Vectorizing maps to generate geo-spatial data on territories of the Holy Roman Empire

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Abstract

Geo-spatial factors were a major driving force for the European Reformation. Power relations between neighboring territorial states, travel routes of scholars, and locations of cultural exchange contributed to the spread of Protestantism. However, researchers cannot study these factors quantitatively because spatial data on territories in the 16th century does not exist. I develop a manual and an automatic method to extract the geo-coordinates of territories from political maps and enrich them with non-spatial attributes gathered from Wikipedia. The manual method extracts unambiguous territories and the automatic method is reproducible and time saving. The generated data can be used to study confessionalization and other aspects of the Reformation. The methodology can be generalized to other geographic areas and historical periods.

Keywords: map vectorization, geo-spatial data, territorial states, Holy Roman Empire, Reformation, H-GIS

1 Introduction

In the 16th century, Europe consisted of many territorial states which were governed by princes and were loosely held together in the Holy Roman Empire (HRE). This geopolitical situation was a major driving force for the Reformation because the princes chose the denomination for their subjects (Harrington and Walser Smith, 1997). This choice was not only based on the personal preferences of the princes but was also affected by geo-spatial factors, such as imbalanced power relations between the territories (Holt, 2003), whereabouts of scholars (Strauss, 1975), and locations of cultural exchange (Strohm, 2017).

To study the effect of these factors on the Reformation we need spatial data of the territories. This allows us to position territories on a map, measure territorial gains and losses, and identify neighborhood relations between territories. We can approximate the spread of ideas by extracting travel routes of individuals, and relate territories to places of cultural exchange, such as university tows, as well as to geographic barriers affecting reachability of places, such as mountain ranges and rivers. In short: spatial data allows us to study processes in a global interconnected context rather than focusing on individual territories.

However, data on HRE territories in the 16th century is not available for spatial analyses and scattered across multiple sources. Several modern political maps of the HRE in the 16th century exist but are not digitized or their digitized version is not publicly available (Hilgemann and Kinder, 2020; Isphording et al., 2011; Schindling and Ziegler, 1989-1995; Westermann, 1997; Wikipedia, 2010). Publications in historical research provide non-spatial information about territories in unstructured text formats which is cumbersome to extract manually (Schindling and Ziegler, 1989-1995). This lack of spatial data is not unique to 16th century Europe but also concerns other geographic areas and historical periods (Baeten and Lave, 2020; Levin, Kark, and Galilee, 2010; Thévenin, Schwartz, and Sapet, 2013; Zaragozí et al., 2019). What we need is a method to construct spatial data sets from several analogue and non-spatial sources.

In this paper, I address this gap by constructing a spatial data set of territories of the HRE in the 16th century. This is a challenging task because the HRE was a large, volatile, and unclear structure. In the 16th century, the HRE consisted of about 600 territories, some as small as the surrounding grounds of a monastery. Territories often changed their borders since land was lost or won during wars. They were separated into smaller pieces due to division of the estate, or merged into larger pieces due to marriage. These changes are hard to pin down because they were not always recorded precisely. Even if a territory had stable borders it is difficult to locate it in space because territories often consisted of noncontinuous parts, the exclaves, and were perforated with enclaves of other territories. Matters are complicated further by the fact that relations between territories were diverse making it difficult to identify truly independent territories. For example, condominates were regions that were ruled together by several territories. A bailwick was a conquered territory where the conqueror appointed a bailiff to govern the territory even though that territory was not annexed. In the feudal system, a weaker territory had to provide food to a stronger territory in return for protection. Weaker dependencies such as tax relations and protectorates were also common.

In my data generation approach, I account for these challenges by relying on established selections of territories that were generated by Historians and considered relevant for the Reformation, and by tracking temporal changes in the attributes of the territories if available. I digitize modern political maps of the HRE to locate territories in space, crawl non-spatial attributes of these territories from Wikipedia, and merge the spatial and non-spatial data. I conduct the data generation process manually and automatically, and argue that the automatic approach should only be used if the raw data match the historical period of interest. The final data set comprises 275 territories. My method provides a reproducible way to generate spatial data for HRE territories in the 16th century. The data can be enriched with other territory attributes or combined with existing data sets. The method can be applied to other cases where enriched spatial data can be extracted from maps and Wikipedia. The data and method help researchers in fields of History, Digital and Computational Humanities, Geography, and Social Science to analyse novel geo-spatial aspects of the Reformation.

2 Materials and Methods

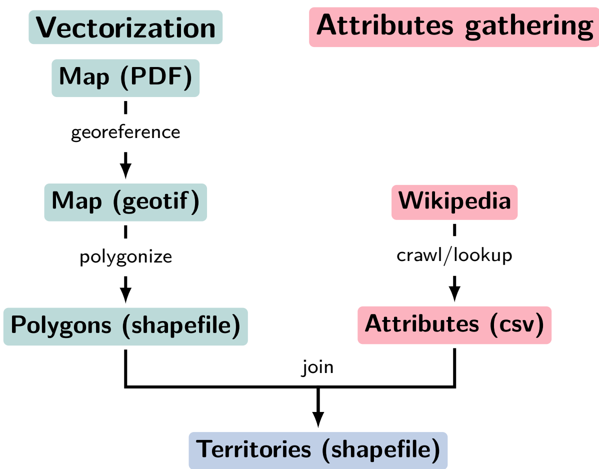


Figure 1: Approach to generate a data set of vectorized territorial states of the Holy Roman Empire during the European Reformation.

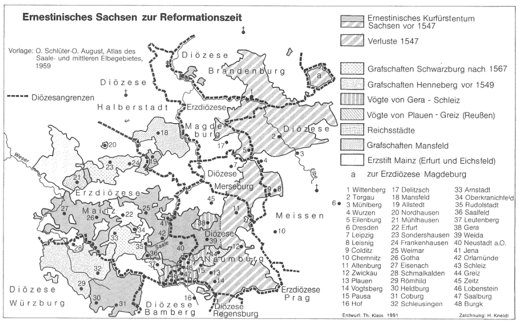
Figure 1 summarises my approach to generate a data set of vectorized territorial states of the Holy Roman Empire (HRE) during the European Reformation. I construct two separate data sets of the territories: vectorized and attributes data. The vectorized data contain the geo-coordinates of the territory borders which allows us to locate the territories in space. The attributes data contain non-spatial attributes of the territories such as type of rule or religion. Both data sets account for temporal changes, such as territorial gains and losses after wars

I construct each of these data sets with two methods, manual and automatic. By comparing these two methods, I show that the automatically generated data are of lesser quality because they do not cover all territories that were relevant in the 16th century and extracted territories have ambiguous attributes.

Finally, I automatically merge the vectorized and attributes data to obtain a single data set of territories including temporal spatial and non-spatial characteristics of the territories.

2.1 Vectorizing territories

Vectorizing territories means extracting the geo-coordinates of territory borders from political maps. These maps show the geo-political situation of the HRE during the Reformation. I use modern maps that have been created by Historians based on historical records.



(a) Map of Saxony from Schindling and Ziegler (1989-1995) for the manual method

(b) Map of HRE from Wikipedia for the automatic method (Wikipedia, 2010)

Figure 2: Maps of the Holy Roman Empire

2.1.1 Manual: polygon tracer

Select map. I use the maps of Schindling and Ziegler (1989-1995) to extract territories, which represents an established reference work for the study of geo-political processes during the Reformation. The authors provide a selection of about 300 territories which played a significant role during the Reformation. Each map contains between one and 5 territories. I scan the selected maps to obtain PDFs which I use in the subsequent analysis. As an example, Figure 2a shows the map of Saxony.

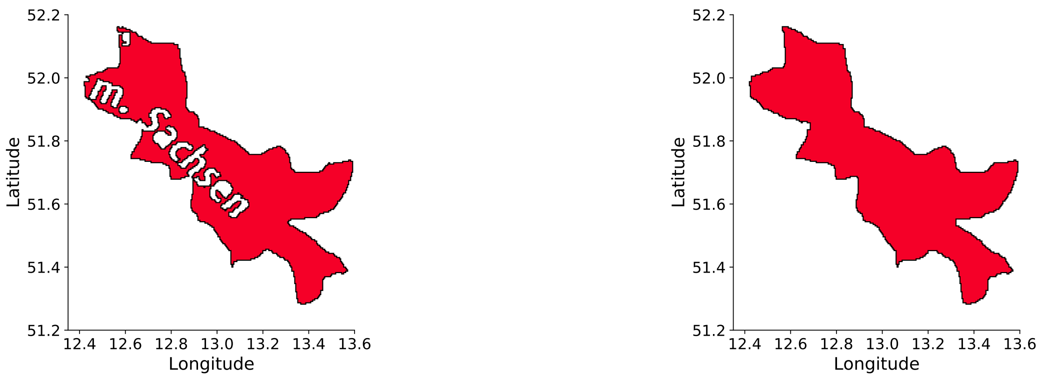
Georeference map. Each point on a PDF-map has to be associated with a physical location in the real world. This georeferencing process constructs an internal coordinate system for each PDF-map which is projected onto a real-world geographic coordinate system. I use QGIS (v. 3.16), an open-source Geographic Information System (GIS) to run and validate georeferencing (QGIS Development Team, 2021). See Appendix A for a detailed description of georeferencing. Since I georeference several maps independently of each other small inaccuracies in georeferencing will result in overlapping polygons when the files are finally combined (see Appendix I for an example).

Poligonize PDF. I use the georeferenced maps to manually trace the border of each territory with the computer mouse using the polygon tracer tool of QGIS. This yields vectorized polygons each representing a territory and being located in space (see Appendix B for a detailed description of manual polygonization). For some territories, Schindling and Ziegler (1989-1995) track changes in territory borders. For example, when Ernestinian Saxony lost the Schmalkaldic War, a conflict between protestant and catholic princes, it was forced to give parts of its territory to Albertenian Saxony. I include these temporal changes by tracing several polygons for the same territory at different points in time. I ensure that I provide a unique identifier for each polygon and time point to later map them to the entries in the attributes data. The resulting polygons represent vectorized territories. They can be edited with GIS software, or with geo-processing libraries of programming languages, such as `geopandas` for python and `simple features` (sf) for R (Kelsey et al., 2021; Pebesma, 2018).

2.1.2 Automatic: match on raster band value

Select map. In the automatic method, I use colored political maps to extract territories by their color. Since the maps provided by Schindling and Ziegler (1989-1995) are black and white they cannot be used for this method. Several atlases provide colored political maps of the HRE in the 16th century (Hilgemann and Kinder, 2020; Isphording et al., 2011; Westermann, 1997). However, since the maps are not available as high-quality scan, which leads to several color values for the same territory rather than one, they are not suited for this method. The best available alternative is a map from Wikipedia showing the geo-political situation in the HRE around 1400 (Fig. 2) (Wikipedia, 2010). This map is of high technical quality but of lower content-related quality compared to the maps by Schindling and Ziegler (1989-1995) because the selection criteria for the territories are not made transparent and the captured historical period is before the Reformation. This affects the accuracy of the extracted territories, as I will show in the results. I removed legends from map wit the Open Source image processing software `gimp` to facilitate polygonization (*GIMP*, 2019).

Georeference map. Like for the manual method, I georeference the map with QGIS to associate each point on the PDF-map with a physical location in the real-world (Appendix A). Since all terrritories are captured in one map only one internal coordinate system is created and extracted polygons will not overlap.



(a) After polygonization

(b) After internal buffering

Figure 3: Extracted polygon corresponding to parts of the Electorate of Saxony. 3a: After polygonization, labels leave holes in the polygon. 3b: After internal buffering, the holes are closed.

Polygonize raster bands. Raster bands store the color of pixels as a combination of the primary colors red, green, and blue (see Appendix C for a detailed description of raster bands). I group consecutive pixels of the same raster band value into polygons with python's `GDAL` library (Contributors GDAL/OGR, 2021). The resulting polygons are defined by a sequence of geo-coordinates describing the border of the polygon and by the raster band value. The polygons correspond to territories but also to noise such as labels, borders, rivers, lakes, and seas. Figure 3a shows an example of an extracted polygon. For the three raster bands I extract 611,854 (red), 604,621 (green), and 585,356 (blue) polygons, respectively. These numbers differ because not all polygons have all raster band values. For example, the blue color of water has no red whereas the red borders and imperial cities have no blue. However, the majority of polygons has 3 raster band values and polygons across the three raster bands are therefore duplicated. It is important to keep these duplicates to later merge polygons of the same territory by color. I save the polygons as shapefiles and will further process them with python's geoprocessing libraries `shapely` and `geopandas` (Gillies, 2007; Kelsey et al., 2021).

Filter polygons. Filtering discards polygons that do not correspond to territories, such as borders, rivers, lakes. Filtering reduces the computational cost of the analysis because fewer polygons have to be processed in later steps. For the map at hand,

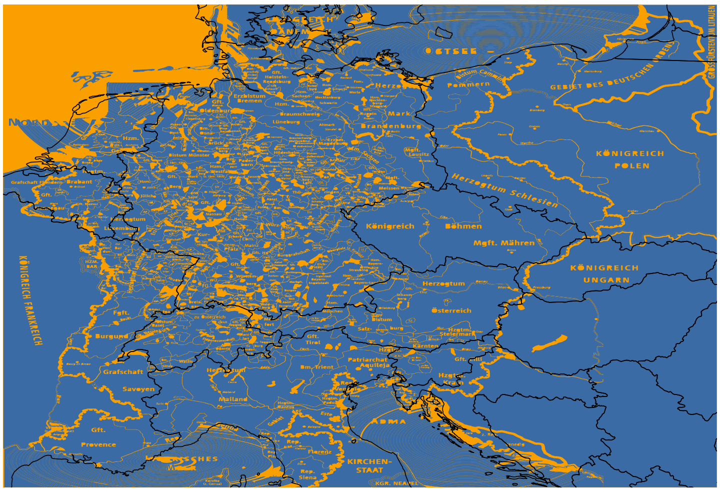


Figure 4: Result after filtering polygons.
polygons identified as territories polygons identified as noise

polygons representing territories tend to be larger than those representing noise. Exceptions to this rule are seas and some lakes. Taking into account these exceptions and an eyeballed estimate of the number of territories on the map, I select 1,000 polygons with the largest surface areas and discard the rest. Figure 4 shows the kept and discarded polygons on a map. I removed the North Sea polygon manually because I had created it myself to hide the original legend making it easy to identify.

Buffer polygons internally. Since the labels on the map are printed inside of territories and are extracted as polygons, the territory-polygons contain holes that have to be filled. First, I close holes in the polygon border by dilating the border by a small distance and then eroding it by the same distance. Second, I close holes in the interior of the polygon by reducing the polygon to its exterior border. Figure 3 compares an extracted polygon before and after internal buffering.

Overlay polygons. I overlay the red, green, and blue version of each polygon from the three raster bands to match a polygon to its original color on the map. This results in one shapefile of polygons where each polygon is described by a sequence of geo-coordinates corresponding to the border, and three color values corresponding to the primary colors. (see Appendix D for details on the overlaying step). Since polygons corresponding to seas and lakes do not have red raster band values they are not matched and filtered out.

Fill space between polygons. If a territory is crossed by a river or covered by a label it is split into several polygons. To relate these territory polygons back to each other the space created by the crossing polygons has to be closed so that the territory polygons become neighbors. I close this space by dilating the polygon borders by a small factor and subsequently erode the borders by the same factor. This step creates overlaps between some polygons which result in a few ambiguous polygon-entry mappings whose consequences are evaluated in the spatial join.

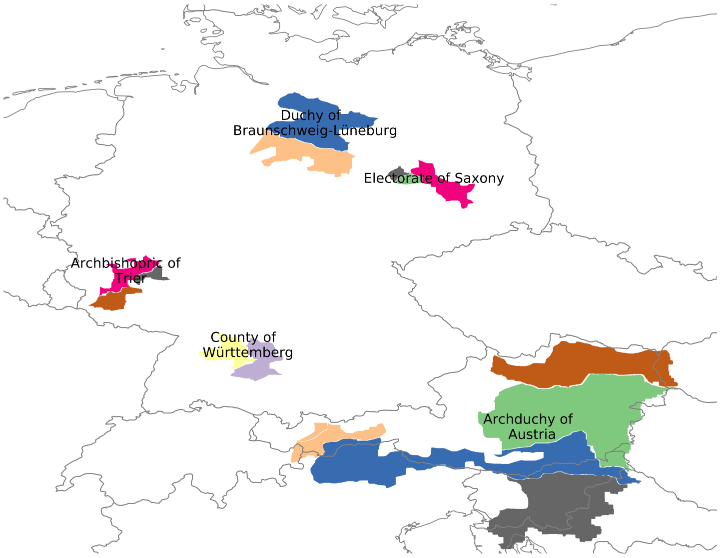


Figure 5: Selection of territories with their merged constituent polygons. On the original map, Austria is split into separate territories such as County of Tirol and Duchy of Krain. Since these territories all have the same face color on the original map the algorithm interprets them as constituent polygons of one territory.

Merge polygons. Merging completes the previous step and combines polygons that belong to the same territory. I merge two polygons if they have the same color and share a border. Figure 5 shows examples of territories whose constituent polygons were merged.This results in a shapefile of polygons where each polygon corresponds to a territory and is defined by the geo-coordinates of its border and the tree raster band values.

2.2 Gathering non-spatial attributes of territories

To enrich the spatial information on polygons in the vectorized data I gather non-spatial attributes of the polygons from Wikipedia, such as name, religion, and type of rule. Appendix E provides a description of all selected attributes. I chose Wikipedia as data source because it is open source, provides digitized data and covers many relevant territories from the 16th century. I chose attributes that allow me to address questions about confessionalization during the Reformation, which I will address in future work. The data could of course be enriched with other attributes customized for other applications.

2.2.1 Manual: Wikipedia lookup

I select all territories that are covered in Schindling and Ziegler (1989-1995) and look up information on attributes on their Wikipedia pages (Appendix E.1). When Wikipedia did not provide data on these attributes I checked the territory-specific texts in Schindling and Ziegler (1989-1995). If information was still not available after this step, I marked it as missing value. Since territories changed over time my unit of analysis is the state of a territory during a specific period. For example, if a territory became Lutheran in 1540 two version of the territory are included in the data one before and one after 1540. The manual Wikipedia lookup resulted in 558 unique temporal states of 303 territories.

2.2.2 Automated: Wikipedia crawl

Select territories. Wikipedia provides a list of 806 territories that have existed in the HRE at some point during its 1,000 years reign (Wikipedia, 2021). I use this list as a starting point and later filter out territories that have existed in the 16th century. I use the German version of Wikipedia pages because they are more detailed than the English version. I use the python package `wptools` to access the Wikipedia page as html (Siznax, 2018), and the package `Beatifulsoup` to parse its content (Richardson, 2007). From the list I can extract the name of the territory, the type of rule, and the country the territory is part of today. Since Wikipedia does not provided temporal information in a structured way I gather static attributes of territories. My unit of analysis therefore is a territory rather than a state of a territory during a certain period as was the case in the manual method. I use this crawled list of territories to access the Wikipedia pages of the individual territories and crawl information from them in a fully-structured and a semi-structured way.

Access attributes (fully structured). The fully-structured method accesses the Wikidata page of the Wikipedia page. Wikidata is the official database behind Wikipedia and is fully structured because it uses the same structural format for all its data. I use the wikidata-API to crawl attributes of each territory (Wikidata Team, 2021). See Appendix E.2 for a detailed description of all attributes. For example, the dates of inception and dissolution will be used to select territories that have existed during the 16th century, and the geo-location will be used to merge territories in the vectorized and attributes data. The fully-structured crawl resulted in 127 territories for the 16th century.

Access attributes (semi structured). Since Wikidata is not a rich data source for territories yet, I turn to another source of attributes and crawl the infoboxes of the Wikipedia pages (see Appendix F for an example of an infobox). These infoboxes seem promising because they provide structured information about the page's topic and in the case of territories in the HRE, are subject to a standardized format. However, editors are not forced to follow this standard, as is the case on Wikidata, and can therefore add, remove, or change keys. Thus, infoboxes are semi structured. For example, the possible keys to access the dates of inception are "Periode" (period), "Vorläufer" (predecessor), "Entstanden aus" (arisen from), and "Entstehungszeit" (period of formation). I checked the infoboxes of several Wikipedia pages of territories to get relevant keys for my attributes of interest, which are the same as for the fully-structured method. The semi-structured crawl resulted in 806 territories for the complete lifetime of the HRE. Filtering for the 16th century discraded all territories. Appendix G compares the manual, fully- and semi-structured extraction methods along the number of missing values across attributes.

2.3 Merging vectorized and attributes data

To combine the vectorized and the attributes data sets polygons have to be mapped to the correct territory name. The reliable method is to use the same identifiers in the vectorized and attributes data and merge the data sets on them. This method ensures that each polygon is uniquely mapped to one Wikipedia entry but it is time consuming because the identifiers have to be provided manually. I use this method for the manually assembled data.

The alterantive, time-saving method is a spatial join. This method merges a polygon and an entry in the attributes data if the geo-location of the entry is located inside that polygon. However, the spatial join causes ambiguous mappings for the manually assembled data because polygons overlap and one point location is mapped to several polygons. I use the spatial join for the automatically assembled data.

3 Results

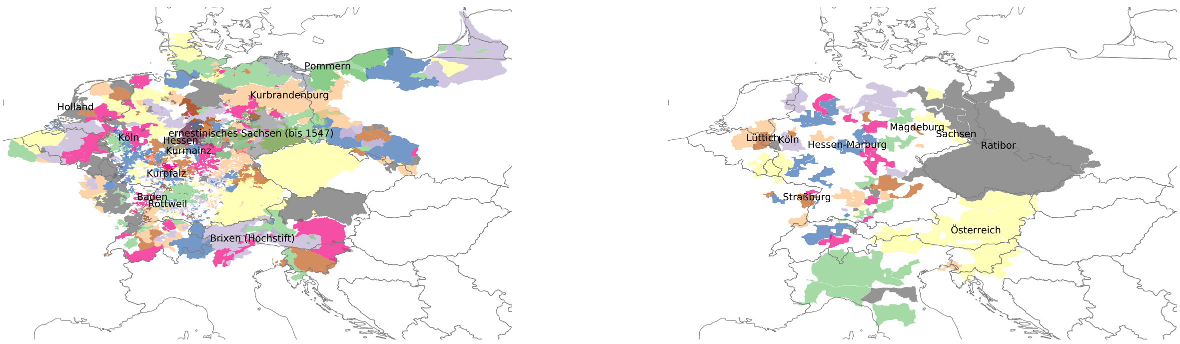
The manual and fully-structured methods extracted 275, and 67 territories of the 16th century, respectively. The semi structured method did not yield any territories for the 16th century but 63 territories for the full lifetime of the HRE.

Table 1: Descriptive statistics of manual and automatic data

	Manual*	Automatic	
		Fully structured*	Semi structured†
# Wikipedia entries*	303	127	117
# Polygons	272	487	487
# Territories after mapping, restrict to one-to-one mappings	275	67	63
Period of existence lifetime of territory in years	mean: 433.34 SD: 236.85 median: 441	mean: 609.76 SD: 221.10 median: 623	-
Confessional stability Number of years for which territory retains a denomination after 1517	mean: 146.43 SD: 107.54 median: 129	-	-
Timing of confessional switch Year in which territory became Protestant	mean: 1549 SD: 26 median: 1541	-	-
Power status Types of rule are ranked 1: large power, 15: small power	mode: 2 range: 1-15	mode: 2 range:1-15	mode: 2 range: 1-15
Surface area in km^2 crs: ESRI:54012	mean: 3316.94 SD: 6575.05 median: 911.83	mean: 7136.65 SD: 22754.47 median: 2025.12	mean: 8518.53 SD: 27017.29 median: 1189.08
# Territories in alliances S: Schmalkaldic League C: Catholic League N: no alliance	S: 40 C: 8 N: 228	-	-

The unit of analysis is a territory for all methods.
* One-to-one mapping and 16th century.
† One-to-one mappings and complete HRE period (800-1806).
#: Number of
SD: standard deviation

Table 1 shows descriptive statistics for the manual and automatic methods. Within methods, we see that the standard deviations for all measures are large showing that territories vary a lot, and a typical territory does not exist. Between methods, we see that only the power status yields similar results. The most common type of rule is an imperial territory (rank 2), such as an imperial county or an imperial city (see Appendix H for a complete ranking of types of rule), and all data sets include the most and the least powerful territories: electorate (rank 1) and city (rank 15), respectively. Since the manual data are temporal whereas the automatic data are static, temporal statistics can be computed only for the manual data. Of interest is that territories tended to become Protestant in 1541, a rather long time before the Peace of Augsburg in 1555, where princes were officially entitled to choose the denomination for their subjects.

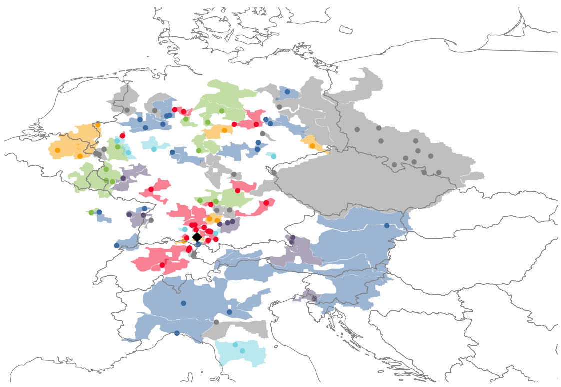


(a) Manual method **(b)** Automatic fully-structured method

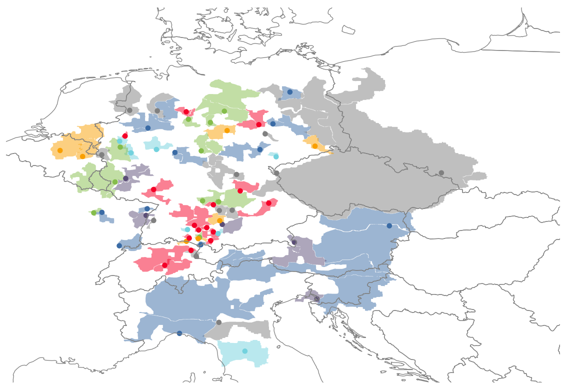
Figure 6: Coverage for manual and automatic fully-structured method. Colored polygons correspond to extracted territories. They are unambiguously mapped to one Wikipedia entry. In (a), temporal states of territories are aggregated over time.

3.1 Evaluate manual and automatic methods

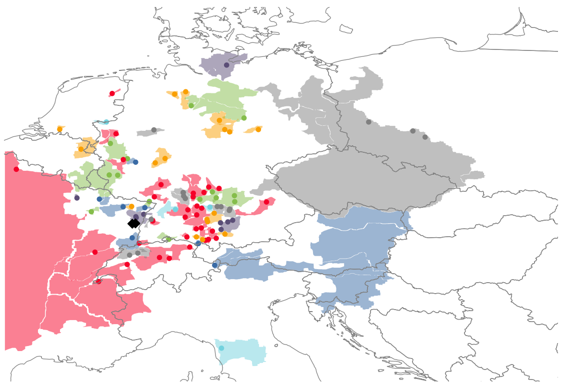
Coverage. Coverage measure to what extent an extraction method yields relevant territories, and whether these territories cover a large geographic area of the HRE. For this analysis, relevant territories are those that had existed during the 16th century. Figure 6 shows the extracted 16th century territories from the manual and automatic fully-structured method. We see that the manual method yields more territories which cover a larger geographic area compared to the automatic method. This shows that many polygons on the original map used in the automatic method lack information on geolocation, and that Wikidata entries lack information on dates of inception and dissolution. We also see that the two maps in Figure 6 depict different territories for the same geographic area, such as a united Duchy of Silesia (Schlesien) for the automatic method and a divided one in the manual method. This indicates a mismatch in historical periods of the original maps. Whereas original maps for the manual method show the geo-political situation in the 16th century, the original map for the automatic method shows the situation around 1400. Although the manual method yields a better coverage than the automatic fully structured method it still lacks territories as the many white spots especially in the South-West of the HRE show. This is because Schindling and Ziegler (1989-1995) did not cover these territories.



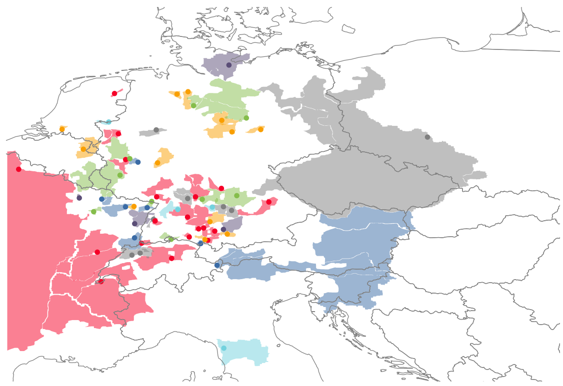
(a) Fully structured
16th century + ambiguous mapping



(b) Fully structured
16th century filter + corrected mapping



(c) Semi structured
complete HRE period + ambiguous mapping



(d) Semi structured
complete HRE period + corrected mapping

Figure 7: Coverage for manual and automatic fully structured method. Colored polygons correspond to extracted polygons. Colored points correspond to Wikipedia entries mapping to the extracted polygons (one-to-one and one-to-many mappings). Black diamonds correspond to Wikipedia entries that map to several polygons (many-to-one mapping). Since the semi structured method did not yield territories for the 16th century results are shown without temporal restrictions for that method.

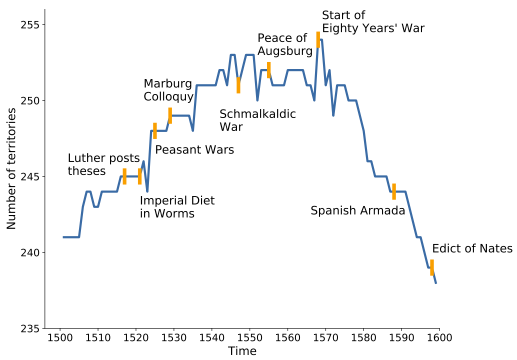
Mapping. Mapping assesses to what extent polygons unambiguously correspond to Wikipedia entries. A perfect mapping is one-to-one because one polygon is uniquely mapped to one Wikipedia entry and vice versa. The manual method results in a one-to-one mapping because I used manually engineered identifiers. In contrast, the automatic method results in ambiguous mappings depicted in Fig. 7. Several points of the same color in one polygon indicate one-to-many mappings where one polygon is mapped to several Wikipedia entries. Diamonds in locations where two polygons overlap indicate many-to-one mappings where many polygons are mapped to one Wikipedia entry. Figures 7a and 7c show the ambiguous mappings for the fully and semi structured methods respectively. We see that one-to-many mappings occur much more often than many-to-one mappings. I resolved ambiguous mappings by selecting unique polygon-entry mappings at random from the available ones. Figures 7b and 7d show the result of the mapping corrections. We see that the same polygon is mapped to different territories in the two methods, as the different point locations in the same polygon show. Both may even be incorrect because the choice of the unique mapping was random. One-to-many mappings result from a mismatch in historical periods between the selected entries on Wikipedia and the original map, like in the case of coverage. Many-to-one mappings result from the vectorization of polygons where a buffer function was applied to fill gaps between polygons. Although the current polygon-to-Wikipedia entry mapping is better in the manual data than in the automatic one, the manual data is likely to cause ambiguous mappings in future applications. For example, if we would like to assign locations of individuals on their travel routes to territories the manual data will result in many-to-one mappings because polygons overlap due to small inaccuracies in georeferencing of individual maps (see Appendix I for an example).

The above results show that the manual method yields a data set of higher, yet not optimal, quality than the semi-automated method. I will therefore use the manually constructed data to further explore territories in this paper.

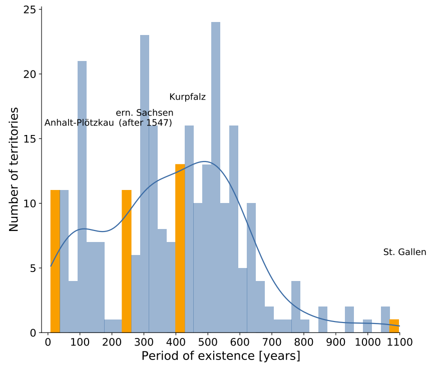
3.2 Descriptive statistics of manually assembled data

To explore the manually assembled territories I discuss visualizations and descriptive statistics on selected attributes of the data. Figure 8a shows the number of extracted territories that existed at different points in time in the 16th century. We see that the number ranges between 228 and 246 and that most territories existed in the middle of the 16th century. This is because Schindling and Ziegler (1989-1995) concentrated on territories that drove the confessionalization in the HRE which gained momentum around 1555 when princes were allowed to choose the denomination of their subjects (Peace of Augsburg).

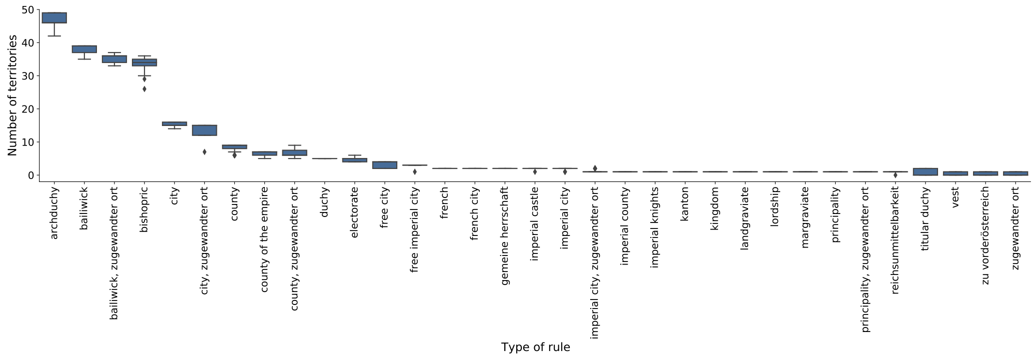
Figure 8b shows the number of extracted territories that had existed for a certain number of years. We see that most territories have a lifetime of 400 to 600 years. Given that the political system had been stable for such long periods the importance of the



(a) Number of territories over time



(b) Lifetime of territories



(c) Number of territories per type of rule across 10 years sliding window

Figure 8: Frequency of territories along selected attributes

Reformation as transformative movement gains additional weight.

Figure 8c shows the average number of territories per type of rule over a 10 years sliding window. We see that the distributions for all types of rule are narrow indicating that the territories in the data stuck to one type of rule in the 16th century. Note that the types of rule were no standardized titles but fuzzy categories with ambiguous modern interpretations. For example, many Wikipedia entries mix up imperial and free cities. Whereas the imperial city was only subordinate to the Emperor the free city was subordinate to a territorial prince but had extensive rights and privileges. As a consequence, the crisp categorization into different types of rule and Wikipedia entries on HRE territories have to be used carefully.

Figure 9 shows the adoption of Protestantism across space and time. We see that territories in the North-East of the HRE adopted Protestantism first and territories in the South-West did so later. Whether these two regions acted independently of each other or whether neighborhood effects played a role for the spread of Protestantism can be analyzed with this data set in future studies. As with the type of rule of a territory, its religion is also a fuzzy concept. Although the princes decided over the denomination of their subjects the subjects did not always obey the official laws. A prince indifferent to religious matters may have let his subjects do as they like without interfering in their religious practices even if they differed from the official law. A weak prince may have adopted a certain denomination because his subjects pressured him to do so. So the official adoption of a new denomination happened after the adoption in the general population. Under a strong prince subjects may have practiced their denomination in secret if it did not match the official one. And even if subjects obeyed to the official denomination their implementation of that denomination in daily life may still have differed. So Lutheranism in territory A is not comparable to Lutheranism in territory B. These nuances should be taken into account when crisp categorizations of denominations are further interpreted.

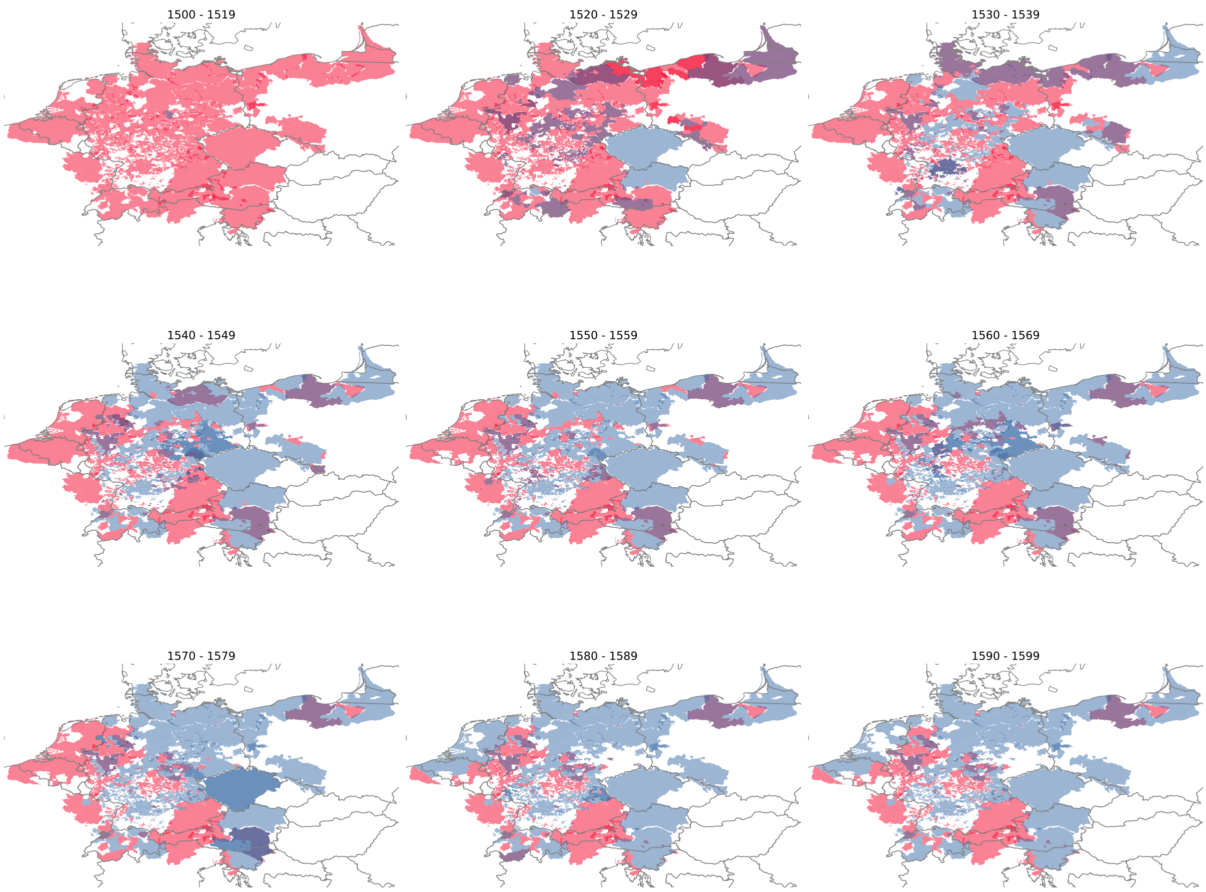


Figure 9: Adopted denomination of territories across time
protestant catholic mixed
Territories switched their state during the examined period and are therefore plotted on top of each other. A change of state can be due to (1) territories changing their denomination within Protestantism (e.g., Bohemia), (2) territories uniting with other territories into larger ones (e.g. Liegnitz-Brieg and Wohlgau are united), or (3) territories splitting into smaller territories (e.g., Pommern splits into Pommern-Stettin and Pommern-Wohlgast).

4 Discussion

I have presented two methods to compile a spatial data set of territories of the Holy Roman Empire in the 16th century. This data set is useful to study geographic and geo-political aspects of the Reformation.

With the manual method, I manually traced the border of territories on modern political maps and combined the resulting polygons with attributes I had manually looked up on Wikipedia. In the use case of this paper, the manual method provided temporal data because I considered changes in territories' attributes. The manual method also optimized for the choice of the examined historical period because maps with Reformation-relevant territories were available. With the automatic method, I extracted polygons of the territories from their color values on a modern political map and used a spatial join to combine those polygons with attributes I had crawled from Wikipedia. The automatic method is reproducible and time saving. Both methods are flexible since they can be enriched with all sorts of territory attributes or geo-spatial information.

By constructing exemplary statistical measures and visualization, I provided a glimpse of how the generated data could be used for quantitative analyses of the Reformation. Confessionalization, the spread and insitutionalization of Protestantism, could be studied through neighborhood and power relations between territories. Mobility in the 16th century could be studied through travel routes of scholars which could be mapped to the territories they traverse. Reachability of territories could be studied by locating geographic landmarks, like rivers and mountain ranges, in the territories to investigate the ease of dissemination of information.

Both, the manual and automatic methods have limitations which affect the conditions under which they should be used. The manual method is time consuming because polygons have to be traced manually. This also reduces the reproducibility of the method. Since the manual method used several maps, georeferencing results in different projected geo-coordinate systems which cause the resulting polygons to overlap. This will lead to ambiguous mappings if we want to locate specific places inside of territories, such as whereabouts of individuals. In the use case of this paper, the automatic method faced a mismatch in historical periods because the original map depicted the HRE around 1400 whereas the resulting territories were filtered for the 16th century. As a result, the polygons did not correspond well to the territory names extracted from Wikipedia. Although many HRE territories are covered on Wikipedia the amount of available structured data is small and the resulting data set is not as rich as the manual one.

These limitations provide some guidelines for future usage and improvements of the presented methods. Both methods yield optimal results if polygons are extracted from one rather than several maps and if the original map depicts the historical period of interest. The manual method should be used if a small number of territories is processed and only low-quality maps are available, such as historical maps with heterogenous color values per polygon. The automatic method should be used if a large number of territories is processed and a high-quality colored political map is available. If Wikipedia is used as a source, the automatic method should be used if static data is sufficient because Wikipedia does not yet provide temporal data in a structured format. However, the coverage and quality of Wikipedia data or other data sources is likely to improve in the future, making the restriction to static data for the automatic method no longer necessary.

The presented methods are not restricted to the use case of 16th century territories but can be applied to other geographic areas and historical periods. For example European colonization of Africa could be studied in terms of changes of territory borders that were constructed on drawing boards (Bassett, 1994; Lefebvre, 2011).

In summary, I presented a methodology to generate spatial data of territories from political maps. The methodology is reproducible because many steps are automatized. The methodology is flexible because the generated data can be enriched with all sorts of territory-specific attributes. The methodology is generalizable because it can be applied to territories of other geographic areas and historical periods. In the use case of this paper, the spatial data of 16th century HRE territories will help to investigate the geo-spatial aspects of the Reformation.

Disclosure statement

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this article.

Data availability statement

The data generated with the methodology of this paper are available in the ETH Research Collection (Roller, 2021b,c). The associated source code is available in the ETH Data Archive (Roller, 2021a).

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A Georeferencing

Georeferencing projects an internal coordinate system of a raster map onto a geographic coordinate system. This is achieved by locating points on the raster map for which geo-coordinates are available. If a sufficient number of these points are provided and evenly spaced across the map an internal coordinate system can be computed.

Georeferencing in QGIS is done via the Georeferencer GDAL plugin. To enable this plugin, select Plugins ➔ Manage and Install Plugins and enable the Georeferencer GDAL plugin in the Installed tab.

I upload a PDF raster map to the georeferencer and select the following transformation settings.

- Transformation type: Thin Plate Spline
- Resampling method: Nearest neighbour
- Target SRS: EPSG:4326 - WGS 84
- Output raster: file name of georeferenced map + file type (geotif =.tif)
- Save GCP points: ticked (allows to modify the internal coordinate system of georeferenced maps)
- Load in QGIS when done: ticked (loads georeferenced map in QGIS where it can be validated)

Per map, I look up the geocoordinates of around 20 locations, mark them on the map and provide the longitudes and latitudes (Fig. 10). For most locations I use the towns that are drawn on the map, and for some locations I use geographic landmarks like river bends or coastlines. After having marked 20 locations I add additional locations until the residuals of the individual locations are reduced (Fig. **??**). The smaller the residuals the more accurate the georeferencing. Once georeferencing is complete I validate the result by overlaying the georeferenced map with the countries and cities maps from the Open Source Natural Earth data set (*Natural Earth*, 2021) (Fig. **??**). If my georeferenced cities are in the same locations as those in the validation set georeferencing was successful and I use the georeferenced map for polygonization..

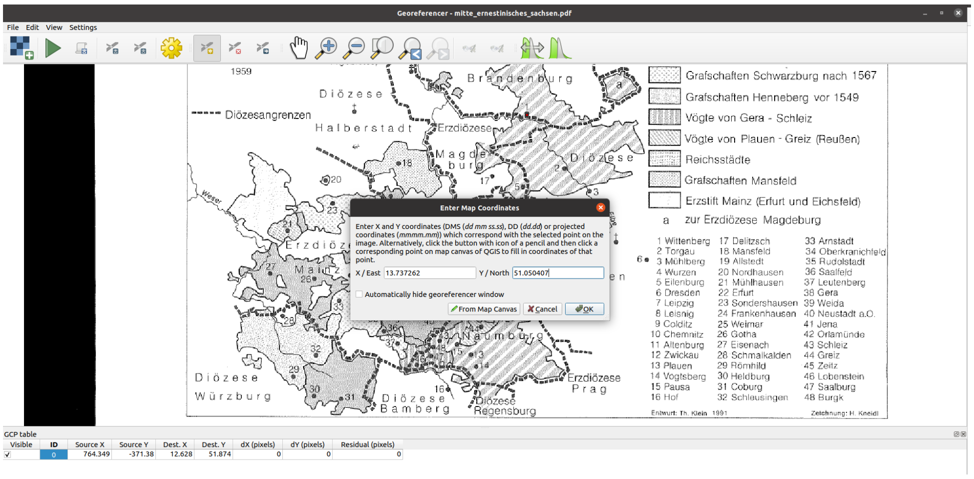


Figure 10: Georeferencing the map of Ernestinian Saxony. Geocoordinates of Dresden are added with the georeferencer tool in QGIS. The geocoordinates of Wittenberg have already been added.

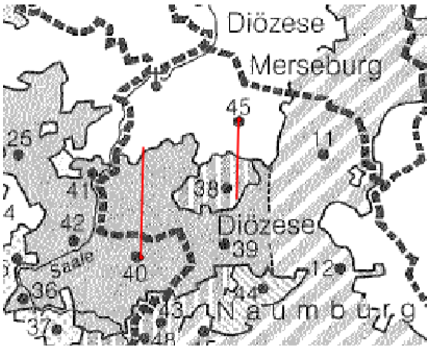


Figure 11: Residuals of two geo-coordinades provided during georeferencing

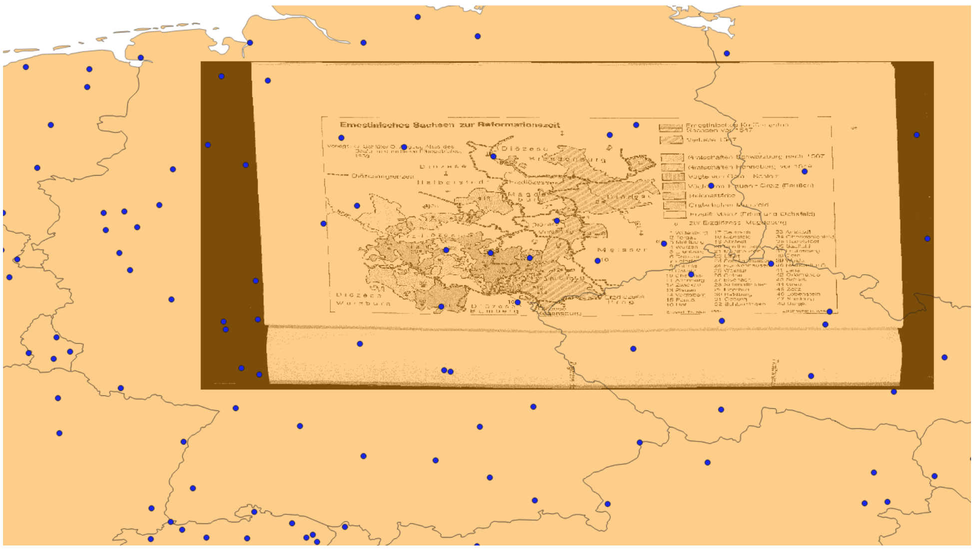
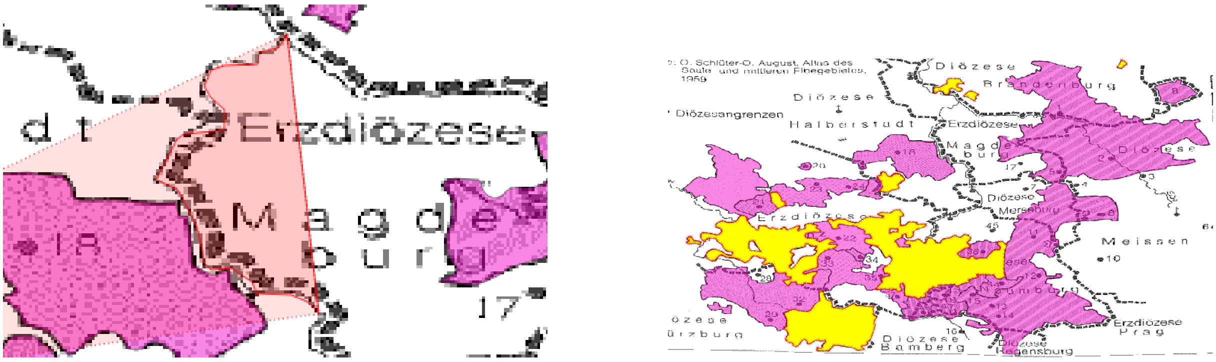


Figure 12: Validate georeferencing result with country and ciy map of Earth Natural lowers

B Manual polygonization

Polygonization extracts shapes from maps with their geocoordinates. I upload my georeferenced map into QGIS and add an additional shapefile layer to the project. For this layer, I select polygon as geometry type and add id_name as attribute field. This id_name will later be used to merge polygons with the Wikipedia entries into territories. I activate the new shapefile layer, enable editing, and add a polygon feature by tracing the border of the polygon on the map with the mouse cursor (Fig. 13a). Once the polygon is saved I provide an id_name (Fig. 13b). To avoid intersections and small gaps between polygons I tune the snapping options by selecting Project ➔ Snapping Options ➔ Advanced Layer configuration ➔ Avoid intersection + enable items on previous layer (Enable snapping on intersection) + 10 pixels. I screen the generated polygons for invalid shapes with QGIS' validation function: Processing ➔ Tools ➔ Vector geometry ➔ click validate. I export the resulting polygons as a shapefile.



(**a**) Polygon tracer in progress (**b**) Final polygon after tracing

Figure 13: QGIS polygon tracer

C Raster bands

The original and georeferenced PDF-maps consist of pixels which store color values and are arranged in a grid, the raster. The color of a pixel is a mixture of the three primary colors red, green, and blue. Values of each primary color are stored in a separate grid, the raster band, and raster bands are layed ontop of each other to yield the color value of the pixel (Fig. 14). For example, if a pixel appears green on the map, its corresponding value in the green raster band is high whereas the values in the red and blue raster bands are small. Pixels of the same color have the same raster band values.

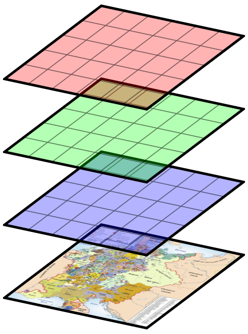
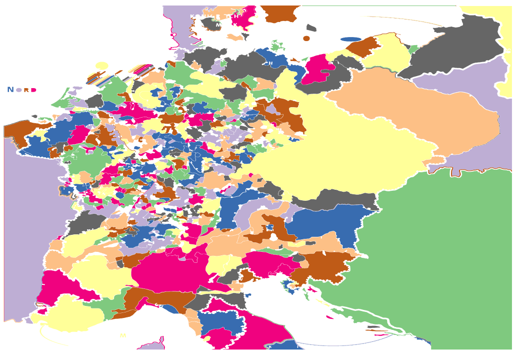


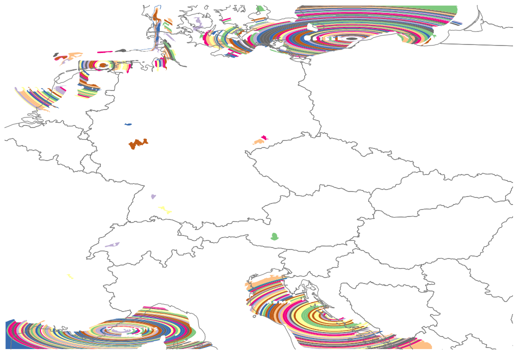
Figure 14: Raster bands layed ontop of each other define an image.

D Overlay polygons of different raster bands

Figure 15 shows the polygons that are kept and discarded during the overlaying step, where polygons of the three raster bands are matched.



(a) Kept polygons



(b) Discarded polygons

Figure 15: Extracted polygons after overlaying polygons of the three raster bands. 15a shows the polygons that could be mapped to all three raster bands in color and those that could not in white. 15b shows that the unmapped polygons are mainly seas and lakes. These polygons are blue and therefore do not have values in the red raster band and hence no corresponding red polygons. The arrangement of sea polygons into concentric ellipses captures the color style of the seas on the map where areas of dark blue fade out into lighter ones (banding).

E Attributes from Wikipedia

E.1 Manual

id_name Unique name of the territory during a particular historical period. Used to map Wikipedia entries to polygons. For example, ernestinian Saxony (after 1547).

territory_name Name of territory independent of historical period. For example, although ernestinian Saxony changed its territory and type of rule over time, all its instances are called ernestinian Saxony.

territory_start Founding year of the territory. This is equivalent to the earlier of the start dates of secular and ecclesiastical rule.

territory_end Year when the territory ceased to exist. This is equivalent to the later of the end dates of secular and ecclesiastical rule.

territory_secular_rule Type of secular rule in the territory. For example, margraviate or duchy.

territory_start_secular_rule Year when the territory adopted a particular type of secular rule.

territory_end_secular_rule Year when a particular type of secular rule ended in the territory.

territory_ecclesiastical_rule Type of eclesiastical rule in the territory. For example, archbishopric or abbey.

territory_start_ecclesiastical_rule Year when the territory adopted a particular type of ecclesiastical rule.

territory_end_ecclesiastical_rule Year when a particular type of ecclesiastical rule ended in the territory.

territory_religion Official denomination of the territory. For example, Lutheran or catholic.

territory_start_religion Year when the territory adopted a particular denomination.

territory_end_religion Year when a particular denomination ended in the territory.

alliances Whether the territory was part of the Schmalkaldic League (SL), an alliances of protestant princes, or part of the Catholic League (CL), and alliances of princes who were loyal to the Emperor.

start_alliance Year in which territory joined alliance.

capital_name Name of the territory's capital. For example, Dresden for ernestinian Saxony after 1647.

capital_lat_long Latitude and longitude of the capital in decimal degrees.

book Volume of Schindling and Ziegler (1989-1995) where the map of this territory was taken from. The book series covers five regions of the Holy Roman Empire, one per book: **SW**: Südwesten (southwest), **SO**: Südosten (southeast), **MD**: Mittleres Deutschland (central Germany), **NO**: Nordosten (northeast), and **NW**: Nordwestem (northwest). If *book* is given but *id_name* is empty, the territory is covered by Schindling and Ziegler (1989-1995) but not included because its geometry is too complicated. This is the case for the Imperial knights in the siuthwest of the HRE. If *book* is empty but *territory_name* is given, the territory is covered on Wikiedpia but not by Schindling and Ziegler (1989-1995). For example, the margraviate of Baden-Hachberg or the county of Reuss. These territories were discovered during the research and considered to be important. It can be used for other analyses that do not require a geometry.

region Bookchapter in Schindling and Ziegler (1989-1995) where the map of this territory was taken from. For example, Kurpfalz (Electoral Palatinate) and ernestinisches sachsen (ernestinian Saxony).

source URL to the website where information on the territory was found. Mostly Wikipedia.

table_on_wikipedia Whether or not the Wikipedia page of this territory has an infobox.

E.2 Automatic

E.2.1 Fully-structured crawl

old_name Name of territory together with its type of rule or an indication to a specific Wikipedia page. For example, "Überlingen#Freie Reichsstadt" or "Wissembourg#Geschichte".

modern_name Name of territory.

type_of_rule Type of secular or ecclesiastical rule in the territory. For example, margraviate or bishopric.

modern_country Country the territory is part of today. For example, "Germany" for ernestinian Saxony.

wikipage Identifier of the territory's Wikipedia page used by `wptools` (Siznax, 2018).

wikibase Unique key to access the Wikidata page of the territory.

description Short summary of the territory's history.

instance_of Higher-order category on Wikidata the territory belongs to. Often this attribute refers to the modern state of the territory. For example, the previous imperial city Buchau is today called Bad Buchau, because of its thermal springs and rehabilitation facilities. Buchau is an instance of a "spa town".

inception Founding year of the territory.

dissolved Year when the territory ceased to exist.

religion Official denomination of the territory. For example, Lutheran or catholic.

geoLoc Longitude and latitude of one point inside the territory in decimal degrees.

capital Name of the territory's capital. For example, Dresden for ernestinian Saxony after 1647.

E.2.2 Semi-structured crawl

The meaning of the following attributes is equivalent to the ones in the fully -structured crawl: old_name, modern_name, type_of_rule, modern_country, instance_of, inception, dissolved, religion, capital.

infobox Whether or not the Wikipedia page of the territory has an infobox.

infobox_keys List of territory attributes covered in the infobox.

F HRE-specific infobox of Wikipedia

Figure 16 shows the infobox of the Wikipedia page of the Margraviate of Baden. Infoboxes like this are used to crawl Wikipedia attributes in the automatic semi-structured method.

Figure 16: Wikipedia infobox of the Margraviate of Baden

G Missing values of Wikipedia attributes

Table 2 shows the number of missing values for selected attributes for the manual method and the fully- and semi-structured crawls. We see that the automatic methods yielded almost three times as many territories as the manual one (806 vs 303). This is because the automatic crawl was not restricted to the 16th century and therefore returned entries on all territories that have ever existed in the HRE. Filtering for 16th century territories discards most of the entries as the large number of missing values for the dates of inception and dissolution show. In the manual data many missing values occur for the type of ecclesiastical rule. This is not of great concern because many territories did not have an ecclesiastical ruler so their type of rule is only secular. In contrast, the large number of missing values for alliances is not balanced by another attribute and therefore has to be used with caution in future analyses.

Table 2: Number of missing values of non-spatial attributes from three extraction methods: manual, fully- and semi structured.

	Manual		Automatic	
	Temporal* (558) UoA: temporal state of territory	Aggregated* (303) UoA: territory	Fully† (806) UoA: territory	Semi† (806) UoA: territory
Name	0	0	0	0
ID maps to polygon	35	20	-	-
Date of inception	58	35	413	679
Date of dissolution	49	27	472	600
Type of secular rule	19	14	17	17
Type of ecclesiastical rule	492	260	-	-
Religion	21	13	732	615
Start date of denomination	37	19	-	-
End date of denomination	29	16	-	-
Alliance	456	250	-	-
Capital	9	5	594	598
Geo-coordinates of the capital or of another location within the territory	9	5	451	0

( ): Total number of entries

UoA: Unit of analysis

* Historical period is restricted to the 16th century

† Historical period includes the complete HRE period (800-1806). Restricting the historical period to the 16th century discarded all entries.

H Rank types of rule

Types of rules are ranked to get an ordinal measure of power status. The lowest rank corresponds to the most powerful type of rule and the largest rank to the least powerful one. The ranking is inspired by the remarks of the Holy Roman Empire Association (*Structure of the Holy Roman Empire*, n.d.). The ranking is neither static nor universal because types of rules were volatile, mixed with each other, and ambiguous in their meaning since the same title could mean different things in different parts of the Empire or during different historical periods. Thus, the ranking serves as an explorational tool for power status rather than an established measure thereof.

1. Electorate
2. Imperial territories (e.g., imperial city, free city, imperial county, imperial abbey)
3. Kingdom, archduchy, archbishopric
4. Duchy
5. Principality, bishopric
6. Palatine county
7. Margraviate
8. Langraviate
9. Princly county
10. County of the Empire
11. County, abbey
12. Lordship
13. Bailiwick, vest
14. City
15. French city

I Manual polygonization results in overlapping polygons

Figure 17 shows the overlapping polygons of ernestinian and albertinian Saxony. Since these two territories were depicted on separate maps, georeferencing resulted in different projected geo-coordinate systems: one for each map. These overlaps do not cause a problem when mapping polygons to Wikipedia entries because this mapping is based on a manually engineered index. however, it will cause a problem when spatial joins will be used in the future to map polygons to other locations, such as the whereabouts of scholars.

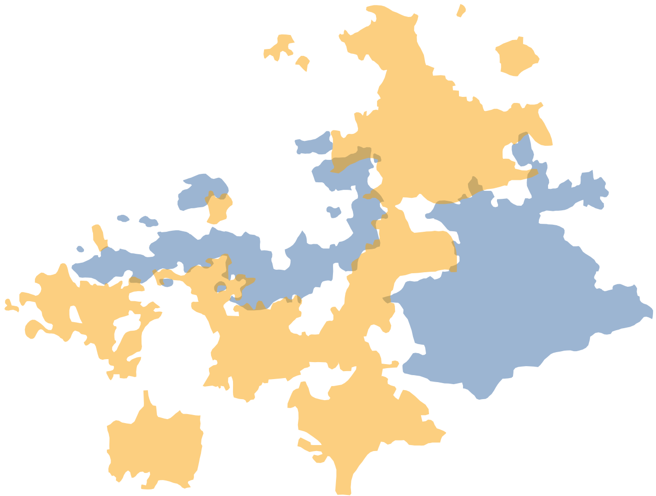


Figure 17: Overlapping polygons as a result of manual polygonization. Since maps were georeferenced separately the projected geo-coordinate systems do not align and polygons overlap.

ernestinian Saxony (before 1547) albertinian Saxony (before 1547)