The potential of old maps and encyclopaedias for reconstructing historic European land cover/use change [1]

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Abstract

Continental to global reconstructions of historic land cover/use are important inputs for many environmental, ecological and biogeochemical studies. While local to regional reconstructions frequently make use of old topographic maps and land use statistics, continental to global reconstructions are mostly model-based reconstructions. As a result they are subject to large uncertainties. A wealth of historic land cover/use maps and statistics have been produced and these are now more accessible due to the ending of copyrights and secrecy statuses, enthusiastic hobby communities and national cartographic institutes or cadastres that have a strategy towards data sharing with society. In this paper we made use of historic statistics and old topographic maps to demonstrate the added value for model-based reconstructions of historic land cover/use for Central Europe back to 1900. We harmonized these diverse data types and different types of historic land data were incorporated into the land use reconstructions. The added value of using these data was evaluated using historical maps by performing a reconstruction with and without the historic information. The accuracy of the land allocation in the historic reconstruction was improved by 16.5% using historic maps. Additionally, historic maps improved the representation of the spatial structure of landscapes. The historic land cover/use statistics used showed a strong agreement with independent estimates, like historic maps.

Introduction

Historic land cover/use data at large scales (Hurtt et al., 2006, 2011; Kaplan, Krumhardt, & Zimmermann, 2009; Klein Goldewijk, Beusen, & Janssen, 2010; Klein Goldewijk, Beusen, Van Drecht, & De Vos, 2011; Pongratz, Reick, Raddatz, & Claussen, 2008; Ramankutty & Foley, 1999) have improved our understanding on how humankind altered our planet during the Anthropocene (Ellis et al., 2013) and helped to study effects of land change trends and transitions on environmental and ecological processes (Foley et al., 2005). Information on historic land cover/use provides insights in the cultural heritage of landscapes (Plieninger, Hochtl, & Spek, 2006). Moreover, historic reconstructions are a fundamental data source to estimate greenhouse gas emissions and to understand the evolution of the biogeochemical cycle (IPCC, 2013). Many local to regional reconstructions are based on old topographic maps and land use records (Bicik, Jelecek, & Stepa'nek, 2001; Carni, Jarnjak, & Ostir-Sedej, 1998; Godet & Thomas, 2013; González-Puente, Campos, McCall, & Muñoz-Rojas, 2014; Jawarneh & Julian, 2012; Marull et al., 2014; Orczewska, 2009; Petit & Lambin, 2002; Skalos et al., 2011; Skokanova' et al., 2012). However, at continental and global scales, most reconstructions of historic land cover/use are modelled based on population statistics and scarce historic land cover/use data. As a result, there is a large uncertainty in these reconstructions (Klein Goldewijk & Verburg, 2013). Several authors have mentioned that more historic data are needed to reduce the uncertainties in reconstructions (Fuchs, Herold, Verburg, Clevers, & Eberle, 2014; Gaillard et al., 2010; Klein Goldewijk & Verburg, 2013).

A broader use of available historic input data would help to verify, correct or withdraw assumptions used in historic reconstructions. It is hypothesized that the use of multiple harmonized land cover/use statistics and maps would lead to improved estimates of change trends and better spatial allocation of historic change.

The current use of historic data is limited due to a number of constraints: the need for harmonization across different inconsistent data sources, the different acquisition techniques used (sampling, aerial photographs, remote sensing) and the data formats (from analogue prints to digital data and from hand drawn survey maps via aerial photographs to digital remote sensing data). In addition, in many cases land cover/use data were published in local languages, requiring local knowledge to read them. Copyright, national interest, competition and secrecy (e.g. military maps) prevented the accessibility. Furthermore, changing country borders, especially in Europe, made it hard to compare any area related statistics.

Despite these constraints, a wealth of historic land cover/use data have been produced over decades and centuries. Nowadays, this type of data is becoming more and more accessible due to the ending of copyrights, e.g. for historic land cover/use maps (Schlueter, 1952, 1953, 1958) and encyclopaedias with statistical information (Bibliographisches Institut, 1909; Chisholm & Phillips, 1911). The ending of secrecy statuses for historic military maps eases accessibility, e.g. for soviet military topographic maps (Vlasenko, 2008). Many enthusiastic communities have started to collect and share historic land cover data (e.g. Rumsey, 2014). National cartographic institutes and cadastres have an increased willingness for transparency, open data policy and data sharing with society (Bundesamt fuer Kartografie und Geodaesie, 2014; Centro National de Information Geografica, 2013; Eotvos University Department of Cartography and Geoinformatics, 2013; Geoportail, 2013a, 2013b; Koningklijke Bibliotheek van Belgie, 2014; Mapster, 2014; National Libary of Scotland, 2013; University of Stockholm, 2013a, 2013b).

The objective of this paper is to make use of historic statistics and topographic maps to improve a historic reconstruction of land cover/use for Europe and evaluate the added value of using such additional data. In this paper the focus will be on the forest/non- forest classification. Section 2 describes the methods used to harmonize historic statistics and incorporate historic maps into land use reconstructions for Europe. Section 3 explores the added value of such data in reconstructions of land cover/use. This is followed by a discussion in Section 4.

Material & methods

Study area and period

The different data types (historic statistics and maps) explained in this section were available for almost whole Continental Europe for different time steps. However, in order to demonstrate the application of the methods and their added value we focused for this paper on the time around 1900 and an area that we defined as Central Europe. This area comprised in our definition the following countries: Germany, Luxemburg, Poland, Czech Republic, Slovakia, Austria, Hungary, Romania, Bulgaria and Slovenia (Fig. 1). In total, the study area covers more than 30% of the EU27 area. We have chosen this study area to prove the added value of historic maps and statistics, first, for a considerable large area of Europe and, secondly, to avoid the explanation of too many different data sets that otherwise would have been required for this study. Further- more, we focused on the year 1900 since this year was the starting year of our model reconstruction of historic land cover/use, later on explained in this paper.

Data

Historic maps

For our analysis we used historic maps from two large scale surveys: The ‘Generalkarte’ (general map) of the 3rd Military Mapping Survey of the Austrian-Hungarian Empire (Eotvos University Department of Cartography and Geoinformatics, 2013) and the Central European land cover map of the protohistoric settlement areas in Europe (Schlueter, 1952, 1953, 1958). Table 1 gives an overview of the features of the maps and Fig. 2 illustrates the coverage for each data set. The Schlueter map was scanned full colour with 600 dots per inch (dpi) in TIFF and A0 format in order to get a digital version. A high number of dpi assured that linear features in the map (letters, roads, land cover class borders) could be represented with enough detail and later on be classified separately. Furthermore, a high number of dpi prevented blurring of colours around edges of land cover classes. The map tiles of the Austrian-Hungarian Empire were already scanned. The ‘Generalkarte’ of the Austrian-Hungarian Empire map is the coarsest map (1:200000) with the largest area coverage of all three mapping activities of the 3rd Military Mapping Survey (namely ‘Aufnahme- blaetter’ (1:25.000), ‘Spezialkarte’ (1:75.000) and ‘Generalkarte’). The ‘Generalkarte’ consisted in total of 265 map sheets of which the first tiles were printed in 1887. The Schlueter map only consisted of one map sheet that was printed in the 1950's. Both maps display the land cover/use around the year 1900, the starting date of our historic reconstruction.

Statistics

We used sub-national statistics of the Meyers Conversation Encyclopaedia of 1909 (Bibliographisches Institut, 1909), which refers to official statistics around the year 1900. The encyclopaedia is digitally available at www.zeno.org and statistics can be found under the German name of the countries and provinces. A list of available statistics for countries and provinces within todays territory of the European Union can be found in Appendix A. We provided their German and English name. For this paper we only made use of country and province statistics that fall within our study area

Overview of the methods

The methodological approach of this paper consists of three major steps (Fig. 3). The first step comprised the georeferencing and classification of the historic maps into forest/non-forest, followed by a qualitative analysis of the classification results. Secondly, we performed the collection and reconstruction of historic statistics of around 1900. This included the border correction of historic to present borders and consistency checks of the reconstructed statistics with statistics of recent decades, but also with independent statistics of the same time. The third step integrated both previous steps into a reconstruction approach of historic land cover/use. Two data sets were produced (one with using historic map information, one without; both used the same historic statistics) to assess the added value of using historic maps as data input for historic reconstructions.

Methodology

Pre-processing and classification of historic map

We georeferenced and projected the maps into an equal area projection (ETRS Lambert) in order to enable comparing areas. The age difference of the prints and probably also the storage of the maps explained why some map tiles were more affected by bleaching than others. The bleaching altered the colour information of each map tile differently and prevented an automated classification by colour. Therefore, we had to digitize the individual map tiles of the 3rd Military Mapping Survey of AustriaeHungary by hand. The Schlueter map on the other hand was hardly affected by bleaching.

We collected 100 training areas for each land cover/use class, including letters printed on the map, and performed a supervised maximum likelihood classification. To remove the letters from the final land cover/use classes, we first used an expand filter, which creates a buffer zone around pixels of a class, of three pixels (1 pixel ca. 77.45 m) to remove enclosed letters within a land cover/ use class area. In a second step a shrink filter, which removes the buffer zone again, of three pixels was applied to return the outer edges of a land cover/use class area to its original state. The threshold of three pixels for each filter in our case proved to be the optimum to remove letters.

In order to assess and compare the quality of both classifications we analysed the classification results of each data set with 100 randomly stratified sample points and calculated the overall accuracy. Half of the sample points were taken from the forest stratum and half from the non-forest stratum.

Data preparation and border correction of historic statistics

Land cover/use statistics for reconstructions are commonly gathered and compared on national scale. Due to the frequently changing national borders in Europe our statistics of 1900 had to be corrected for present-day borders to make them comparable with recent data. To allow such corrections, we first had to reconstruct historic national and sub-national borders for the year 1900 to give all available statistical information a consistent spatial identity. Sub-national statistics enable merging different provinces together in ways that the merged provinces resemble present countries. Present country borders often developed from former sub-national administrative units. An example is Czech Republic, which evolved from the former provincial borders of Moravia, Bohemia and Austrian Silesia. We used political maps of the year 1900 from the Meyers Conversation Encyclopaedia (Bibliographisches Institut, 1909) to digitize and georeference historic borders. Map coordinates and unique landmarks (churches, coastal shapes, crossroads) were used for georeferencing.

After the reconstruction of historic national and sub-national borders, we linked the resulting vector data set with land cover/ use statistics for cropland, forests, grassland (including pastures and natural grassland) and other land (including urban and infrastructure) of the Meyers Conversation Encyclopaedia (Bibliographisches Institut, 1909). Land cover/use statistics were used and aggregated, where necessary, to the four abovementioned target classes (Appendix A).

The final vector file with statistical information of 1900 was converted into a raster data set in equal area projection (ETRS Lambert) and overlaid with a vector file of current national borders. Thereby a spatial resolution of 1 km by 1 km was chosen that was sufficient to represent the details of the country border shape. In a final step, we calculated the average land cover/use fraction of all raster cells within the individual country borders for each land cover/use class. We reconstructed the statistics for all EU27 member states including Switzerland (Appendix A and B), but for this paper we focused only on the reconstructed statistics within our study area. For some of the sub-national units of 1900 (Appendix A and B) the land cover/use information could not be reconstructed due to missing statistics. These administrative units were then not considered in the calculation of the average land cover/use fraction. In order to assess the quality of the reconstructed statistics we cross-checked their values with independent data sources of the same time (e.g. with historic maps) or with recent statistical data sources (e.g. Baŕatossy et al., 1996, 2001; Czuraja, 1982; Food and Agriculture Organization of the United Nations (FAO), 1947a, 1947b, 1948, 2012a, 2012b).

Integration of historic maps and statistics into reconstructions

We integrated the results of the maps and statistics into a model-based reconstruction approach (Historic Land Dynamics Assessment (HILDA-v2.0) (Fuchs, Herold, Verburg, & Clevers, 2013, 2014). The approach is based on allocating national level land cover/use statistics through probability maps derived from associations between location factors and current land cover/ use. We modified the approach of Fuchs et al. (2013) by incorporating our country border corrected historic land cover/use statistics into our data base of stable country border statistics for recent decades. This allowed us to generate a time series for each land cover/use class over the last 110 years on a national scale.

To fully use the potential of historic maps, we fed these maps directly into the spatial allocation algorithm of the reconstruction approach. Fig. 4 gives an overview of how the historic statistical and map data were used for the historic reconstruction. The information from the classified historic maps was integrated into the probability maps used for spatially allocating land use. In case of areas covered by both maps the map information of the 3rd Military Mapping Survey of AustriaeHungary was chosen, since the maps of the survey had a higher spatial detail than the Schlueter map. Based on the historic maps we modified the probability maps in such a way that forest would always first be allocated to areas that have forest in the historic maps while retaining the relative probabilities of allocation in the forest and non-forest area. This was achieved by scaling the probability for forest in forest areas between 0.5 and 1, while probabilities were scaled between 0 and 0.5 outside the forest area as indicated in the historic maps. This allows spatial allocation of the statistical areas also in case of absence of a perfect match between historic statistics and forest area in the historic maps.

Probability maps mainly provided information where a change had likely taken place, but rarely when. By incorporating historic land cover/use maps for allocation purposes, the difference between maps related to different time periods only provided information whether a land change had taken place within the period the maps covered. Sometimes these periods could span several decades, which made it hard to assign the change of a certain location to a certain time.

To improve the forest probability maps for different time periods, we incorporated volume stock maps of Gallaun et al. (2010). Volume stock information contains temporal information of the age of a forest, which can be related to forest changes. The assumption was that the higher the volume stock of a forest the older the trees are and therefore the forest. The age of trees in a forests was used to describe the persistence or vulnerability of a forest to change. In the back-casting reconstruction procedure for decreasing forest area this meant that pixels with the lowest volume stock value were converted first to other land cover/use classes, while pixels with the highest values were converted last. We scaled the volume stock maps between 0 and 1 and multiplied them with our forest probability maps. Then we rescaled the probability maps again between 0 and 1.

Assessment of the added value of historic maps in reconstructions

In order to demonstrate the added value of historic maps for the allocation process, we processed one reconstruction of the last century with historic map information and one reconstruction without that information. We compared the forest areas of the two classification results with the forest areas of the historic maps and calculated the producer's accuracy, user's accuracy, overall accuracy and the total error. The forest areas of the historic maps are considered in this case as reference. The different accuracies can be expressed as follows:

$$\text{Producer's accuracy} = \frac{\text{\# of pixels correctly classified as forest in the model}}{\text{\# of all forest pixels in historic maps}} \times 100$$

$$\text{User's accuracy} = \frac{\text{\# of pixels correctly classified as forest in the model}}{} \times 100$$

# of all forest pixel in the model

Overall accuracy = # of pixels correctly classified / total # of pixels x 100

Total error = 100 – Overall accuracy

The land cover/use statistics of 1900 from the encyclopaedia were used as input for our model approach to reconstruct the area extent for each class in 1900. Due to the reconstruction method of the encyclopaedia statistics these national values might differ from the derived forest area of the historic maps. The difference of these two independent estimates affects the total error in our assessment. However, in our accuracy assessment we want to describe the quality of our model reconstruction. Therefore, we have to calculate the final model error, which was calculated as follows:

Final model error = total error – area difference between maps & encyclopaedia statistics

We calculated each of the accuracy parameters for the combi- nation of all countries that were part of the study area.

Results

Classified historic maps for the year 1900

The results both of the automated and manually classified forest areas around 1900 are highlighted in purple in Fig. 5. The Schlueter map and all available mapping tiles of the 3rd Military Survey of the Austrian-Hungarian Empire are shown in the background.

A detail of the two map types and their classification results can be seen in Fig. 6. The top left (Schlueter) and top right (3rd Military Mapping Survey) of Fig. 6 show the original maps without the classification results but both with the same map extent, depicting the greater area of Vienna in Austria. Fig. 6 bottom left and bottom right highlight the classification results of forest in purple on top of the maps. Fig. 6 bottom left shows the result of the maximum likelihood classification after additional filtering to remove letters. Fig. 6 bottom right shows manually digitized forest areas, again with the same map extent.

Due to the different scale of both maps (see Table 1), the map of the 3rd Military Mapping Survey shows a higher level of detail than the Schlueter map. However, bleaching effects of the map tiles and shading made it difficult to distinguish the colour information. The automated classification with filtering was adequate in the Schlueter map, but parts of some letters could not be removed. The original Schlueter map did not distinguish between wooded wet- lands and non-wooded wetlands. For that reason the wooded wetlands of the Danube river were not classified as forest in the Schlueter map.

We assessed the quality of both classification techniques with 100 randomly stratified sample points for each data set. Thereby 50 sample points covered classified forest and 50 points non-forest areas. In the Schlueter map 47 sample points of non-forest and 41 sample points of forest were correctly classified, leading to an overall accuracy of 88%. The assessment of the

3rd Military Map- ping Survey of AustriaeHungary showed that 47 sample points of non-forest and 44 sample points of forest were correctly classified that totalled up to an overall accuracy of 91%.

Historic land cover/use statistics for the year 1900

Fig. 7 (left) illustrates the reconstruction of historic national and sub-national borders for forest (a), cropland (b), and grassland (c), respectively. The reconstruction of borders enabled to assign land cover/use statistics to every administrative region for the year 1900. Administrative regions with no information of specific classes were left blank. In Fig. 7 (right) the current country borders and the conversion of land cover/use statistics of the year 1900 into raster format with 1 km spatial resolution is depicted. With the conversion into raster format every 1 km grid cell contained the information of its former administrative unit. This enabled to assign every grid cell value to a country and calculate the average per administrative unit. The derived values represent the relative area coverage of a class for the associated country. Appendix A contains a complete list of derived land cover/use statistics for forest, cropland and grassland from the Meyers Conversation Encyclopaedia for every national and sub-national unit.

Through a closer look at the time series for individual countries we compared the reconstructed land cover/use values of 1900 with the reported numbers derived from other sources. Fig. 8 shows examples for changes in forest cover/use, such as Germany and Poland (Fig. 8 top). Both countries have a lot of statistical information available, especially after the end of the 2nd World War. During the period between the two World Wars there were hardly any data available. For that reason it was important to derive forest estimates for the year 1900 that could be used as a starting point for modelling. The blue cross symbol in 1900 visualizes the land cover/ use estimates from encyclopaedia statistics. Although both countries experienced frequently changing country borders throughout the century the statistical information for 1900 could be derived from sub-national land cover/use information of that time. Fig. 8 shows that the reconstructed values for the two countries were in agreement with the independent estimates from historic maps (red (in web version) diamonds) and with the overall land cover/ use trend.

The reconstructions for Hungary and Slovakia were deviating compared to the previous example (Fig. 8 bottom). Similar to Germany and Poland, Hungary and Slovakia had frequently changing country borders throughout the last century. However, in 1900 both countries were part of the Kingdom of Hungary (not to be confused with the Hungarian Empire). For the Kingdom of Hungary we only had national statistics available and no subnational data of the different regions. The Kingdom of Hungary consisted mainly of the agricultural plains around Lake Balaton and the mountainous region with forests in the north. Therefore, the land cover/use classes were unequally distributed in the kingdom. One drawback of using area statistics found in encyclopaedias is that an equal distribution of the land cover types across the territory is assumed. After the fall of the Kingdom of Hungary the country was split into the different countries. The present areas of Hungary and Slovakia were part of it. Slovakia mostly contained the mountainous forest areas, whereas Hungary comprised the agricultural plain area. Fig. 8 nicely shows how this spatially unequal distribution affected our time series. The blue (in web version) crosses are clearly deviating from the overall land change trend. The estimates for forest seem to be too high for Hungary and too low for Slovakia. The comparison with historic maps for the same time indicates how far off the statistics might be.

Reconstruction of historic land cover/use and assessment of the added value

We incorporated the classification of the historic forest areas into our reconstruction approach to support the spatial allocation of historic statistics and compared it with the reconstruction that had no supporting information of historic maps. For all countries of our study area the result of that comparison is shown in Fig. 9. In the upper part of Fig. 9 (top left and right) the different results of the historic reconstruction for the year 1900 can be seen. Fig. 9 top left depicts the reconstruction results with no supporting information by historic maps and Fig. 9 top right depicts the results of the reconstruction with historic map information.

Although both methods allocate the same amount of land cover/ use area per class to each country it can be seen that the reconstruction results in Fig. 9 top left and right clearly differ. The forest in Fig. 9 top left is allocated predominantly to the mountainous areas in the region, indicating a strong dependency of the probability maps on terrain features. Instead, the forest in Fig. 9 top right appears more heterogeneously distributed, reflecting the influences of landscape fragmentation.

The accuracy of the allocation process in both reconstruction methods is shown in the lower parts of Fig. 9 (bottom left and right). The green (in web version) and white colours in both parts of the Figure highlight the agreement in forest and non-forest areas, respectively, between the reconstruction and the historic maps. The red colour (in web version) indicates where the forest was found in the historic maps but not in the historic reconstruction (false negative). Orange (in web version) shows where the historic reconstruction allocated forest areas differently from the historic maps (false positive).

By comparing the two accuracy results spatially, it can be seen that the reconstruction with historic maps as support information for allocation (Fig. 9 bottom right) achieved a better agreement with the historic maps than the reconstruction without historic map information (Fig. 9 bottom left). The agreement in forest cover between maps and the reconstruction that made no use of historic maps was mainly obtained in mountainous regions. Instead, the reconstruction with historic maps had major areas of disagreement in some specific countries, like Slovakia, Romania, Czech Republic and Austria.

The overall accuracy of the reconstruction without historic maps was 73.71%. For the reconstruction with historic maps the overall accuracy was 90.15% (Table 2). Both reconstruction methods used statistics as input data for the forest area coverage per country. This amount could differ from the forest area coverage per country obtained by the historic maps. In total this difference was 2.78% for the whole area. In order to calculate the model error by the reconstruction approach the difference between statistics and maps had to be subtracted from the total error, which is the complement of the overall accuracy.

The reconstruction without historic maps had a final model error of 23.51%, whereas the model error with the use of historic maps was reduced to 7.07%. In other words, the accuracy of the reconstruction was improved by using historic maps as supporting information for allocation by almost 16.5%.

A detailed overview of country specific accuracies is given in Appendix C. The overview shows that the majority of the disagreement shown in Fig. 9 bottom right is subject to the difference in forest area coverage between statistics and maps. For instance, Romania gave an overall accuracy of ca. 85%, but only 0.16% of the error is explained by the reconstruction method. The vast majority is explained by the difference between statistics and maps. The same effect also appeared for countries like Slovakia or Slovenia.

Discussion

Accuracy of data and data processing

Most of the techniques used in this study, such as digitalization of analogue maps, automatic land cover/use classification or spatial allocation of information, are standard tools in geographic information science and remote sensing image processing, and have proven to be valuable for optimally using the information available in historic sources. Historic maps usually contain already a spatial reference and thematic content, which makes them often easier to process than raw satellite images or aerial photographs. However, the spatial scale, text, contour lines and the quality of the paper print (bleaching) influenced the required effort and final quality of our classification. Very old printed maps like the 3rd Military Mapping Survey had to be classified manually, significantly increasing the effort. The accuracy assessment of the classified maps with the chosen classification technique showed an overall accuracy of 88% relative to the original Schlueter map and 91% relative to the original 3rd Military Mapping Survey of AustriaeHungary. Problems in the manual digitization arose mainly when the green forest areas were covered by contour lines or when the green colour in the maps was bleached. It was to the judgement of the digitizer to decide which areas belonged to forests. In case of doubts, additional expert judgement was consulted and/or colour contrast was enhanced to improve visibility of the green forest areas. To consistently use historic maps in a land use reconstruction model the minimum mapping unit (MMU) for the historic maps should at least match the spatial resolution used in the reconstruction model. Preferably, the spatial resolution of the historic maps should be several orders of magnitude higher. In our case the maps had an MMU of 62 m2 (3rd Military Mapping Survey) and 77 m2 (Schlueter) while the reconstruction model was applied at a1 km2 resolution, thus ensuring a good match.

We also assessed the quality of the used historic maps itself. Our encyclopaedia data confirmed the forest areas in the maps with relatively small deviations (on average 2.78%, but up to 22.5% for some countries). Reasons for deviations could be attributed to the mapping technique, the minimum mapping unit and the used forest definition.

Added value of historic data in historic reconstructions

We demonstrated that historic national and sub-national data for Europe from around 1900 could be gathered from various sources, such as maps and statistics, and incorporated into re-constructions of historic land cover/use. Many large scale historic reconstruction models rely on assumptions for the period before the end of the Second World War. In this context, large scale historic data before that period are a valuable data input for these models. We showed that reconstruction models could reduce their modelling error by using historic data and we presented a set of tools in this study that allowed to expand and apply these tools to other periods and to other regions.

The reconstruction approach without the use of historic maps tended to allocate forest as large continuous areas preferably in mountainous regions as a result of the assumed strong influence of terrain factors (e.g. slope or altitude) on the allocation. This approach ignored fragmentation effects of landscapes and could be seen as an artefact of the reconstruction approach if no historic maps are used. In order to assess the difference in spatial allocation pattern amongst the reconstruction approaches we calculated the number of patches and the average area of the patches for the original historic maps, the rescaled historic maps to 1 km spatial resolution and the two different reconstruction results for their overlapping areas (Table 3). Table 3 confirms our visual interpretation of Fig. 9 that the reconstruction approach using historic maps is better able to represent the spatial structure and fragmentation of forest areas. The reconstruction using historic maps was, for both historic maps, closest to the number of patches and average patch size of the comparable historic map at 1 km spatial resolution. The reconstruction without historic map information resulted in more ‘clumped’ forest areas (less patches but bigger patch sizes).

Implications of using historic data in land reconstruction approaches

Historic data, especially from multiple data sources, can be used in reconstructions for verification and each implemented data set can potentially correct for biased assumptions used during the interpolation of data between years and areas.

Historic land cover/use data can hardly compete with current data as they mostly lack the spatial detail and coverage, the temporal frequency or the thematic class depth of present products. However, most of the historic land cover/use products are of surprisingly good quality, since they were intended for census, taxation or military purposes where quality standards were high and crucial. Mapping techniques, map projections and statistical methods at the beginning of the 20th century were at advanced levels. Old topographic maps have several advantages. Historic maps are already georeferenced and classified. They do not suffer from atmospheric influences (e.g. cloud cover or haze) as is often the case in remote sensing images. This sometimes makes them more valuable than early satellite products (e.g. Landsat images of the 70's) that have many limitations. Historic mapping surveys measured land cover/use directly in the field, providing field measurements, semantic expert classification (e.g. for land use) and validation in a single source. Europe is a special case where the wealth of historic land cover/use data is a result of the existence of the many small countries where each country conducted its own surveys. The frequent military conflicts among the European countries (e.g. the two World Wars and the Cold War) led to a vast amount of data sets. This allows a comparison of multiple data sources for the same time period. Colonisation, the Cold War and proxy wars (Korea, Vietnam, Afghanistan, Middle East, etcetera) expanded the mapping and statistical activities of industrialized countries to many other regions in the world (Bibliographisches Institut, 1909; Chisholm & Phillips, 1911; Mapster, 2014; Nyssen & Petrie, 2013; Rumsey, 2014; University of Texas Libraries, 2014; Vlasenko, 2008).

Global land cover/use reconstructions can make use of historic statistics and extend their input data base in many regions of the world by several decades up to centuries. Another possibility would be to validate the assumptions and allocation approaches of global reconstructions by comparing their results with historic maps and statistics. In some regions, especially in Continental Europe, data sets from the 18th century onwards exist that allow to analyse the industrial revolution period (Centro National de Information Geografica, 2013; Geoportail, 2013a, 2013b; Koningklijke Bibliotheek van Belgie, 2014; Mapire, 2015; Mapster, 2014; Rumsey, 2014).

Different research fields, such as environmental, ecological and biogeochemical sciences (e.g. on climate change), will benefit from improved, extended and less uncertain land cover/use change databases at large scales.

Conclusion

In this paper we described a set of methods required to enable the use of historic data in model-based reconstructions of historic land cover/use, including changing historic national borders, correction of statistics for such changing borders and the automatic classification of historic land use maps. Our results confirmed that the concept of a data driven reconstruction model for historic land cover/use improved the modelling accuracy as compared to a traditional approach based on assumptions and proxy variables for the spatial allocation and land change trends. We showed that historic reconstruction models can make use of historic statistics when statistics are corrected for changing country borders. By implementation of historic forest maps we reduced the modelling error of forest/non-forest areas by about 16.5%. Furthermore, historic maps not only improved the reconstruction of the quantity and location of forest/non-forest areas, but also the structure and shape of these landscape elements. The current trend of open data policy with historic land cover/use data should be seen as a chance to close data gaps and to promote model-based reconstructions of historic land cover/use. The open access of archives offers a unique opportunity and potential to look back in Europe's land cover/use history, over large areas and multiple centuries.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at doi:10.1016/j.apgeog.2015.02.013.

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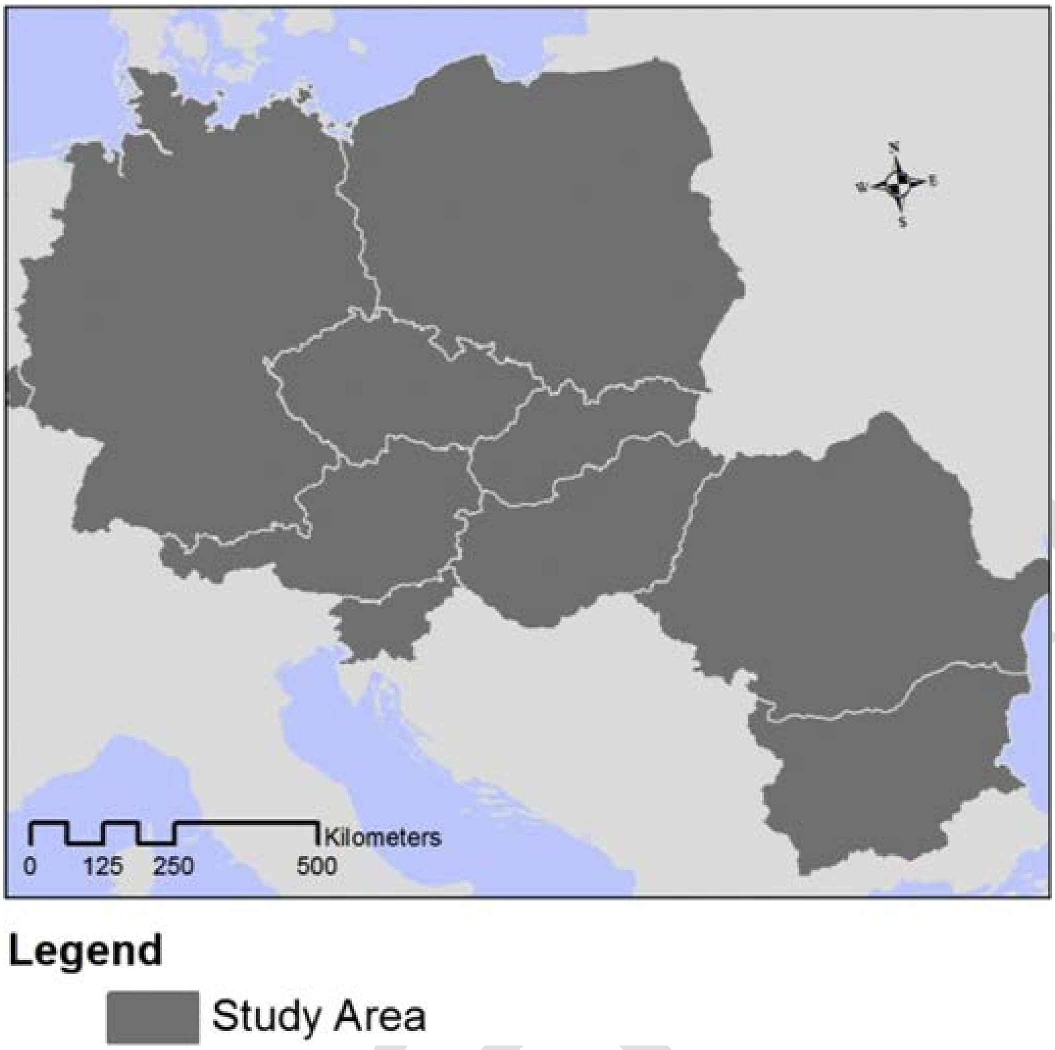

Fig. 1. Overview of the study area.

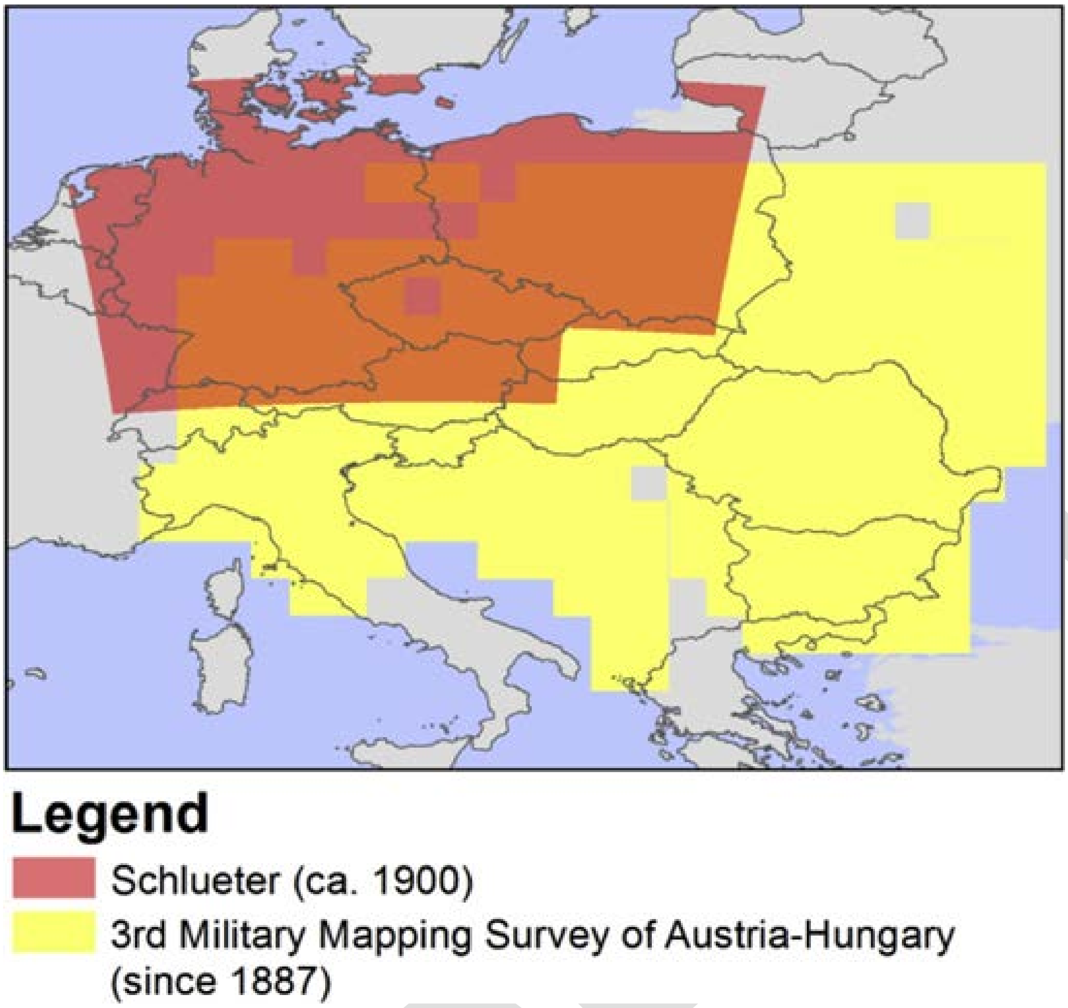

Fig. 2. Overview of historic map coverage.

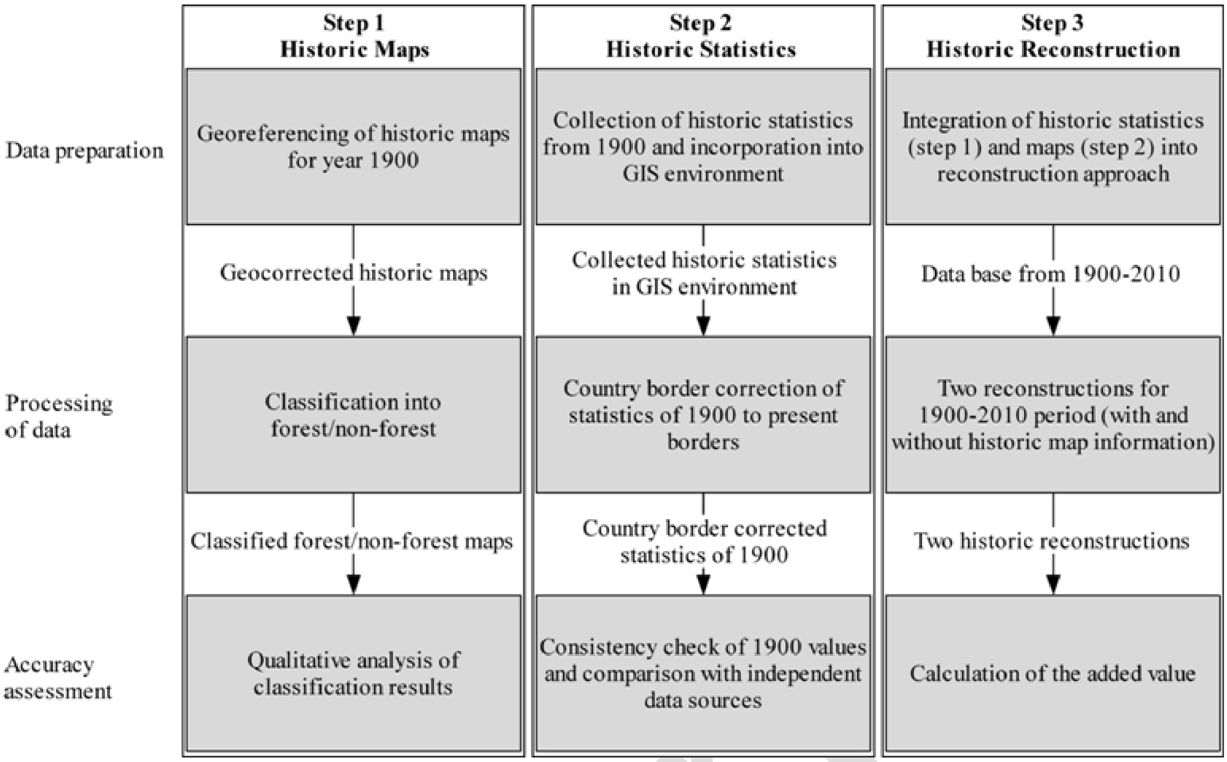

Fig. 3. Methodological approach of this paper.

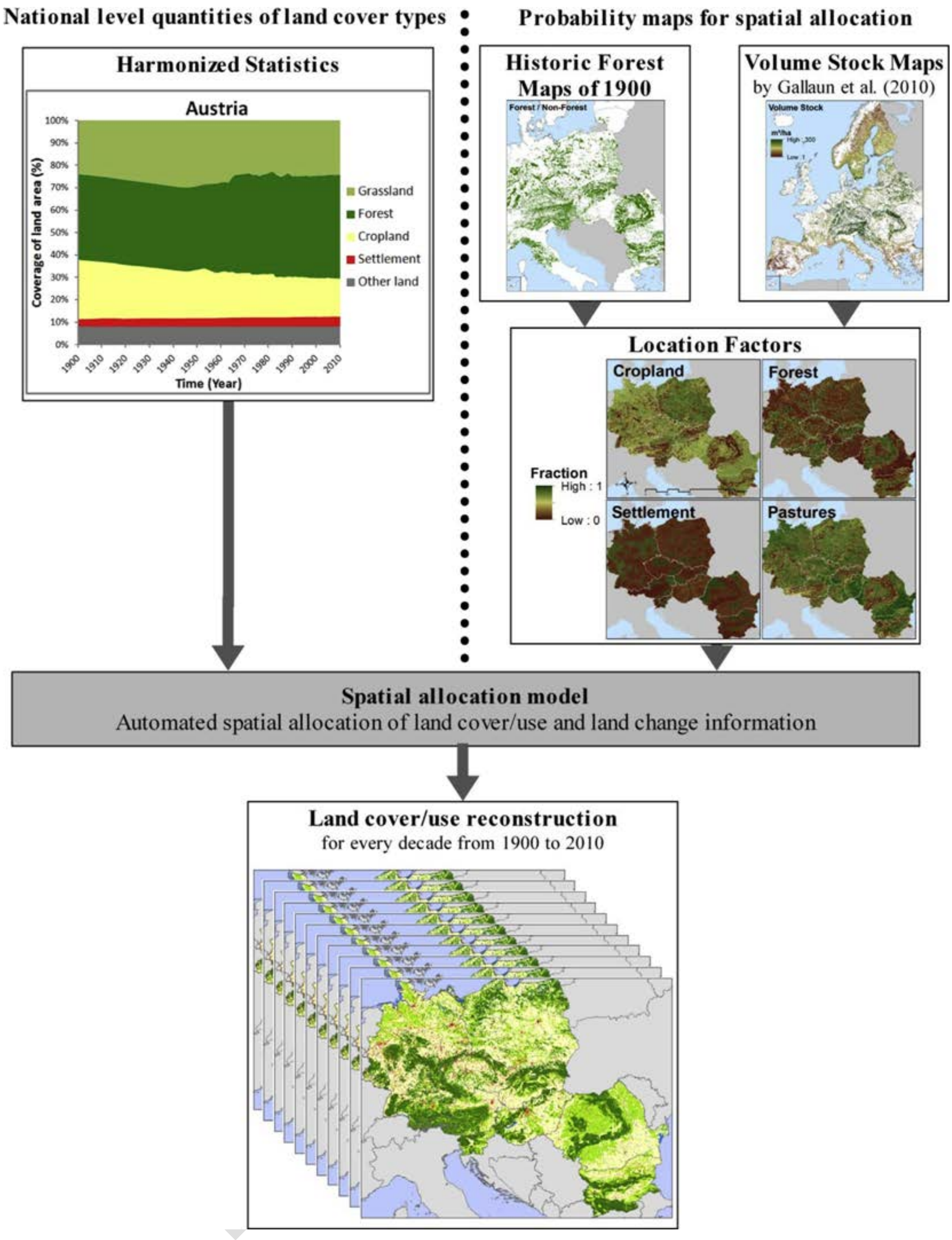

Fig. 4. Approach used in this study for the reconstruction model.

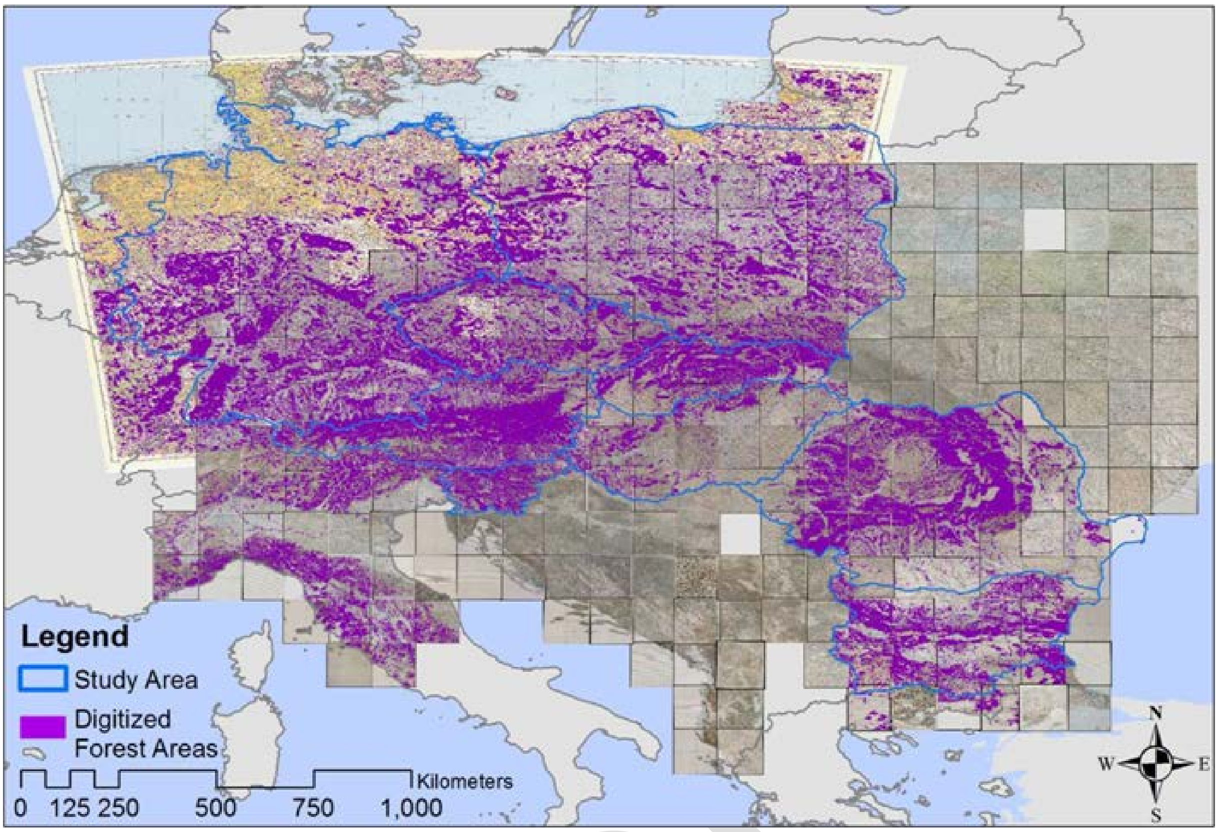

Fig. 5. Results of both the automated and manually classified forest areas around 1900 highlighted in purple. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

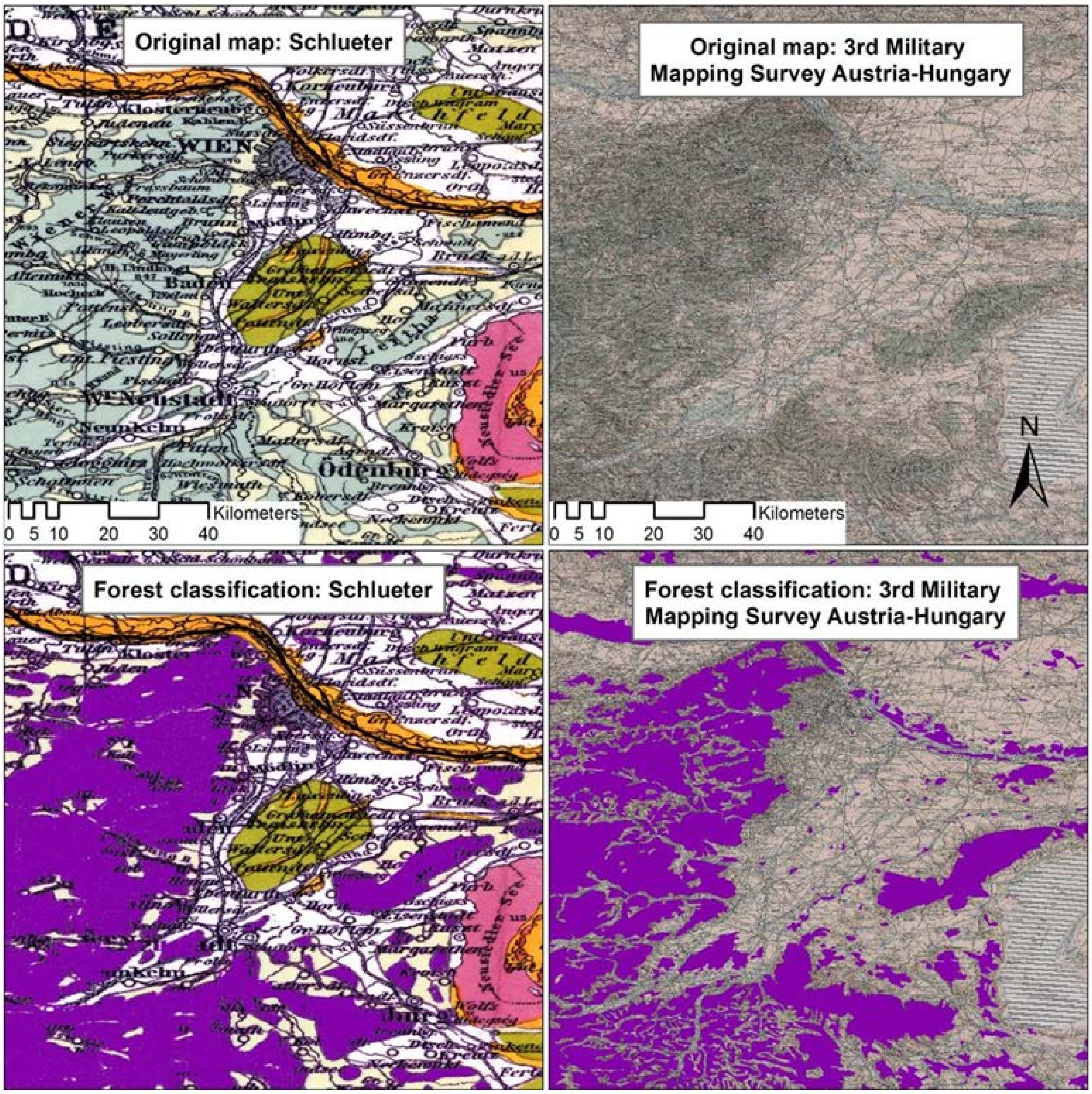

Fig. 6. Original maps and classification results of historic forest area around 1900 (in purple) showing greater Vienna (AT). Left: Schlueter (forest area is result of the maximum likelihood classification with additional filtering to remove letters) Right: 3rd Military Mapping Survey AustriaeHungary (forest area is manually digitized). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

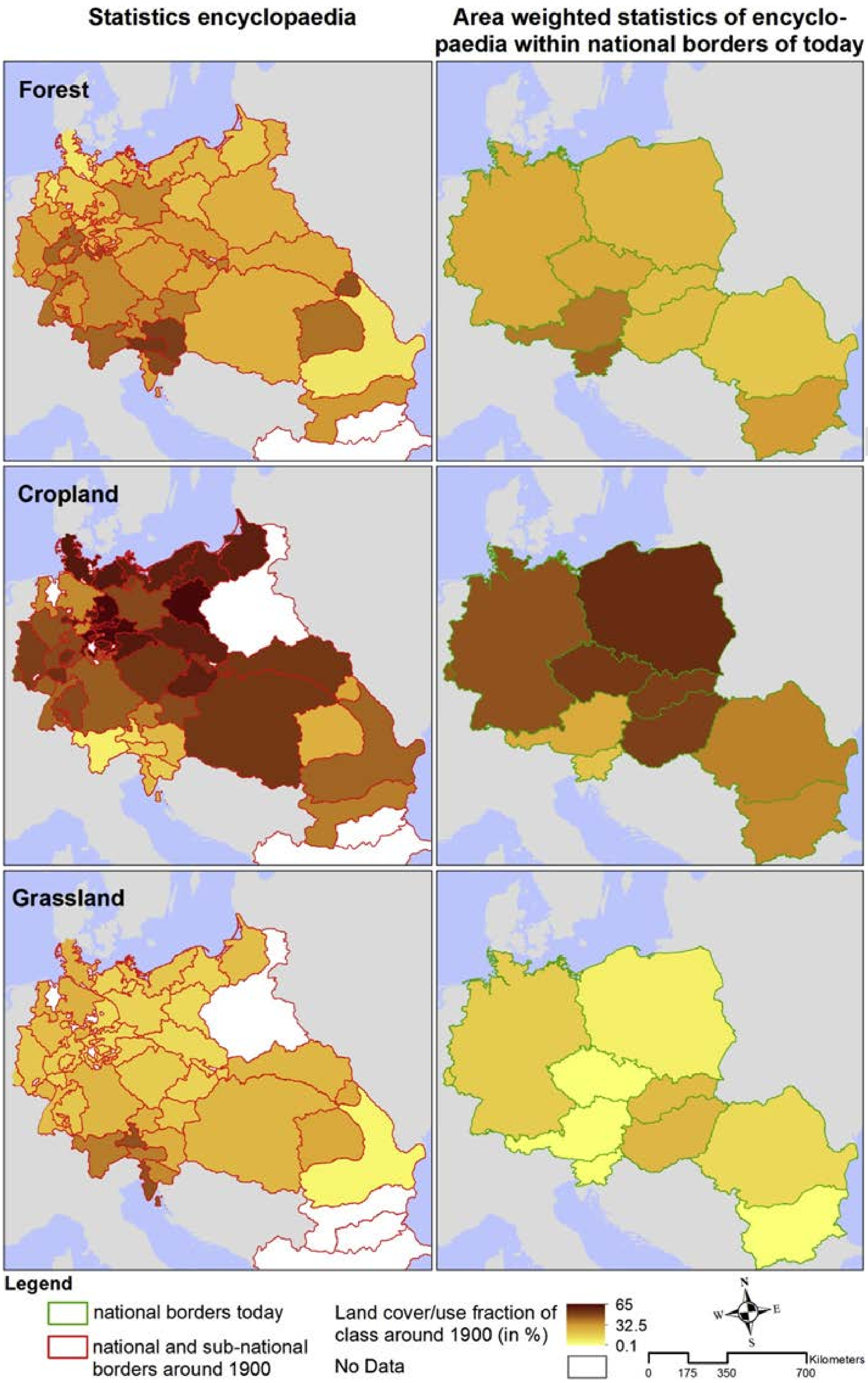

Fig. 7. Reconstruction result for historic national and sub-national statistics around 1900 derived from encyclopaedia.

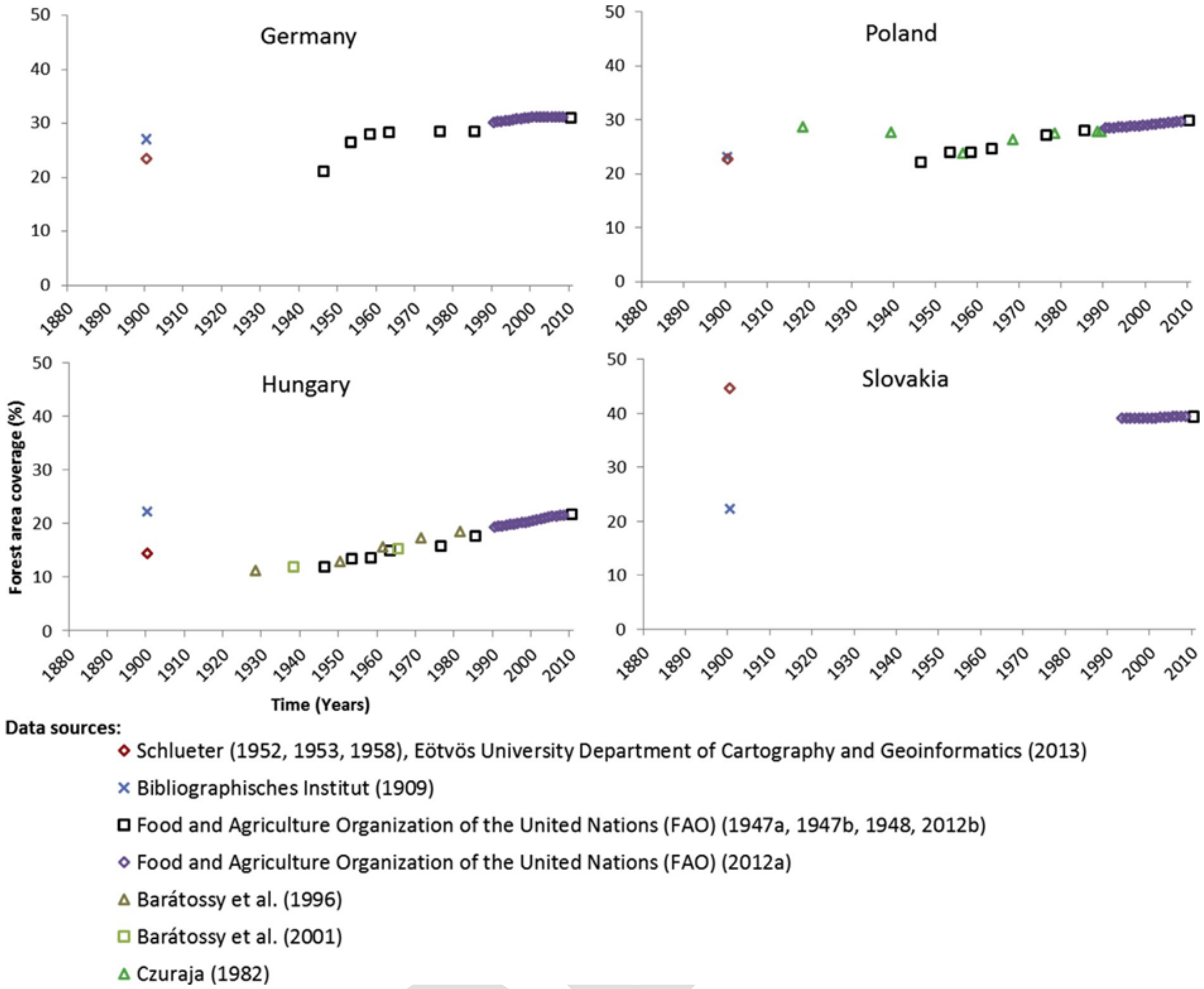

Fig. 8. Integration of reconstructed forest statistics of 1900 with other statistical forest data sources for different countries.

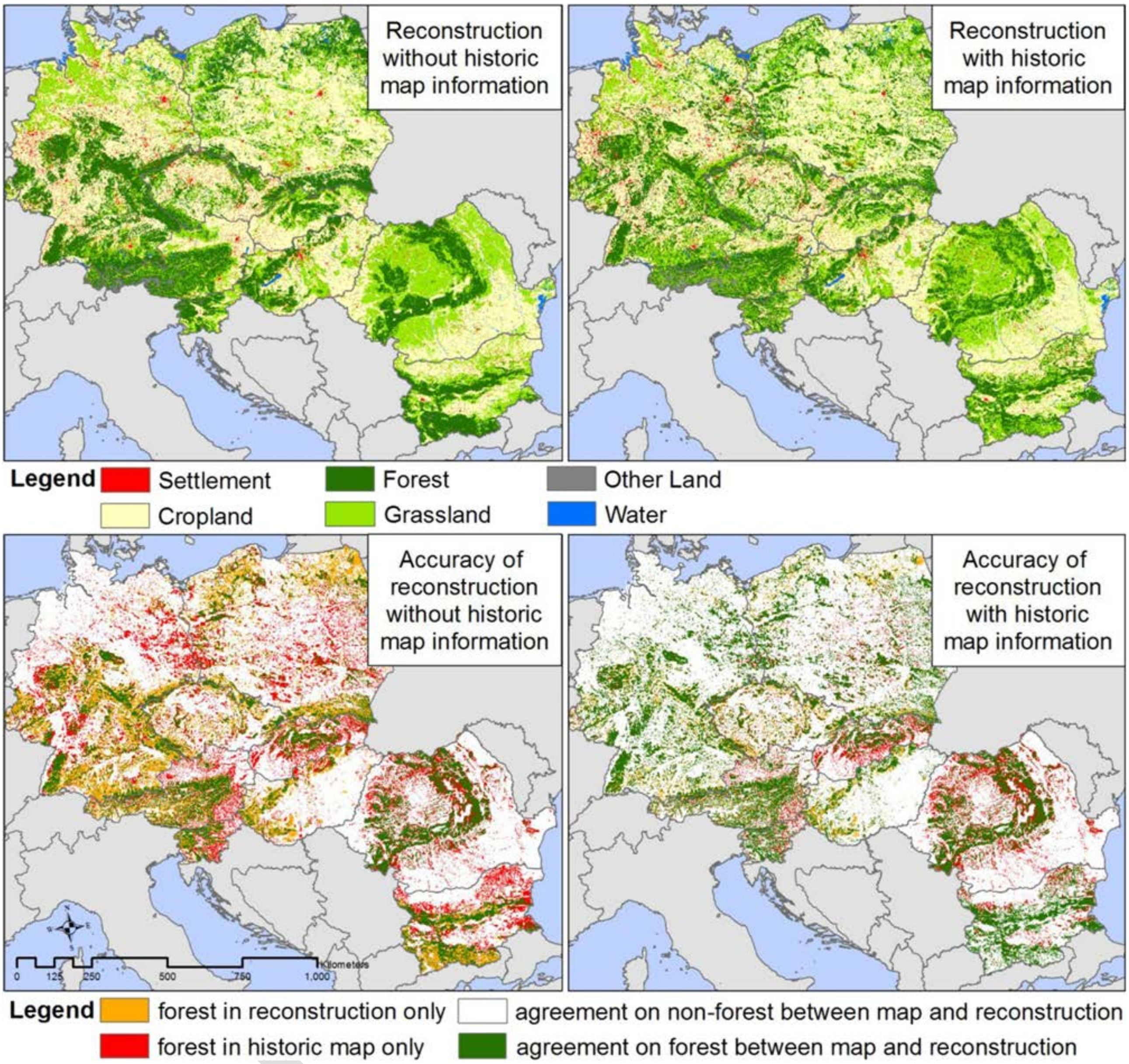

Fig. 9. Reconstruction results for the year 1900 for countries which were completely covered by historic maps (top) and accuracy assessment of the reconstruction results (bottom).

Table 1. Features of used historic maps for the reconstruction of historic land cover back to 1900.

Map name	Area coverage	Covered period	Land cover/use classes	Spatial scale
3rd Military Mapping Survey of Austria–Hungary (‘Generalkarte von Mitteleuropa’, 265 map tiles)	2,122,916 km²	Around 1900	1 forest, 2 settlements and roads 3 agricultural areas	1:200000
Otto Schlüter – Die Siedlungsräume Mitteleuropas in frühgeschichtlicher Zeit	916,513 km²	Around 1900	1 forest (around 1900 A.D.) 2 forest (cleared since 900 A.D.) 3 forest (cleared before 900 A.D.) 4 forest–heath areas 5 ice and rocks 6 natural high-altitude grazing areas 7 settlement areas in prehistoric times 8 swamp (around 1900 A.D.) 9 former swamp 10 sea marshes	1:1500000

Table 2. Overview of accuracy assessment for the whole study area showing results for the reconstruction with and without the use of historic maps. A detailed overview of accuracies per country can be found in Appendix C.

All 10 countries	Reconstruction with historic maps	Reconstruction without historic maps
Producer's accuracy	77.70%	48.80%
User's accuracy	86.15%	53.93%
Overall accuracy	90.15%	73.71%
Forest area in historical statistics	25.52%	25.52%
Forest area in historical maps	28.30%	28.30%
Area difference between map and statistics	2.78%	2.78%
Total error (reconstruction + historic maps)	9.85%	26.29%
Final model error	**7.07%**	**23.51%**

Table 3. Difference in forest fragmentation effects amongst the different reconstruction approaches and historic map sources.

Feature	No. of patches	Avg. area of patches (in km²)
Data set		
Austria–Hungary map original resolution (62 m × 62 m)	34,838	7.55
Austria–Hungary × 1 km resolution	18,922	13.88
Reconstruction *with* historic 1 km map information for Austria–Hungary map area	16,924	12.14
Reconstruction *without* historic 1 km map information for Austria–Hungary map area	8446	25.37
Schlueter map original resolution (77 m × 77 m)	1,048,575	0.09
Schlueter map 1 km resolution	36,408	6.88
Reconstruction *with* historic 1 km map information for Schlueter map area	17,728	11.98
Reconstruction *without* historic 1 km map information for Schlueter map area	14,645	14.52