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Challenges and Possible Approaches for Using GIS as a Tool in Historical Geography Landscape Research: a Meta-analysis Review

Keywords: Land cover; landscape; GIS; uncertainty; completeness; historical maps.

Summary: The use of GIS tools and methods in historical geography (HGIS) has enabled the synthesis and spatial analysis of past landscapes using various sources, including historical maps. Nonetheless, the use of historical maps in GIS raises new challenges. This paper aims to estimate eight main parameters of uncertainty of relevance when examining historical maps. We examined how these parameters were reported and dealt with by reviewing 82 papers published since the 1990s. We found that there was a rise in the use of GIS tools and methods in examining historical maps in the last 20 years. While half of the reviewed papers reported on the registration accuracy of historical maps, most of them did not estimate other sources of uncertainty. This gap in the use of GIS was not due to the lack of appropriate methods. Rather, it seems that researchers are unaware of the importance of reporting and on the ways to do this. Papers published in geographical, GIS and remote sensing journals were more likely to report on uncertainty parameters. In order to encourage the use of uncertainty estimation in HGIS, we review and recommend some of the approaches and best practices in this field.

Introduction

In its basic definition, the field of Historical Geographic Information Systems (HGIS) uses Geographic Information System (GIS) technologies, tools and methods for the study of history (Knowles 2005). From the middle of the 1990s HGIS has become a popular approach and method not only in historical research but also in geographical research (Gregory and Healey 2007, Bailey and Schick 2009). HGIS uses GIS software programs that represent the geographic features on the earth's surface in a digital way. Moreover, GIS software programs allow their users to collect geographic data such as vector shapes (points, lines, and polygons) as well as raster layers (scanned maps, aerial photos and satellite images). In addition to extracting historical data, the particular strength of GIS software programs is that they enable the synthesis and complex analysis of the spatial components of maps in ways which were not possible previously (Gregory and Healey 2007). The use of GIS tools in HGIS research and its final products are not bound only to the 'academic world' but they have far reaching implications in the 'real world' where HGIS methods are used in planning, conservation, law suits and other fields.
Dealing with historical maps, historical geographers have always faced challenges when aiming to interpret past landscapes, due to issues of map accuracy and map completeness. The use of GIS for the study of historical maps enables us to face such challenges in an explicit and quantitative way. The challenges could be divided into three broad areas, the first challenge relates to the procedure of surveying and mapping, the second challenge relates with beliefs and cultural viewpoints which are often projected on the map and the third challenge relates to the reproduction of the map and its transformation to a digital form (Harley 1968, Turnbull 1996,

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Fisher 1999). The first challenge relates to the accuracy of the field survey based on which the historical map was done. This depends on the technology, time and purpose of the survey which has an effect on the accuracy of measurements and position of objects shown on the map. The second challenge relates with how the world was perceived and interpreted. Incomplete information on the map could result from a lack of interest in specific land use and land cover features by past cartographers and surveyors. A map does not necessarily mirror reality precisely but illustrates what the surveyor was interested in, many times by omitting selected types of information (Harley 1989). Occasionally, incomplete information on the map could also be a result of human error (i.e. missing a remote village by mistake). The third challenge relates to errors which may be introduced during the process of map reproduction such as scanning, geo-referencing, digital data processing and digitization (Leyk et al. 2005). Many errors occur due to vagueness and ambiguity of poorly defined features such as forests, which due to their undefined borders and natural vegetation composition, are open to a wide range of interpretations which are not necessarily correct (Fisher 1999, Tucci and Giordano 2011). This is especially challenging when needing to digitize historical maps to a vector model, where objects are supposed to have strict boundaries.

As an example of an error and its persistent occurrence we may mention the example of Lake Salvator in Queensland, Australia which was depicted by Sir Thomas Mitchell in 1846. The land where the lake was depicted by Mitchell was dry with no signs of a lake in a survey done in 1889. Nonetheless, the lake persisted to appear on more modern maps. At the end, an in-depth study was conducted on this lake which found out that this lake has never existed and was probably invented by Mitchell (Finlayson, 1984). This is just one example demonstrating why it is so important to have a critical eye when dealing with historical sources in general and historical maps in particular.

While there are several books and guides that deal with how to employ GIS in HGIS research in general (Gregory and Ell 2007, Gregory and Healey 2007, Gregory et al. 2003, Knowles and Hillier 2008, Knowles 2002), issues of spatial, thematic and temporal uncertainties are still not sufficiently dealt with in the HGIS literature. The aim of this paper was to review different research papers which used GIS tools and methods which focused on land cover / land use changes and to examine how often and in what manner issues of potential errors and uncertainties were dealt with during the process of HGIS research. More specifically, the main aim of this paper was to review the current state of art on how geo-referencing, estimation of uncertainties, categorization and reclassification, feature interpretation, extraction and assessment of information and completeness of information were dealt and reported using GIS tools and methods on land cover / land use changes. We hypothesized that the theoretical understanding of uncertainties in historical maps and more advanced use of HGIS tools will be found in papers published in geographic and geospatial scientific journals.

Methods

In this research we aimed to review ~80 HGIS papers that examined land cover / land use changes using historical maps. The stages of paper selection for this review were divided into four different stages (Fig. 1).

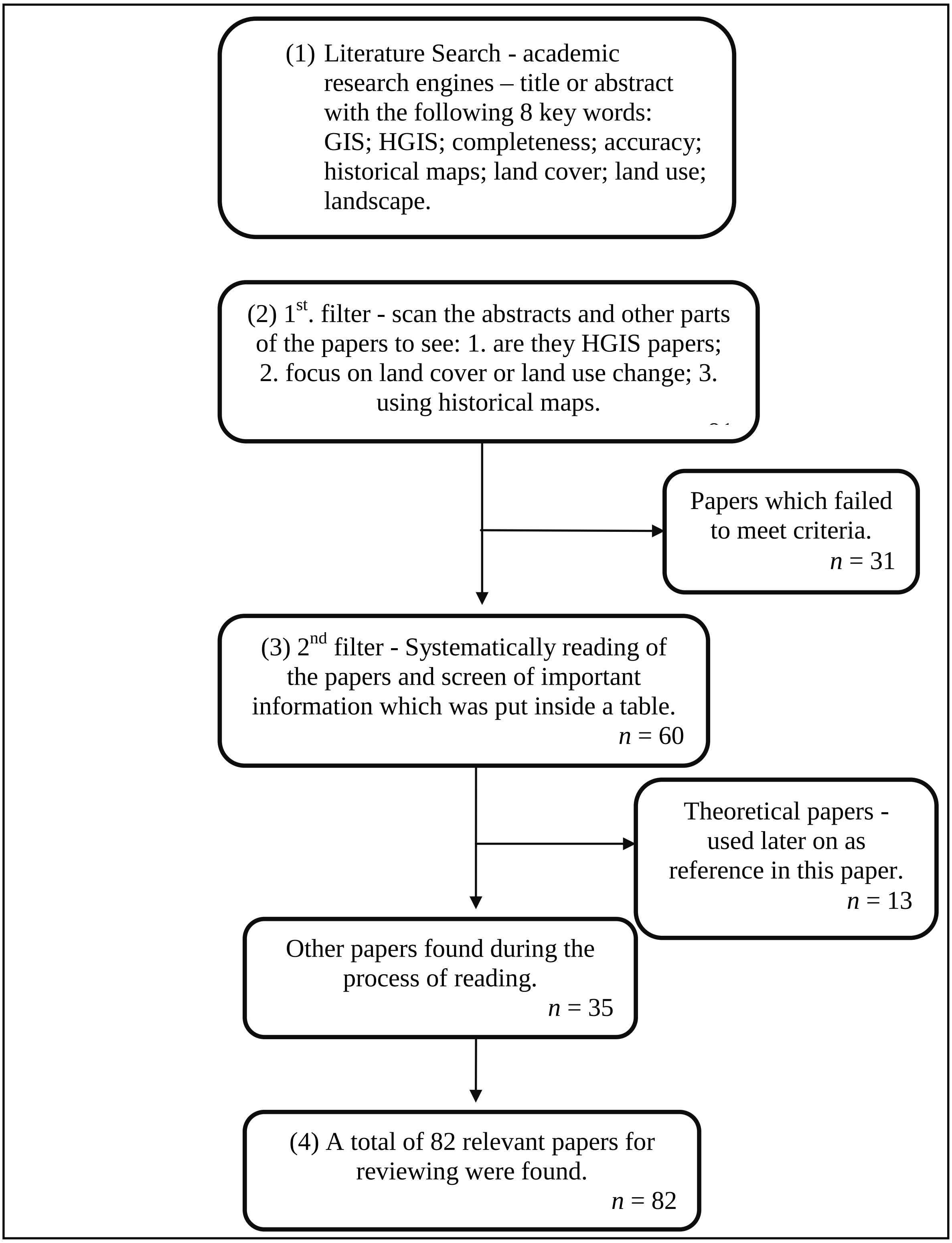

Figure 1. Scheme showing the process of data collection conducted during the research.

The first stage of the research was to identify as many as possible relevant papers that used GIS tools and methods to examine land cover and land use changes from historical maps. This was done using four main search engines: Web of Knowledge (WoK 2013), Engineering Village (EV 2013), Social Science Research Network (SSRN 2013) and Google Scholar (GS 2013). We defined eight different keywords for the search engines, which if appeared in the paper title or abstract would be selected. The list of keywords included: GIS; HGIS; completeness; accuracy; historical maps; land cover; land use; landscape. In this way we identified 91 HGIS papers. The second stage was to briefly go over the retrieved papers and examine if indeed the papers met the criteria mentioned above - whether they were GIS papers using historical maps to study land cover or land use changes. This was done by reading the abstracts and by briefly scanning through the papers' main sections. This stage reduced the relevant papers to 60. In the third stage these 60 relevant papers, were read systematically. We summarized these papers into a table that included general information on the papers (such as longitude and latitude of the research area; year of the main/earliest map used; what were the underlying sources of verification (other maps, aerials, books); what landscape features were examined) and examined our eight parameters (discussed below). Some of the parameters dealing with uncertainties, errors and other issues of using GIS were binary, some were numeric, and others were detailed as text. In this process we found that 13 papers were more theoretical papers and did not have a case study as we were seeking, and in this way the total number of reviewed papers was reduced to 47. However, during the process of reading the different papers we found 35 additional relevant papers which were added to the review. At the end of this process we reached a total of 82 papers.

Once all the information was gathered into one table we calculated how many papers examined and reported the different parameters considered significant for the current study. Each individual paper was subsequently examined in terms of the spatial information provided and different uncertainty parameters reported in their analysis. Papers examining and reporting about different uncertainty parameters, exhibit a greater degree of understanding of the complexities involved in reconstructing past landscapes from historical maps. When examining the use of historical maps in HGIS research there are many different parameters which can be examined. We chose to focus in this article on eight basic uncertainty parameters (presented in Table 1) which are relevant in the analysis of landscapes from historical maps.

In order to examine possible factors, explaining why in some papers more uncertainty parameters were examined and reported, we classified the reviewed papers by the type of journal in which they were published (i.e. GIS journal, geographic journal, ecological journal etc.). The classification of journals was done by using the formal classification used in "Web of knowledge" internet site (WoK, 2013, Web of Knowledge). Once the division was concluded we examined whether in papers published in journals belonging to a certain class, more uncertainty parameters were reported.

Lastly, recommend approaches (best practices) for estimating the uncertainty of each parameter examined were given and were drawn from the reviewed papers and from our own experience in conducting HGIS research (Levin 2006, Levin et al. 2009, Levin et al. 2010, Frantzman et al. 2014, Schaffer and Levin 2014, Schaffer et al. 2015).

Results

The majority of the 82 HGIS research papers reviewed in this paper are from North America (mainly USA) and from Europe. The countries with the highest numbers of papers were the USA (14), followed by Israel (seven), Switzerland, Australia, Belgium and Germany (with four papers each).

Based on our review, it seems that there is an increase in the number of papers using HGIS to study land cover and land use changes since the beginning of the 2000s. We found seven HGIS papers published in the 1990s, 46 published papers in the 2000s and 28 published papers during just the five years period between 2010 and 2014.

While there were five papers which did not report on any of the eight parameters there was also not a single paper which reported on all of the eight parameters. Two papers reported on five of the examined parameters (Leyk et al. 2006, Gimmi et al. 2011) and only one paper reported on seven out of the eight examined parameters (Schaffer et al. 2015). The majority of the papers reported on one parameter (29 papers) or two parameters (19).

The parameter that was reported by the majority of the reviewed papers was the parameter of "Historical map scale" (57 papers out of a total of 82 papers). The second most reported parameter which was reported in some papers was *"Registration accuracy"* (33 papers out of a total of 82) followed by *"Categorization and reclassification"* (27 out of 82), *"Position accuracy"* (18 out of 82), *"Feature's interpretation"* (17 out of 82), *"On-screen digitizing scale"* (10 out of 82), *"Confusion matrix"* (8 out of 82) and finally the parameter that was hardly reported was *"Completeness of information"* (6 out of 82 papers) reporting on it (Table 1). The average number of reported parameters in the reviewed papers was 2.17 (Table 2).

Parameters	**What did we check**	**Number of articles**		
		No	**Yes**	**Partially**
Historical map scale	Did the Authors report on the scale of the historical map?	25	57	0
Registration accuracy	Was the registration error (root mean square error) reported?	46	33	3
Categorization and reclassification	Did the Authors explained on issues of categorization and reclassification of the landscape classes on the historical map?	55	27	0
Position accuracy	Did the Authors report examining the accuracy of position of the mapped objects?	54	18	10
Feature's interpretation	Did the Authors report examining the certainty in the definition of the feature depicted on the historical map?	61	17	4
On-screen digitize scale	Did the Authors report on the scale used in digitizing the historical map?	72	10	0
Confusion matrices	Did the Authors report using a confusion matrix in their analysis on the landscape?	74	8	0
Completeness of information	Was there a complete check whether all features on the ground did appear also on the historical map?	75	6	1

Table 1. Results gathered from all 82 reviewed papers examining the eight parameters ordered from the most reported parameter to the least reported.

Parameters	**Percent of total reported parameters in all the reviewed papers**	**Percent of total reported parameters by type of journal**				
		Ecology	**Environment**	**Environmental sciences**	**Geography**	**Physical**
Historical map scale	70%	59%	67%	50%	**70%**	62%
Registration accuracy	40%	33%	27%	25%	**43%**	38%
Categorization and reclassification	33%	**48%**	40%	25%	38%	43%
Position accuracy	22%	15%	13%	13%	**30%**	29%
Feature's interpretation	21%	19%	**27%**	13%	22%	19%
On-screen digitize scale	12%	11%	13%	13%	**16%**	10%
Confusion matrix	10%	**15%**	0%	0%	8%	10%
Completeness of information	7%	11%	0%	0%	**16%**	14%
Total average number of parameters reported	**2.17**	2.11	1.87	1.38	2.43	2.24
Total number of papers out of all papers		27	15	8	37	21

Table 2. Results of the comparison between the eight parameters examined to the journals type (as defined on "Web of knowledge") and authors main research area of the reviewed papers. In this table only categories which had eight or more papers are shown. The journal and author categories with highest scores for each parameter are highlighted in bold.

The papers reviewed in this article were published in 39 different journals and conference proceedings. The journals with the highest amount of papers reviewed in this research were from the following five journals: "Landscape ecology"(7 reviewed papers), "Landscape and urban planning"(6 reviewed papers), "Biogeography" (5 reviewed papers), "Land use policy" (4 reviewed papers), and "Applied geography" (3 reviewed papers). The papers reviewed in this article were divided into 34 different classes of journals (some papers belonging to more than one class). The classes of journals to which at least eight reviewed papers belonged were: Ecology, Environment, Environmental Sciences, Geography and Physical (Table 2). Amongst the journal classes, the Geography class had the highest reporting percentage for five of the eight parameters and on average 2.43 parameters were reported in papers belonging to Geography journals (compared to an overall average of 2.17; Table 2).

Discussion

In general, the greater number of HGIS studies in certain regions, such as North America and Europe, can be explained by the fact that topographic and survey-based mapping began there already in the 19th century, and therefore such countries have a larger number of historical maps on which HGIS research can be carried on (Collier 2002). The increase in HGIS research on land use and land cover changes in the past 20 years, is probably due to increases in computer power, the greater availability of scanned historical maps from various archives and libraries, and the proliferation of GIS software programs, which allow more users to scan and analyze large historical maps. However, it is important to note that these results were gathered from the papers found and reviewed and that there are additional papers which were not included in our research.

Registration accuracy

Once a historical map is scanned, geo-referencing the map to examine the registration accuracy of the map often constitutes the first form of analysis. In the geo-referencing stage the aim is to register the scanned historical map into a world coordinate system so that it can be used in GIS together with other layers. This is commonly done by collecting control points (Jenny 2006). Control points can be collected in two approached: (1) When a graticule is shown on a map (i.e., coordinate grid lines/points), the graticule's intersections can be used as the control points; (2) When no graticule is shown on the map, other features (e.g., triangulation points, mountain peaks, road intersections, prominent buildings) that are recognizable both on the historical map and in a geo-referenced source (e.g., a present day map) are often used. The advantage of using the graticule itself for geo-referencing is that it allows us to evaluate the accuracy with which the past surveyors determined their longitude and latitude (Lloyd and Gilmartin, 1987). For example in Pierre Jacotin's map (1828) of northern Palestine a large error of ~30 kilometers in the longitude can be found (Karmon 1960, Gavish 2005), while towards the late 19th century, with the improvement and greater availability of accurate time-keeping, such longitude errors have been greatly reduced (e.g., to less than 0.5 km as reported in (Levin 2006)).

The main statistical parameter used to estimate the registration error is the Root Mean Squared Error (RMSE) of the registration which is the RMSE of the residuals errors of all of the control points (Levin 2006). The higher the RMSE is the less spatially accurate is the registration of the historical map to a coordinate system, due to both errors in the historical maps and errors in the registration process. After collecting the control points, the scanned map can be transformed into real world coordinates using the coordinate system chosen by the user. At this stage the user is required to select the appropriate transformation method, whether to use a global transformation (i.e. a polynomial transformation) or a local transformation. Several papers reported on using different transformation types to check which of them provided the best RMSE results (Bromberg and Bertness 2005, Levin 2006, Podobnikar 2009). Global transformations assume that there are errors in each of the control points, and aim to minimize the overall errors over the entire map. The higher is order of the polynomial transformation, the lower will be the RMSE, however, it is recommended to use a 1st order polynomial transformation if the map covers a relatively small area so that the curvature of the Earth can be disregarded and when assuming no differential transformation of the historical (as a thumb rule, when the grid lines are straight lines and are perpendicular to each other throughout the map, a 1st order polynomial transformation can be used). Further discussion regarding the right polynomial transformation to use is given in (Buiten and van Putten 1997). Local transformations assume that the control points are perfect and that the historical map underwent differential stretching in different parts of it. In local transformations (e.g., spline, affine; (Zitova and Flusser 2003)), control points are forced to the location identified by the user, and different parts of the map undergo differential stretching (see example in Figure 4 in (Levin 2006)). Comparing different transformation methods, Schaffer et al. (2015), found that the transformation method did not affect their reconstruction of past landscapes or their estimates of map correspondence. Recent software developments by Jenny et al. (2007) now enable easy visualization of map distortion. Their product, MapAnalyst, allows the visualization and study of the planimetric accuracy of old maps, by generating distortion grids, displacement vectors, and new isolines of scale and rotation (Perthus and Faehndrich, 2013).

In the reviewed papers which reported on map registration, most studies geo-referenced historical maps to an updated present day map using different GIS software programs and reported their RMSE (Bromberg and Bertness 2005, Frajer and Geletič 2011, Hamre et al. 2007, Kitzberger and Veblen 1999, Levin 2006, Levin et al. 2009, Leyk et al. 2005a, Sanderson and Brown 2007, Vuorela et al. 2002, Weir 1997). Some papers geo-referenced the historical map not only to present day maps but also to other historical maps (Tucci et al. 2010, Schaffer et al. 2015) or to satellite imagery (Hall et al. 2003). Using historical maps to geo-reference another historical map might be easier when the historical map which needs geo-referencing lacks a graticule and/or that the area has changed too much for the user to identify the features shown on the historical map in present day maps or orthophotos. Using a later historical map that has been geo-referenced can thus allow us to geo-reference another historical map.

There are two main ways to double check the results of the RMSE. One way is to separate the control points in two sets: the training (calibration) set, and the validation set, measuring the RMSE of the validation set after the map is geo-referenced. This approach may also aid in estimating how the RMSE results will improve if we would collect more GCPs (Levin 2006). A second way is to check the RMSE result by jackknifing (or bootstrapping, i.e. omitting and adding different points to the GCP set; (Efron 1982)) for statistically estimating the errors (Sprague et al. 2007, Levin 2006, Davie and Frumin 2007). Since testing the registration accuracy of the map is a first step in examining the information on the map it is surprising that only 40% of the reviewed papers provided this data although we might assume that the maps were also geo-referenced in the other papers but were not reported. The basic approach to geo-reference a historical map has remained the same in the past 20 years however the proliferation of GIS tools made it much easier, faster and more dynamic with many more options to choose from.

Map generalization

In HGIS research map generalization can refer to many different issues such as: historical map scale, the scale in which the original surveying was done, the on-screen scale in which the digitization was done, and the minimal mapping unit which was decided by the mappers. With respect to map generalization, we concentrated on two issues: 1. the scale of the historical map; 2. the on-screen scale in which historical maps were digitized. Each historical map has a different scale (Harley 1968, Gregory 2003). This is important to notice since a historical map might omit (or include) features which may or may not appear on a similar historical map but in a different scale (e.g., large landscape patches or more detailed patches) (Schaffer et al. 2015) (Figure 2A and 2B). Reporting the scale of a historical map is important as scale affects the number of landscape features shown on a map, as well as their geometry and positional accuracy. The scale in which landscape features were digitized from the map is important as it affects the level of details in the reconstructed landscape map, and here too, a decision needs to be made regarding the minimum mapping unit (Saura 2002, Knight and Lunetta 2003). For example, when coming to digitize a map that shows a landscape with symbols of many scattered trees (Figure 2B) the challenge is to decide where to delineate the border around them so as to define the edge of a forest. In most cases, if the digitization is done at a small scale the trees could be all put in one group (one big patch) however if the digitization is done on a larger on-screen scale one might define several forest patches. The on-screen scale of digitization is an important issue to decide upon before beginning the process of digitization itself. Out of the 82 reviewed papers the majority of the papers did report on the scale of the historical map (70% of the papers) but almost completely neglected to report on the on-screen scale in which the digitization took place (only 12% of the papers).

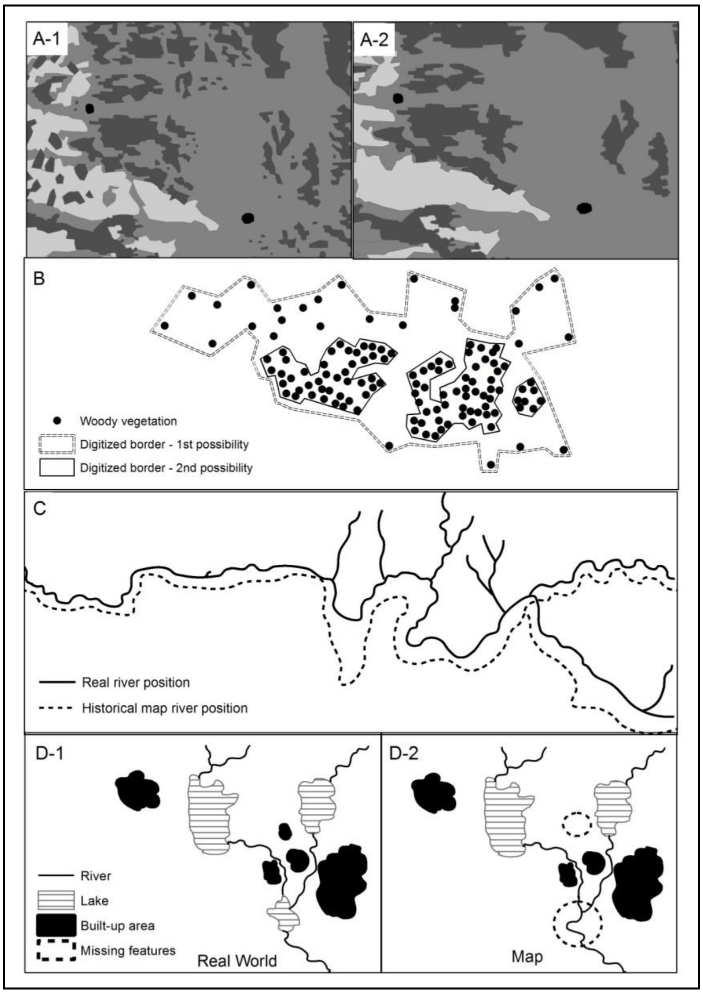

Figure 2. Schematic examples for some the uncertainty parameters discussed in the manuscript. Figure 2A is an example of differences due to map generalization. Figure 2A-1 and 2A-2 are both in the same scale but figure 2A-1 shows the landscape in greater details (smaller patches are also seen) whereas figure 2A-2 only shows the general picture (mostly big patches are found). Figure 2B is an example of attribute uncertainty and map generalization. The person examining the map needs to decide where to draw the border between different features of the landscape – in this case the symbols of scattered trees representing a forest. This is especially complex when the features are poorly defined such as natural ones. Moreover, this depends much on the scale in which the mapping or digitization is done. Figure 2C is an example of position inaccuracy of rivers. The present-day positions of rivers taken from a reference map (black lines) are different from the rivers shown on the historical map (dotted black lines). Figure 2D demonstrates issues related to map completeness. Figure D-1 represents the landscape as it is, whereas figure D-2, represents the landscape as presented on a historical map, with certain features (a lake, and a built-up area) missing (e.g., due to surveying errors).

Positional accuracy

After a historical map is geo-referenced to a world coordinate grid and the scale in which the research will be conducted is set, the positional accuracy of the features appearing on the map can be examined (e.g., buildings, crossroads, river cross, elevation points etc.). If a map is geo-referenced using the graticule of the historical map, then the positional accuracy of the features on the map can be estimated by comparing their location to that shown on modern (and thus more accurate) maps and calculating the RMSE, or by calculating error vectors (Lloyd and Gilmartin, 1987). As demonstrated in Levin (2006), the positional accuracy of features on the map differs between different feature types, with rivers being one of the least accurately mapped features. An example of this can be seen in Figure 2C, which demonstrate the positional accuracy of the rivers drawn on a historical map and in a present-day map. This figure indicates that the rivers on the historical map (shown as black dotted lines) are similar in their overall layout to present-day rivers (think black lines) but that there are many positional inaccuracies. Depending on the landscape type (e.g., mountainous or flat), one might estimate whether the course of these rivers could have altered (with no human intervention) that much within a time frame of 100-200 years. With regards to the positional accuracy of rivers (as well as of other features), it should be noted that their level of detail and completeness also depends on the surveying methods, scale and aim of the map (see Levin et al., 2010). Out of the 82 reviewed papers, only 18 fully reported checking the position accuracy of the features appearing on their historical maps. A few interesting points arise from the reviewed papers. In some papers which reported examining the position accuracy of features, the features examined were man made features such as buildings (Davie and Frumin 2007, Grossinger et al. 2007) and a few examined natural features such as forests, marsh lands and scrubs (Fensham 2008). Ten papers reported a partial examination of position accuracy, and there the main purpose was not a thorough examination of position accuracy but rather the collection of more GCPs to rectify the map or for different transformation purposes (Podobnikar 2009). However, some of these papers, after collecting these points also examined the positional accuracy of several features (Hamre et al. 2007, Karmon 1960, Podobnikar 2009). One possible reason for the low reporting of this parameter in the reviewed papers (only 22% fully reported it) may be because examining the position of features on the map is very time consuming (Hamre et al. 2007). Another possible reason for the lack of reporting on this parameter could be that it was not relevant for the aims of the research.

Attribute accuracy

At the digitization stage, when the thematic content of the map is examined in depth, uncertainties may arise about the nature of the symbols and features depicted on the map, especially when it comes to natural features (e.g., forests) which often do not have clearly defined borders (Figure 2B). There are several reasons for that: 1. the historical map being damaged as a consequence of time; 2. the legend not including all of symbols actually used on the map; 3. the map not having a legend (as in Schaffer et al., 2015). 4. Poorly defined features such as natural vegetation features are harder to categorize and define as would be with defined features such as a building. Only 33% of the reviewed papers reported on the way they categorized the features (using the map legend or other more general categories). Moreover, only 21% of the reviewed papers reported on the way they interpreted the features appearing on their maps (four papers reported this parameter partially). The 18th century geographer, John Green, highlighted the need to be very cautious when interpreting a map (Harley 1968). Up to now, the problem of uncertainties regarding the features has received insufficient emphasis in the literature to date (Gregory and Healey 2007). Using GIS software programs did not change much with regard to the different ways we try to interpret the symbols found on the map (although there are now attempts to automatically classify and segment historical maps into classes using image processing tools based on colors and patterns, e.g. (Levin et al. 2010) (Leyk et al. 2006)). The reviewed papers which did report on this parameter used various methods. Some used archival sources to assist in deciding about the nature of attributes found on the map (Gimmi 2011). In other cases when a map legend was missing it was possible to try and find other maps of the same period and find similarities in the symbols (Wilson 2005). Other times, it was easier to regroup different features into more general categories and thus avoid uncertainties (Haase et al. 2007, Podobnikar 2009, Stein et al. 2010). In other cases where we know that the landscape has not changed much the use of aerial photos (Fensham 2008) or even traveling to the area and taking true ground observations (Van Dyke and Wasson 2005) was done. A complementary approach to the problem of attribute uncertainty used by many scholars is an approach developed by Grossinger (Grossinger et al. 2006). This approach suggests assigning each feature with the certainty class in which the type of this feature was identified (i.e. 1- high certainty; 2-somewhat certain; 3-uncertain about the feature attribute); later, features with a high uncertainty level can be omitted from the examination if wanted (Grossinger et al. 2007, Stein et al. 2010).

Completeness of information

A naive map user may assume that the features represented on a map fully depict all features present at the time the map was surveyed and drawn. However, as the information drawn on a map depends on its scale, aim and on cartographic considerations of selection, simplification and generalization, as well as due to mapping errors, the spatial information drawn on the map can never be complete. Figure 2D demonstrates an example for differences between two maps of the same area at a similar scale. As we can notice from comparing the two maps shown in Figure 2D, there are a lake and a built-up area missing in Figure D-1 (representing the historical map)which are shown in Figure D-2 (representing the real world). To examine whether information on the map is complete or incomplete we need to compare the map to other sources of that period such as maps, aerial photos, and archive sources. The parameter of map completeness was the least reported of all uncertainty parameters (only 7% of the reviewed papers reported it).

Analyzing the completeness of information on a historical map is not always possible, as other contemporary historical sources may be needed (e.g., other historical maps or historical aerial photos belonging to the same period), and these do not always exist. Based on the reviewed papers, completeness of information is usually conducted on defined features such as built areas, religious sites, roads, rivers, wetlands (as in Schaffer et al., 2015). For the completeness of information estimates some used route notes while others used maps combined with aerial photos and some used several sources all together (Frantzman et al. 2013, Gimmi 2011, Grossinger et al. 2007, Levin et al. 2009, Levin et al. 2010).

An innovative way to estimate map completeness was demonstrated for the reconstruction of wetlands in the coastal plain of Israel by Levin et al. (2009). Levin et al. (2009) adopted the ecological approach for analyzing the so called "species richness accumulation curve", which expresses the number of new species added to the curve with each additional sample. In their study, which aimed to estimate the 19th century extent of wetlands along the coastal plain of

Israel, each wetland represented a species and each historical map was equivalent to a sample. They then estimated the completeness of wetland mapping using sample-based rarefaction curves, generated using the software Estimates 8.0 (Colwell 2006).

The use of GIS software programs enables easier comparative analysis of map completeness as it allows different layers to be stacked on top of each other. Nonetheless, this analysis is still time consuming and there is still a serious lack of it in HGIS research on landscapes.

Comparing historical land cover / land use maps

Historical land cover maps can be examined for their accuracy using other historical sources from the same period (historical maps or historical aerial photos), and historical land cover maps can also be used to examine the extent of land cover change. In both cases, a matrix is constructed, where the rows relate (for example) to one historical land cover map, and the columns relate (for example) to another historical source or to a modern land cover map to which one is comparing the historical map, whereas the cells contain information about the amount of area contained in each of the possible land cover combinations. When examining the correspondence between two historical maps, the matrix is known as a confusion matrix, and several measures of correspondence can be calculated (discussed below) (Hunsaker 2001).

The overall correspondence between two historical sources is calculated based on the total of the diagonal of the matrix. We use the term overall correspondence instead of overall accuracy, because we are examining two historical sources, and it may not be possible to verify which of the two historical sources is more correct. Errors of commission occur when areas associated with a certain class are incorrectly identified as other classes. Errors of omission occur whenever areas that should have been identified as belonging to a particular class do not belong to that class. The Kappa Index of Agreement (Cohen 1960) is another commonly used index, expressing the proportion of correct classification above the expected proportion correct due to chance. As noted by Pontius (2000), disagreements between land cover maps may be either due to quantification errors or due to location errors. Quantification error occurs when the total area of a particular land cover class in one map is different from the total area of that class in the other map. Location errors occur when the location of a land cover class in one map is different from the location of that land cover class in the other map (e.g., due to geo-referencing errors). As the standard Kappa index of agreement was considered not appropriate for map comparison, Pontius (2000) developed new kappa indices that relate specifically to location and quantity errors, and these indices can be calculated for example using the Idrisi software (Clark 2012). The K-location metric indicates the extent to which two maps agree in terms of location of each land cover class, and the Kappa Agreement Index due to quantity, expresses the additional agreement (beyond the agreement due to chance) of the two maps in terms of the quantity of each land cover class. In the reviewed articles only 10% of the papers reported in using the confusion matrix in analyzing the landscape.

Conclusion

In this paper we reviewed the current state of HGIS research on land cover / landscape changes. The aim of this paper was to examine the challenges and to demonstrate possible approaches to estimate eight main parameters of uncertainty of relevance when examining historical maps in GIS. We found that there is still a large gap in the use of these eight basic estimates of map accuracy in HGIS studies. It seems that this gap of knowledge is not due to lack of appropriate methods but could derive from three different reasons: 1. Researchers using historical maps with GIS tools and methods are not fully aware of ways for quantifying and including error estimation in GIS analysis; 2. The historical map used was already analyzed by a third party and thus it was not necessary to mention once again the different parameters examined, 3. Some journals or authors which are less oriented towards geospatial analysis might not be interested or aware to the importance of assessing these uncertainty parameters. Concerning the third reason this paper has shown that indeed papers published in the discipline of Geography have indeed reported on more of the uncertainty parameters examined. Although most HGIS studies on land cover changes do not examine all factors contributing to map uncertainty, there are a handful of tools and methods that can be used when examining historical maps in GIS. The uses of GIS tools are not only for academic interests but they have "real world" implications such as in the planning, conservation and in the legal world. As law courts are accepting the evidentiary value of map evidence more than ever before (Lee 2005), it is ever more important to quantify the degree at which the content and positions shown on historical maps, can be relied upon. Estimating the reliability of historical sources is crucial since many of them are used to understand changes that have occurred over time and their effects on human development (Howell and Prevenier 2001). Since the level of accuracy in some published HGIS studies is unclear, we encourage the scientific community of historical geographers to incorporate estimates of map uncertainty as part of their historical analysis of landscape changes.

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Appendix

Paper Name	Reference	Did the Authors report on the scale of the main / earliest historical map used in the research?	Did the Authors report on the screen scale used in digitizing the historical map?	Was the RMS, registration error reported?	Did the Authors report examining the accuracy of position of the mapped objects?	Did the Authors report examining the certainty in the interpretation of the features depicted on the map?	Did the Authors explained on issues of categorization and reclassification of the landscape classes on the historical map?	Was there an attempt to analyze the completeness of the mapped features with respect to the real world?	Was there use of confusion matrix?	What landscape features were examined?
A method for assessing the planimetric accuracy of historical maps: the case of the Colorado-Green river system	(Locke and Wyckoff 1993)	no	no	yes	no	no	no	no	no	river
A Century of Forest Management Mapping	(Weir 1997)	1:14,400 (1872)	no	yes	partially	no	yes	no	no	forest boundaries
Directions of landscape change (1741- 1993) in Virestad, Sweden - characterized by multivariate analysis	(Skanes and Bunce 1997)	1:8,000	yes	no	yes	no	yes	no	no	landscape
A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area	(Clarke and Hoppen 1997)	1:62,500	no	no	no	no	no	no	no	land cover of urban area of SF
Two Hundred Years of Land Use and Vegetation Change in a Remnant Coastal Woodland in Southern Australia	(Lunt 1998)	NO	no	no	no	no	yes	no	no	vegetation and land use
Fire-induced changes in northern Patagonia landscape	(Kitzberger and Veblen 1999)	1:250,000	no	yes	no	no	yes	no	yes	forests
The land use history (1278-1990) of mixed hardwood forest in western Belgium and its relationship with chemical soil characteristics	(Verheyen et al. 1999)	no	no	no	no	no	yes	no	yes	forest and land use
Gross channel changes along the Durance river, southern France, over the last 100 years using cartographic data	(Warner 2000)	1:80:000	no	no	yes	no	no	no	no	river channel
Analysis of land-cover transitions based on 17th and 18th century cadastral maps and aerial photographs	(Cousins 2001)	1:4,000	no	no	no	no	yes	no	no	land cover

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Three hundred years of forest and land-use change in Massachusetts, USA	(Hall et al. 2002)	1:19,200	no	no	no	no	yes	no	no	land use and land vegetation
Impact of data integration technique on historical land-use/land-cover change: Comparing historical maps with remote sensing data in the Belgian Ardennes	(Petit and Lambin 2002)	1:11,520	no	yes	no	no	yes	no	yes	land cover
Systematic Assessment of Maps as Source Information in Landscape-change Research	(Vourela et al. 2002)	ca.1:4,000	no	yes	no	yes	yes	no	no	land use
Conservation of changing landscapes: vegetation and land-use history of Cape Cod national seashore	(Eberhardt et al. 2003)	1:10,000	no	no	no	no	no	no	no	land cover
Forest Cover Change in the Western Carpathians in the Past 180 Years	(Kozak 2003)	1:28,800	no	yes	partially	partially	yes	no	no	land cover such as forests
Consideration of the errors inherent in mapping historical glacier positions in Austria from the ground and space (1893-2001)	(Hall et al. 2003)	NO	yes	yes	yes	no	no	no	no	glacier
Predictive modeling of historical and recent land-use patterns	(Peppler-Lisbach 2003)	1:25,000	no	no	no	no	yes	no	no	land use
Rubber-sheeting of historical maps in GIS and its application to landscape visualization of old-time cities: focusing on Tokyo of the past	(Shimizu and Fuse 2003)	NO	no	no	yes	no	no	no	no	land use
Channel changes in the Jarama and Tagus rivers (central Spain) over the past 500 years	(Uribelarrea et al. 2003)	1:10,700 (ca.1:100,000)	no	no	no	no	no	no	no	river

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Defining conservation strategies with historical perspectives: a case study from a degraded Oak grassland ecosystem	MacDougall et al. 2004)	NO	no	no	no	no	no	no	no	oak ecosystem
Gis methodology for characterizing historical conditions of the Willamette River flood plain, Oregon	(Oetter et al. 2004)	1:12,000 (1:5,000)	no	no	no	no	no	no	no	flood plain
Historical changes in the bird fauna at Coomooboolaroo, northeastern Australia, from the early years of pastoral settlement (1873) to 1999	(Woinarski and Catterall 2004)	NO	no	no	no	no	yes	no	no	landscape
Using GIS to analyze long-term cultural landscape change in Southern Germany	(Bender et al. 2005)	1:5,000	no	no	no	no	no	no	no	landscapes
Reconstructing New England salt marsh losses using historical maps	(Bromberg and Bertness 2005)	1:50,000	no	yes	yes	no	no	no	no	salt marsh
Environmental causes and consequences of forest clearance and agricultural abandonment in central New York, USA	(Flinn et al. 2005)	NO	no	no	no	no	no	no	no	land use
Historical land use changes and their impact on sediment fluxes in the Balaton Basin	(Jordan et al. 2005)	1:28,000	no	no	no	no	no	no	no	land use
A conceptual framework for uncertainty investigation in map-based land cover change modeling	(Leyk et al. 2005)	1:50,000 and 1:25,000	no	yes	no	yes	no	no	yes	forest cover
Historical Ecology Habitat Change of a Central California Estuary: 150 Years of	(Dyke and Wasson 2005)	NO	no	partially	yes	yes	yes	no	no	wetland

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Historical and Computational Analysis of Long-Term Environmental Change: Forests in the Shenandoah Valley of Virginia	(Wilson 2005)	no scale on the map	no	no	no	yes	no	no	no	forests
Triglav national park historical maps analysis	(Podobnikar and Kokalj 2006)	1:28,000	no	yes	no	no	no	no	no	land use
Monitoring urbanization of Iskenderun, Turkey, and its negative implications	(Doygun and Alphan 2006)	1:25,000	no	no	no	no	no	no	no	urban area
Impacts of historical land use changes on erosion and agricultural soil properties in the Kali Basin at Lake Balaton, Hungary	(Szilassi et al. 2006)	1:28,000	no	no	no	no	no	no	no	land use
The Palestine Exploration Fund Map (1871-1877) of the Holy Land as a Tool for Analyzing Landscape Changes: the Coastal Dunes of Israel as a Case Study (Levin 2006)	(Levin 2006)	1:63, 360	no	yes	yes	yes	no	no	no	dunes
Saliency and semantic processing: Extracting forest cover from historical topographic maps	(Leyk et al. 2006)	1:25,000 (and 1:50,000)	yes	no	no	yes	yes	no	yes	forest cover
Application of old maps for studying long-term shoreline change	(Tanaka et al. 2006)	NO	no	yes	partially	no	no	no	no	shoreline
Changes in glacier extent in the eastern Pamir, Central Asia, determined from historical data and ASTER imagery	(Khromova et al. 2006)	1:100,000	no	partially	partially	no	no	no	no	glacier
Evaluating urban expansion and land use change in Shijiazhuang, China, by using GIS and remote sensing	(Xiao et al. 2006)	1:70,000	no	partially	no	no	no	no	no	urban expansion and land use

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Historical landscape ecology of an urbanized California valley: wetlands and woodlands in the Santa Clara Valley	(Grossinger et al. 2007)	NO	no	no	yes	yes	yes	yes	no	land cover types
Changes to Central European landscapes - Analyzing historical maps to approach current environmental issues, examples from Saxony, Central Germany	(Haase et al. 2007)	1:12,000	no	no	no	yes	no	no	no	land cover classes
Land-cover and structural changes in a western Norwegian cultural landscape since 1865, based on an old cadastral map and a field survey	(Hamer et al. 2007)	1:2,000	no	yes	partially	no	no	no	no	land cover classes and structures
Improving land change detection based on uncertain survey maps using fuzzy sets	(Leyk and Zimmermann 2007)	1:5,000 and 1:10,000	no	no	no	yes	yes	no	yes	land cover classes and in between classes
Mannahatta: An Ecological First Look at the Manhattan Landscape Prior to Henry Hudson	(Sanderson and Brown 2007)	ca. 1:10,000	yes	yes	partially	no	yes	no	no	land cover
Measuring rice paddy persistence spanning a century with Japan's oldest topographic maps: georeferencing the Rapid Survey Maps for GIS analysis	(Sprague et al. 2007)	1:20,000	no	yes	no	no	no	partially	no	rice paddy
Changes in the riparian zone of the lower Eygues River, France, since 1830	(Kondolf et al. 2007)	1:2,500	no	no	no	no	no	no	no	riparian forests
Late 18th century Russian Navy maps and the first 3D visualization of the walled city of Beirut	(Davie and Frumin 2007)	NO	no	yes	yes	no	no	no	no	buildings
Landscape Patterns as Indicators of Ecological Change at Fort Benning, GA	(Olsen et al. 2007)	NO	no	no	no	no	yes	no	no	forest land cover, trees

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Historical mapping for landscape reconstruction - examples from the Canton of Valais (Switzerland)	(Stauble et al. 2008)	1:5,000	no	no	no	no	no	no	no	land cover / land use
Leichhardt's maps: 100 years of change in vegetation structure in inland Queensland	(Fensham 2008)	NO	no	no	yes	partially	no	no	no	vegetation land cover
Decline of wetland ecosystems in the coastal plain of Israel during the 20th century: implications for wetland conservation (Levin 2009)	(Levin et al. 2009)	1:63,360	no	yes	yes	no	no	yes	no	wetlands
Indicators for assessing changing landscape character of cultural landscapes in Flanders (Belgium)	(Eetvelde and Antrop 2009)	1:11,500	no	no	yes	no	yes	no	no	landscape features
Geo-referencing and quality assessment of Josephine survey maps for the mountainous region in the Triglav national park	(Podobnikar 2009)	1:28,000	no	yes	partially	yes	no	no	yes	land cover classes
Rediscovering the old treasures of cartography - what an almost 500 year old map can tell to a geoscientist	(Szekely 2009)	NO	no	no	no	no	no	no	no	lake
Land use change in Northeast China in the twentieth century: a note on sources, methods and patterns	(Ye and Fang 2009)	under 1:4,000,000	yes	no	no	no	no	no	no	land use / cover
Shoreline migration and beach-near shore sand balance over the last 200 years in Haifa Bay (SE Mediterranean)	(Zviely et al. 2009)	1:100,000	no	yes	partially	no	no	no	no	coast line
Maps and the settlement of southern Palestine, 1799-1948: an historical/GIS analysis	(Levin et al. 2010)	1:100,000 (Jacotin)	no	Yes	yes	no	no	yes	no	desert-sown, tents and houses

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Historical ecology as a tool for assessing landscape change and informing wetland restoration priorities	(Stein et al. 2010)	NO	no	no	no	yes	no	no	no	habitat
Using Spatial Analysis and Geovisualization to Reveal Urban Changes: Milan, Italy, 1737–2005	(Tucci et al. 2010)	1:10,000	no	yes	no	no	no	no	no	urban area
Bias and error in using survey records for ponderosa pine landscape restoration	(Williams ad Baker 2010)	NO	no	yes	no	no	no	no	no	forests
Human-driven coastline changes in the Adra River deltaic system, southeast Spain	(Jabaloy-Sanchez et al. 2010)		no	yes	yes	no	no	no	no	coastline of the river
Reconstructing the collapse of wetland networks in the Swiss lowlands 1850–2000	(Gimmi et al. 2011)	1:25,000	yes	no	no	yes	yes	yes	no	wetlands
The Application of GIS to the Reconstruction of the Slave-Plantation Economy of St. Croix, Danish West Indies	(Hopkins et al. 2011)	NO	no	no	no	no	no	no	no	plantatio ns
Understanding landscape change using historical maps. Case study Sinaia, Romania	(Patru-Stupariu et al. 2011)	1:28,000	no	no	no	no	no	no	no	land cover
Using old military survey maps and orthophotograph maps to analyze long-term land cover changes e Case study (Czech Republic)	(Skalos et al. 2011)	1:28,800	yes	no	no	no	yes	no	no	land cover and roads
Research of historical landscape by using old maps with focus to its positional accuracy.	(Frajer and Geletic 2011)	1:132,000	no	yes	yes	no	no	no	no	monume nts
Rail survey plans to remote sensing: vegetation change in the Mulga Lands of eastern Australia and its implications for land use	(Fensham et al. 2011)	NO	no	no	partially	yes	no	no	no	vegetatio n boundari es

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The history of Lake Rzecin and its surroundings drawn on maps as a background to palaeoecological reconstruction	(Barabach 2012)	1:25,000	no	no	no	no	no	no	no	lake and land cover
Monitoring directions and rates of change in trees outside forests through multitemporal analysis of map sequences	(Plieninger 2012)	1:25,000	no	yes	no	yes	yes	no	no	landscape and scattered trees
A 150-year record of coastline dynamics within a sediment cell: Eastern England	(Montreuil and Bulard 2012)	1:10,560	no	yes	yes	yes	no	no	no	coastline
Documentary evidence for changing climatic and anthropogenic influences on the Bermejo Wetland in Mendoza, Argentina, during the 16th–20th century	(Prieto and Rojas 2012)	NO	no	yes	no	no	no	no	no	wetland
Visualizing the map-making process: Studying 19th century Holy Land cartography with MapAnalyst	(Perthus and Faehndrich 2013)	1:315,000	no	no	yes	partially	no	no	no	place marks on the map
Patterns and causes of land change: Empirical results and conceptual considerations derived from a case study in the Swabian Alb, Germany Claudia	(Bieling et al. 2013)	1:2500	no	no	no	yes	yes	no	no	land cover
Three centuries of land cover changes in the largest French Atlantic wetland provide new insights for wetland conservation	(Godet and Thomas 2013)	1:28,000	yes	no	no	no	yes	no	no	land cover
Assessment and monitoring of deforestation from 1930 to 2011 in Andhra Pradesh, India using remote sensing and collateral data	(Krishna et al. 2013)	1:250,000	no	no	no	no	no	no	no	forests

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Using forest history and spatial patterns to identify potential high conservation value forests in Romania	Patru-Stupariu et al. 2013)	1:28,000	no	yes	no	no	no	no	no	forest and land cover
Counting nomads: British census attempts and tent counts of the Negev Bedouin 1917-1948.	(Frantzman et al. 2013)	1:250,000	no	no	yes	no	no	yes	no	area of Bedouin tents
Water history facets of landscape change in Israel/Palestine 1920–1970: a question of scale and periodization	(Feitelson et al. 2014)	NO	no	no	no	no	no	no	no	land use
Mapping human induced landscape changes in Israel between the end of the 19th century and the beginning of the 21st century	(Schaffer and Levin 2014)	1:36,360	no	yes	no	partially	yes	no	no	land cover
Urban and landscape changes through historical maps: The Real Sitio of Aranjuez (1775–2005), a case study	(San-Antonio-Gomez et al. 2014)	1:4166.48	no	yes	no	no	no	no	no	landscape heritage
A spatially explicit empirical model on actual and potential ancient forest plant diversity in a fragmented landscape	(De Keersmaeker et al. 2014)	NO	no	yes	no	no	no	no	no	forests
Land-use and land-cover changes in rural areas during different political systems: A case study of Slovakia from 1782 to 2006	(Kanianska et al. 2014)	1:28,800	no	no	no	no	yes	no	no	land cover
A Century of the Evolution of the Urban Area in Shenyang, China	(Liu et al. 2014)	1:100,000	no	yes	no	no	no	no	no	urban expansion
Decline of Birch Woodland Cover in Þjórsárdalur Iceland from 1587 to 1938	(Sigurmundsson et al. 2014)	N/A	yes	no	no	no	no	no	no	woodland

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Quantifying the completeness of and correspondence between two historical maps: a case study from 19th century Palestine	(Schaffer et al. in press)	yes	yes	yes	partially	yes	yes	yes	yes	natural and human landscape

Table S1. Summarized table with part of the issues retrieved from the reviewed papers used in this article.