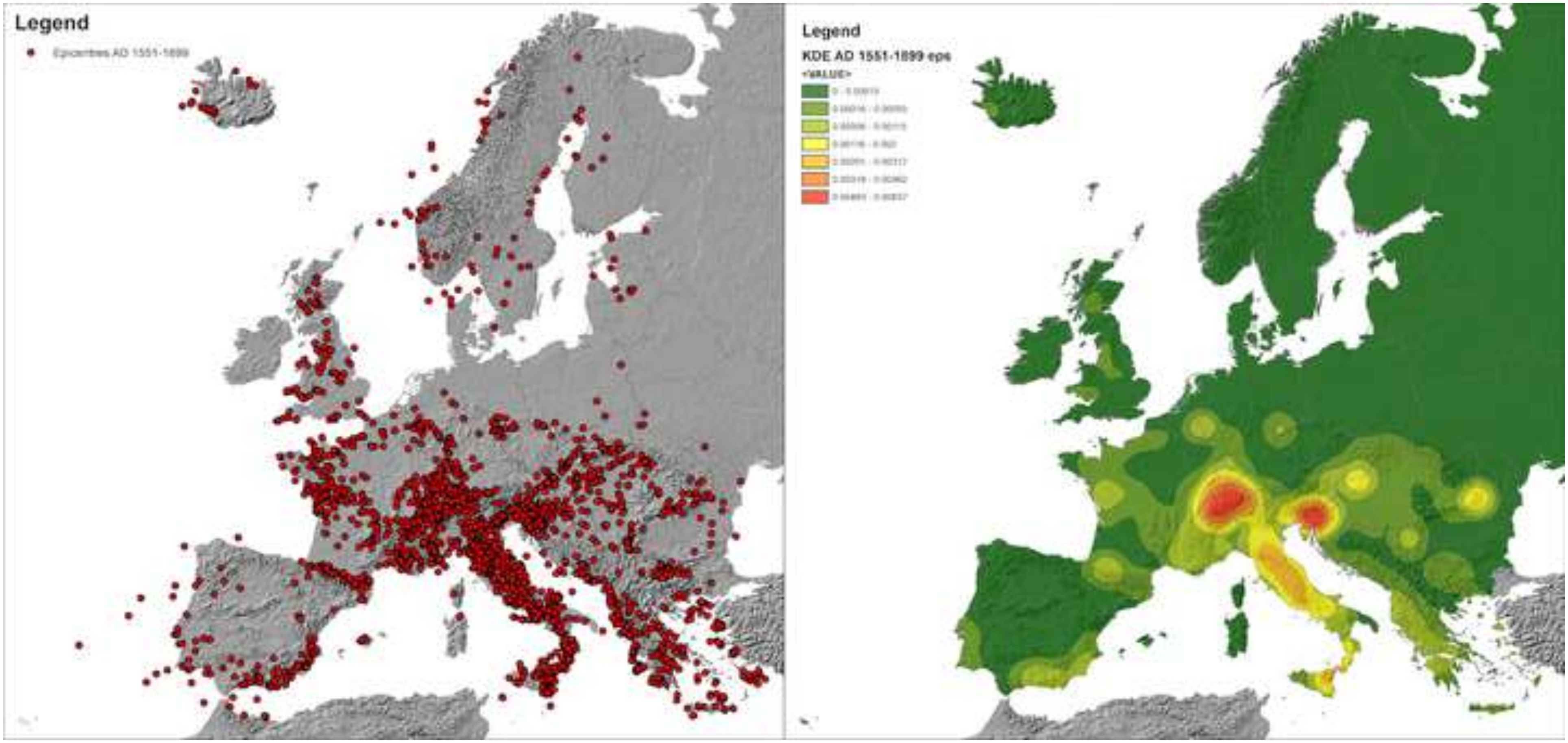

Figure 5

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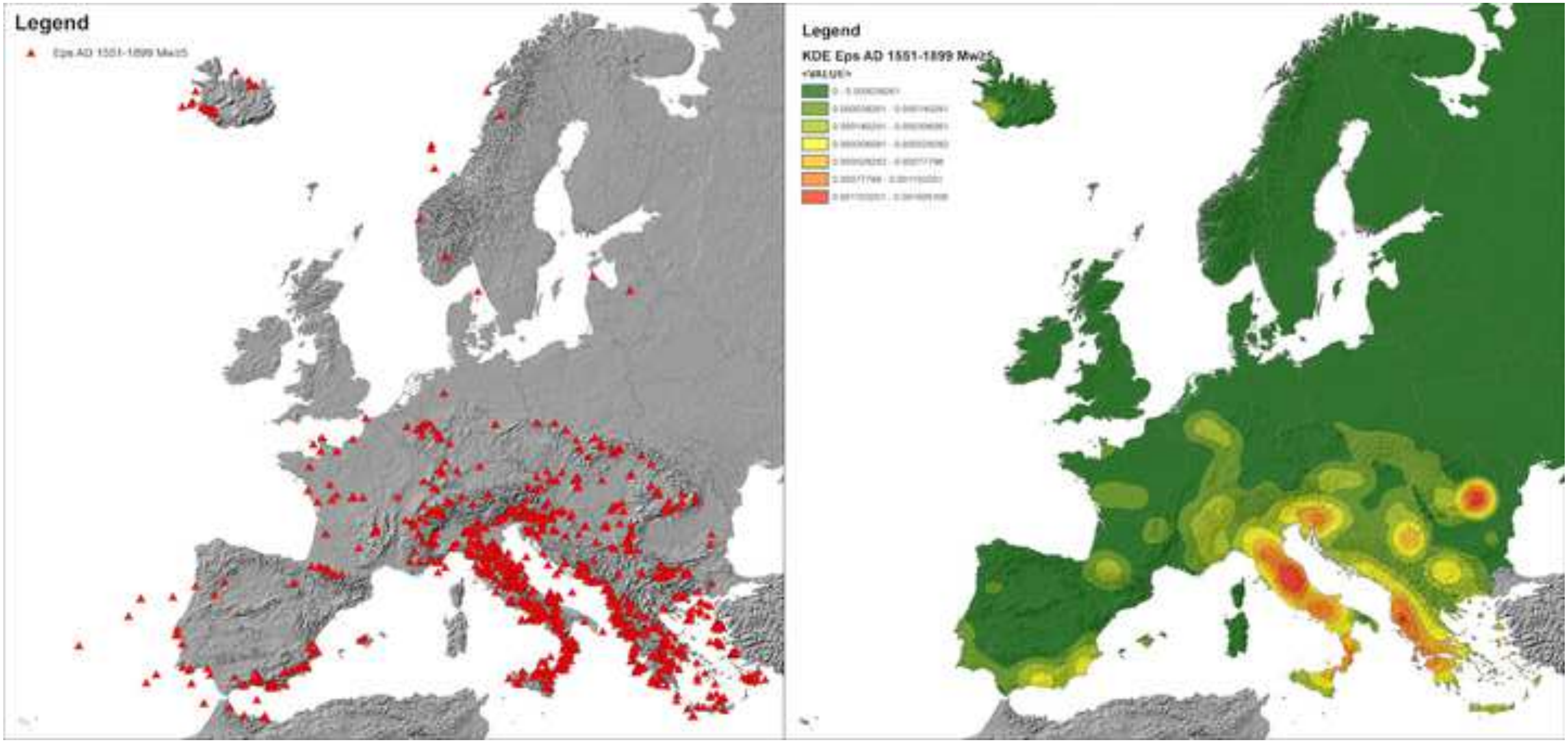

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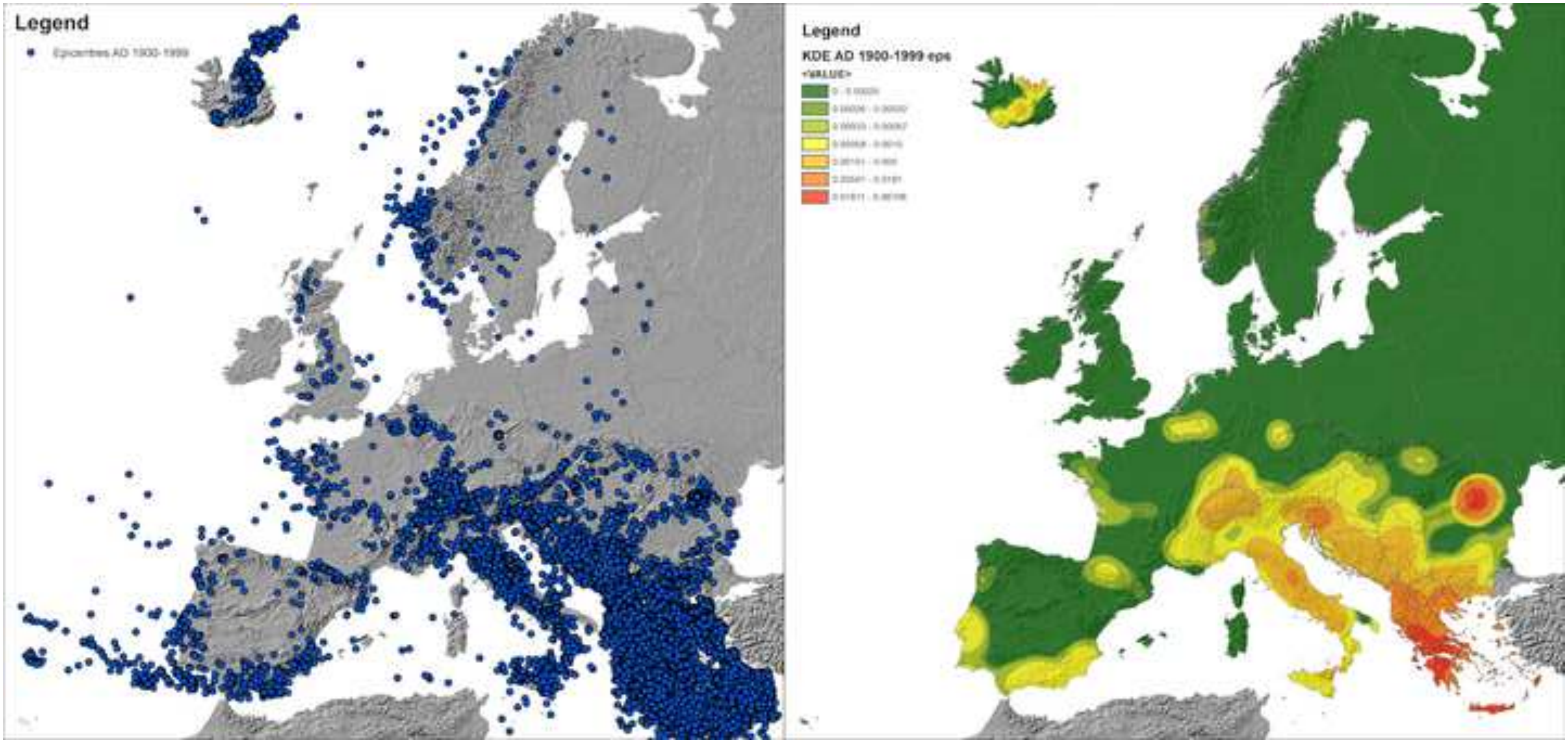

Figure 7

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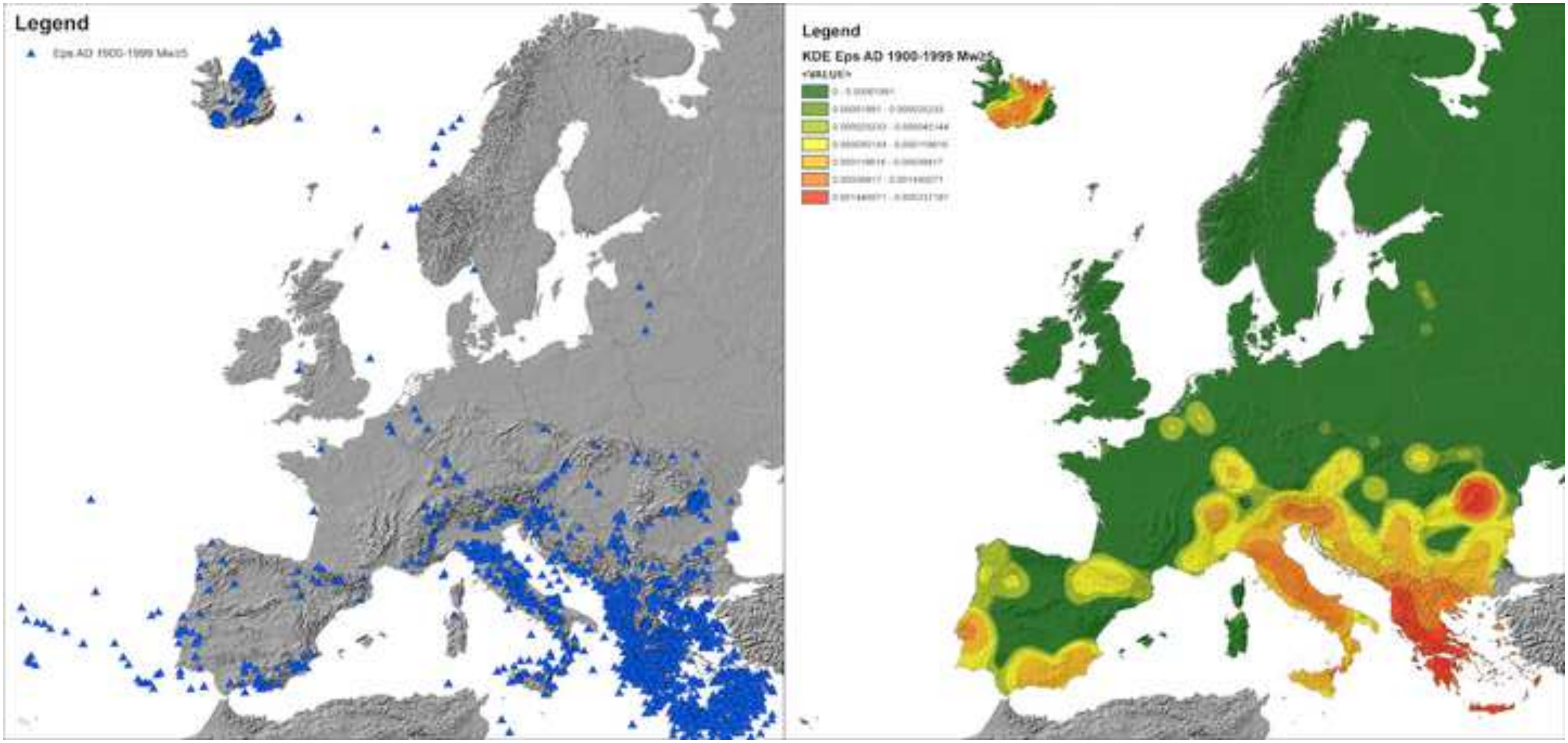

Figure 8 NEW

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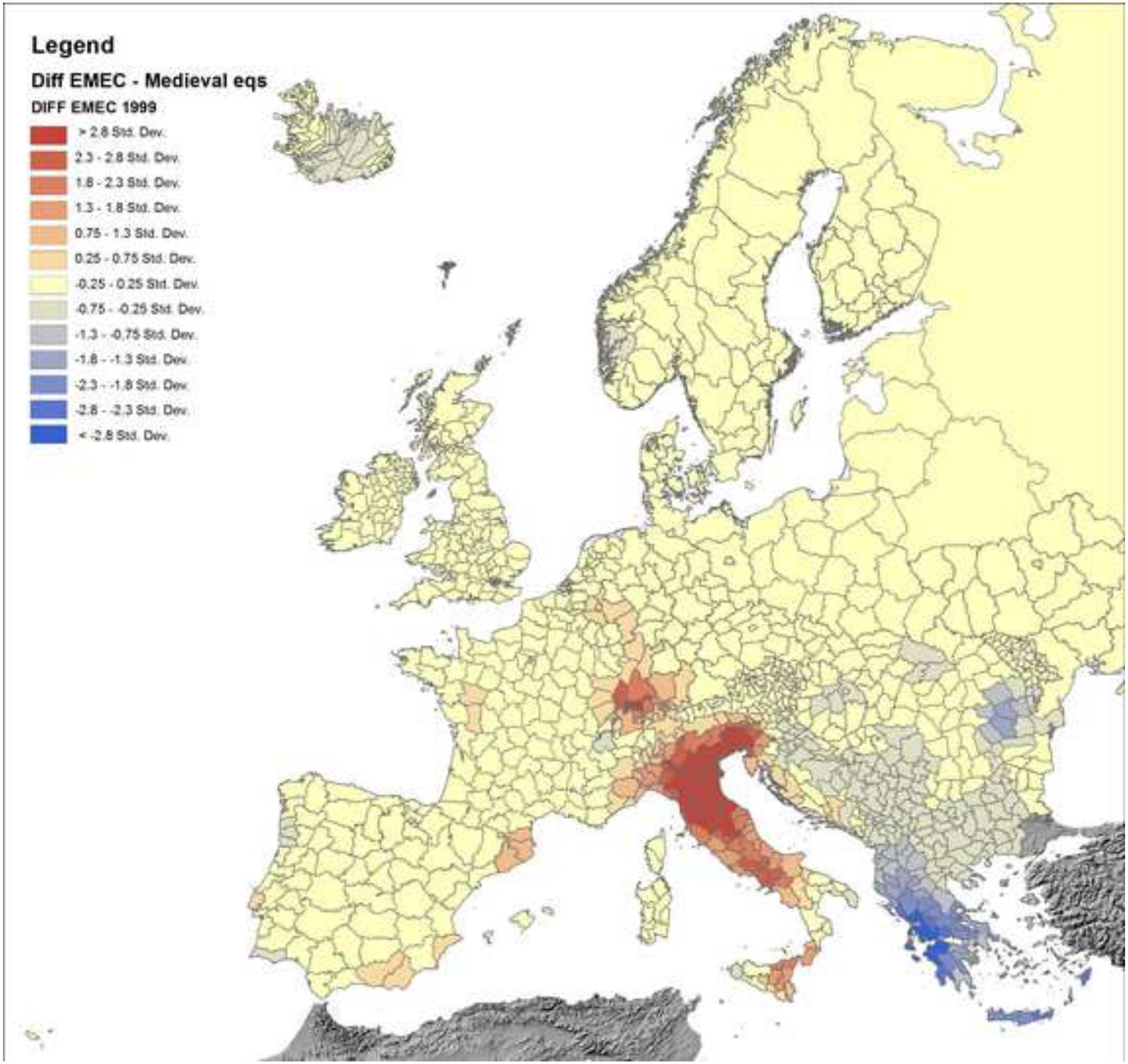

Figure 9. Med eqs with med cities

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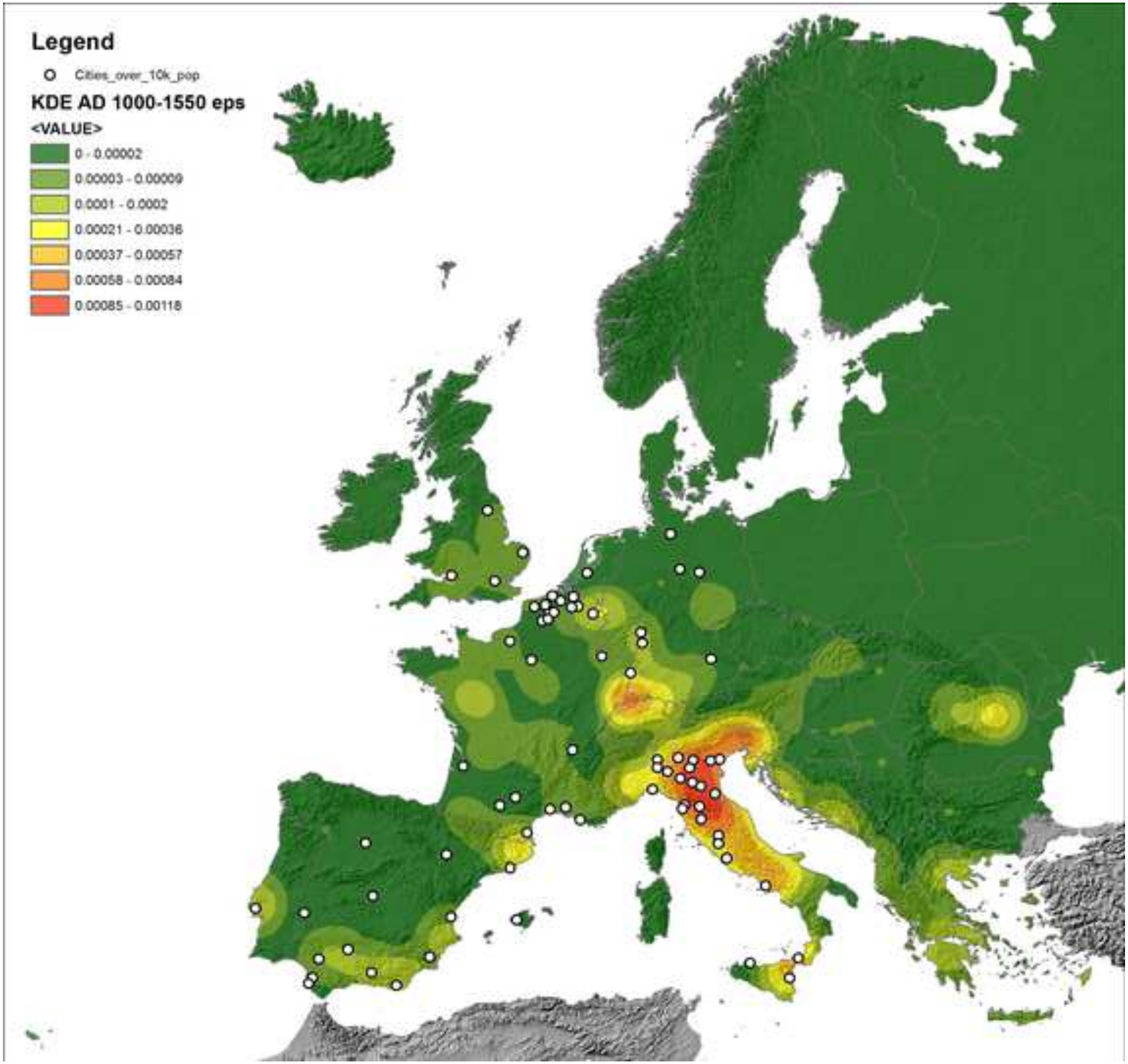

Figure 10 Click here to download Figure fig.10 NEW graph composite GRE-ITA.jpg