

Broad scale forest cover reconstruction from historical topographic maps



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ABSTRACT

Land cover change is one of the major contributors to global change, but long-term, broad-scale, detailed and spatially explicit assessments of land cover change are largely missing, although the availability of historical maps in digital formats is increasing. The problem often lies in efficiency of analyses of historical maps for large areas. Our goal was to assess different methods to reconstruct land cover and land use from historical maps to identify a time-efficient and reliable method for broad-scale land cover change analysis. We compared two independent forest cover reconstruction methods: first, regular point sampling, and second, wall-to-wall mapping, and tested both methods for the Polish Carpathians (20,000 km²) for the 1860s, 1930s and 1970s. We compared the two methods in terms of their reliability for forest change analysis, relative to sampling error, point location and landscape context including local forest cover, area of the spatial reference unit and forest edge-to-core ratio. Our results showed that the point-based analysis overestimated forest cover in comparison to wall-to-wall mapping by 1–3%, depending on the mapping period. The reasons for the differences were mainly the backdating approach and map generalisation rather than the point grid position or sampling error. When we compared forest cover trajectories over time, we found that the point-based reconstruction captured forest cover dynamics with a comparable accuracy to the wall-to-wall mapping. More broadly, our assessment showed that historical maps can provide valuable data on long-term land cover trends, and that point-based sampling can be an efficient and accurate way to assess forest area and change trends. We suggest that our point-based approach could allow land cover mapping across much of Europe starting in the 1800s. Our findings are important because they suggest that land cover change, a key component of global change, can be assessed over large areas much further back in time than it is commonly done. This would allow to truly understand path dependencies, land use legacies, and historical drivers of land cover change.

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1. Introduction

Land use and land cover changes are key components of global change (Foley et al., 2005), affecting changes in biodiversity (Allan et al., 2014; Newbold et al., 2015), climate (Heald & Spracklen, 2015; Stocker, Feissli, Strassmann, Spahni, & Joos, 2014) and other

ecosystem functions (Lawler et al., 2014). Therefore a clear understanding of land use changes over time is crucial to predict future changes and effectively manage ecosystems. Existing spatially explicit long term land use and land cover data offer excellent global products, but these are not suitable for regional applications (Klein Goldewijk, Beusen, & Janssen, 2010; Pongratz, Reick, Raddatz, & Claussen, 2008; Ramankutty & Foley, 1999) leading to uncertainties in existing land use theories such as path dependency (Brown, Castellazzi, & Feliciano, 2014; Chavez & Perz, 2013; Lambin, Geist, & Rindfuss, 2006), land use legacies (Foster et al.,

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2003; Munteanu et al., 2014; Plieninger, Schaich, & Kizos, 2010), and the interactions of change trajectories with other land change driving forces (Jepsen et al., 2013; Lambin & Meyfroidt, 2010; Meyfroidt, Lambin, Erb, & Hertel, 2013). Similarly, high resolution satellite data on land cover change is only available since the mid-20th century (e.g. based on Corona missions; Song et al., 2015) and from Landsat mission launched in 1970s (Belward & Skoien, 2014; Griffiths et al., 2014; Hansen et al., 2013). However, valuable land use information can be obtained from historical maps. The combination of aerial photography, satellite imagery, and historical maps can provide valuable information about centuries of land change and their effects on humans and their environment (Fuchs, Verburg, Clevers, & Herold, 2015; Gerard et al., 2010; Munteanu et al., 2015).

Despite its scientific value, historical map analysis over large areas is still relatively rare, because it requires extensive contextual knowledge (Kaim et al., 2014; Leyk, Boesch, & Weibel, 2005; Plewe, 2002) and because the analysis of historical maps is time and labour intensive, due to geometrical rectification, digitization, and the manual assignment of land use and land cover classes. This is why long term, map-based land change studies are mostly confined to relatively small areas (e.g. Bürgi, Salzmann, & Gimmi, 2015), and historical maps are rarely used for global or continental reconstructions (Fuchs et al., 2015; Klein Goldewijk et al., 2010; Ramankutty & Foley, 1999). The existing global or continental reconstructions offer long time horizons, but their spatial resolution and local accuracy is too low to study land changes at the regional scales. Historical maps represent the only viable approach to assess centuries of land cover change for large areas reliably, and that is why it is important to develop methods to analyse such maps effectively.

Especially in Europe, a large amount of historical land use information is available in the form of triangulation-based historical maps starting in the 19th century. Extensive topographic map collections are available, for example, for the former Austrian Empire (Timár, Biszak, Székely, & Molnár, 2010), Belgium (Depuydt, 1975), the Netherlands, Portugal, and many other European countries (Böhme, 1989) and regions (Nordrhein-Westfalen, 1967) (Table 1). Many of these maps are already scanned and available on the Internet, as is the case for France (<http://www.geoportail.gouv.fr>), the United Kingdom (<http://www.british-history.ac.uk/>; <http://maps.nls.uk/>), Germany (<http://gso.gbv.de/>), Sweden (<http://www.lantmateriet.se/>), the Czech Republic (<http://geoportal.cuzk.cz/>), and Italy (<http://www.igmi.org/>). Similarly, many of the European historical cartographic sources have been successfully used to analyse different land use change processes at local scales. For example, in Germany, 18th century forest vegetation was reconstructed from historical maps (Wulf & Rujner, 2010), in Switzerland wetlands decline was assessed based on topographic maps since 1850 (Gimmi, Lachat, & Bürgi, 2011), and in Sweden 19th century maps showed the decline of deciduous forest over time (Axelsson, Östlund, & Hellberg, 2002). In western France the analysis of historical maps showed that over the last 200 years grasslands were generally rare, and dominated the area only in the 1950s, which is important because many conservation strategies in these areas have focused on the protection of grassland because of their supposed naturalness (Godet & Thomas, 2013). Similarly, in the Ukrainian Carpathians, map-based studies of mountain grasslands showed that livestock farming increased up to the Second World War, causing the timberline to decrease in elevation (Sitko & Troll, 2008). In contrast, in Romania due to the decline of transhumance, forest cover increased at the timberline (Shandra, Weisberg, & Martazinova, 2013). In Poland, historical maps confirmed the stability of the forest cover in the Białowieża Primeval Forest in the last 200 years (Mikusinska, Zawadzka, Samojlik, Jędrzejewska, &

Mikusinski, 2013).

Case studies documenting land use change are usually prepared for relatively small areas, for many reasons, including limited availability and the time necessary to prepare and analyse historical maps. Furthermore, straightforward comparisons of case studies between countries and regions are often problematic because of differences in land use classification catalogues (Munteanu et al., 2014). Although such case studies may provide valuable insights into local long term land change processes (Flyvbjerg, 2006), broader comparative studies are necessary to better understand the full range of land use change patterns and their drivers (Bürgi, Hersperger, & Schneeberger, 2005). A meta-analysis approach can be useful to synthesize land use data at broader scales (Munteanu et al., 2014; Rudel, 2008; Van Asselen, Verburg, Vermaat, & Janse, 2013). However, such meta-analyses entail the risk of biased conclusions, because single local scale case studies are frequently designed to highlight special cases, and do not provide a representative sample of change.

The question thus is how to accurately and efficiently analyse historical maps not only in local studies, but also for large areas. A statistically sound sampling strategy represents one potential solution to this problem. Regularly spaced samples are currently used to assess global forest cover changes (FAO, 2010; Potapov et al., 2011), as well as to collect land use and land cover data at national levels. For instance, Switzerland is covered by a 100-m grid of sample points, each assigned to one of 74 land use categories (SFSO, 2001), and Norway by a 18-km grid used to monitor changes in 57 land cover classes (Strand, 2013). Across Europe, the LUCAS (Land Use/Cover Area frame statistical Survey) sample grid spaced at 2-km distance, is used to monitor and analyse land use changes across the European Union (Eurostat, 2003). The main idea behind sampling procedures, as opposed to complete mapping, is to limit the cost of data acquisition (Strand, 2013). To date, however, gridded sampling designs have rarely been used to collect and analyse historical land use data from archival maps (Loran, Ginzler, & Bürgi, submitted for publication; Munteanu et al., 2015), and most importantly, these sampling strategies have not been validated against a complete, continuous dataset to quantify their limitations.

Our goal here was to identify an efficient and accurate method to analyse historical land cover change at regional or even continental scale. Using the example of forest cover in the Polish Carpathians, we compared the accuracy of point sampling to wall-to-wall digitizing of historical maps, and evaluated the influence of the reconstruction method on forest cover change analysis. Furthermore, we assessed to what extent the differences in forest cover between point-based reconstruction and wall-to-wall mapping can be explained by sampling error, point position, and landscape context. We estimated also the time needed to assess forest cover and its changes using various reconstructions, for large study areas. Finally, we proposed a sound methodology for the efficient analysis of land use change from historical maps for large areas. Our research can thus inform a pan-European historical land use reconstruction initiative, using the already available Europe-wide point grid as a basis.

2. Materials and methods

Our study area covers the Polish Carpathians (20,000 km²), located in the northern part of the Carpathian arc with altitudes ranging from 300 m at the northern margin of the Carpathian Foothills and 2500 m in the Polish part of the Tatra Mts. (Balon et al., 1995). Typical landscapes consist of a mosaic of agricultural lands and forests, with most settlements located in valleys.

We conducted two independent forest cover reconstructions: a forest/non-forest map based on a regular set of points, and a

Table 1

Selected 19th/20th century topographic map surveys available on area covered by LUCAS point grid and Switzerland.

Map/country	Scale	Publishing date	Comments
The Second Military Survey	1:28,800	1806–1869	Scanned – http://mapire.eu/en/ , partly available in georeferenced form by http://www.arcanum.hu
Austria			
Croatia			
Czech Republic			
Hungary			
Italy (northern part)			
Poland (southern part)			
Romania (western part)			
Slovenia			
Slovakia			
Novaya Topograficheskaya Karta Zapadnoy Rossii	1:84,000	1883–1917	Partly available in electronic form – index available at http://easteurotopo.org/indices/s84/
Finland (southern part)			
Estonia			
Latvia			
Lithuania			
Poland (eastern part)			
Other maps			
Belgium (<i>Val der Maelen Map</i>)	1:20,000	1846–1854	
Bulgaria	1:40,000	1899–1905	
Cyprus	1:63,360	1878–1893	
Denamrk (<i>Hoje Målebordsblade</i>)	1:20,000	1842–1899	Scanned, georeferenced, available at http://download.kortforsyningen.dk/
France (<i>Carte de l'état-major</i>)	1:80,000	1820–1866	Scanned, available at http://www.geoportail.gouv.fr/
Germany (<i>Topographische Karten – Meßtischblätter Deutschland</i> ; map covers also western part of Poland)	1:25,000	1870–1943	Scanned, available at http://www.deutschefotothek.de/db/apsisa.dll/ete?action=viewPage&page=kartenforum-sachsen-messtischblaetter.xml or http://greif.uni-greifswald.de
Great Britain (<i>Ordnance Survey Maps</i>)	1:10,560	1843–1893	Scanned, available at http://www.british-history.ac.uk
Ireland (<i>Ordnance Survey Maps</i>)	1:10,560	1825–1846	Scanned, georeferenced, available at http://maps.osi.ie/publicviewer/
The Netherlands (<i>Topografische Militaire Kaart</i>)	1:50,000	1850–1864	Scanned and georeferenced, available via TU Delft- http://studenten.tudelft.nl/en/students/faculty-specific/architecture/facilities/tu-delfts-map-room/map-room-collection/digital-data/tmk-digital/
Portugal (<i>Carta Corográfica de Portugal ou Carta Geral do Reino</i>)	1:100,000	1856–1904	
Switzerland	1:100,000 ^a	1845–1865	Scanned, georeferenced, available by http://www.swisstopo.admin.ch/internet/swisstopo/en/home/products/maps/hist/dufour_digital.html

^a The original survey maps created in 1:25,000 scale for the Swiss plateau and 1:50,000 for mountain areas.Source: Böhme, 1989; Depuydt, 1975; Given, 2002; Konvitz, 1987; Tee, 2007; Timár et al., 2010; <http://observe-fp7.eu/NR/Bulgaria.pdf>, www.deutschefotothek.de, <http://www.british-history.ac.uk/>, <http://maps.osi.ie/>, www.eng.gst.dk, www.swisstopo.admin.ch.

contiguous polygon dataset. As a basis for the point analysis we used the 2-km grid of the pan-European LUCAS point network (Eurostat, 2003). We opted for a systematic sampling design to minimize problems related to spatial autocorrelation, which are common in land cover data (Aune-Lundberg & Strand, 2014; Legendre, 1993; Stehman, 2009). Each point was assessed using historical maps, and assigned as either forest or non-forest for each of three time periods (1860s, 1930s, 1970s). In the polygon approach, we obtained forest polygons either by manually digitizing them for the 1860s and 1930s maps, or by a semi-automated feature extraction procedure based on colour separation and morphological processing followed by manual correction, for the 1970s maps (Iwanowski & Kozak, 2012; Ostafin et al., submitted for publication). We obtained information on forest cover for the 1860s from the Austro-Hungarian Second Military Survey Map (1:28,800; quick looks available at <http://mapire.eu/>), for the 1930s from the Polish Military Map (1:100,000; maps can be consulted at <http://hgis.cartomatic.pl/>) and for 1970s from the Polish Topographic Map (1:25,000; available at <http://mapy.geoportal.gov.pl/>), created between 1975 and 1983 by the Head Office of Geodesy and Cartography (Główny Urząd Geodezji i Kartografii, GUGIK). All of these maps are valuable sources of land use and land cover information and have been widely used in land change studies (Affek,

2011; Kozak, 2003; Krassowski, 1974; Skaloš et al., 2011). The Polish Topographic Map was already available in the georeferenced form. For each map sheet of the Second Military Survey and the Polish Military Map we conducted the rectification based on at least 20 control points and using 2nd order polynomial transformation. The RMS error differed slightly between the maps and was on the order of 10–40 m (40–70 m for a few map sheets of the oldest edition) for the Second Military Survey (1860s) and 25–30 m for the Polish Military Map (1930s).

We compared the point and polygon datasets at two spatial scales: the regional scale, i.e., the whole territory of the Polish Carpathians, and at the local scale, i.e., the commune or Local Administrative Unit 2 (LAU 2) administrative level, focussing on communes that were completely within the boundaries of the Polish Carpathians ($n = 186$) (Fig. 1).

2.1. Datasets comparison at the regional level

For the regional-scale analysis, we compared the forest cover proportions of three different datasets. The first dataset was a 2-km point grid (hereafter 'original points'), consisting of 5064 LUCAS-based points covering the Polish Carpathians. Forest information was assigned manually by four students trained for this analysis,

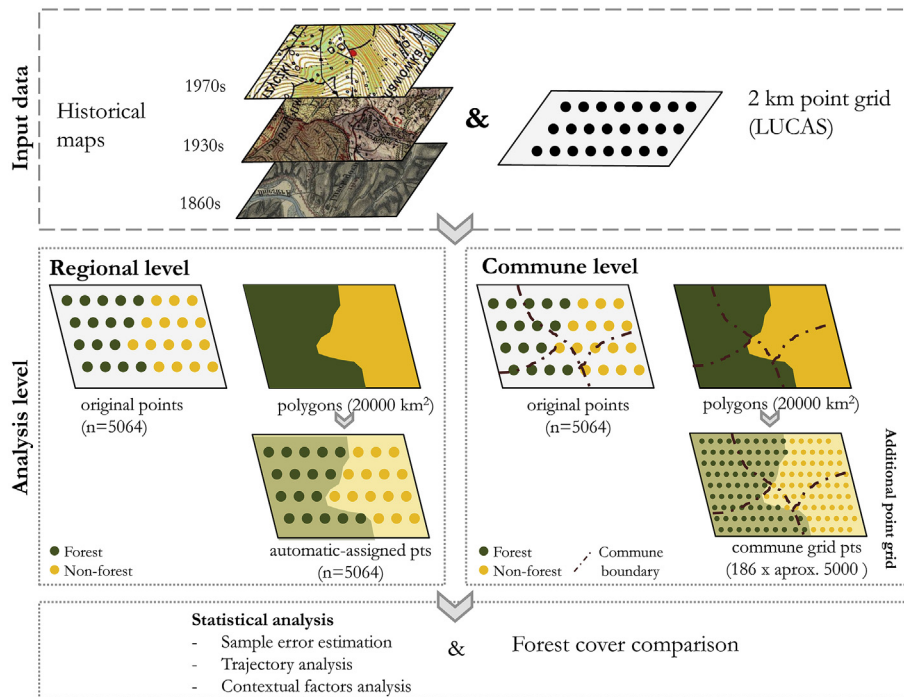


Fig. 1. General analytical approach flowchart.

who interpreted the map content. To avoid the problem of spatial inaccuracies of the maps, we used a backdating approach (Feranec, Hazeu, Christensen, & Jaffrain, 2007), referring point locations for each period to the respective locations in the latest map in the set (1970s). Forest cover was attributed to the point corresponding to its location on the 1970s map, even if it differed slightly from locations on previous maps (Fig. 2).

The second dataset was the polygon layer of forest cover (hereafter 'polygons'), which we digitized manually (at a scale ranging from 1:2000 to 1:4000) for the Polish Carpathians covering the 1860s and 1930s time layers. For the 1970s, the forest boundaries were obtained semi-automatically using colour separation, morphological analysis and manual correction of errors (Iwanowski & Kozak, 2012; Ostafin et al., submitted for publication). In order to use map algebra operations in the next steps, all polygon forest layers were converted into 10-m raster datasets (Fig. 3).

The third dataset was also a 2-km point grid, (hereafter 'automatically-assigned points'), equivalent to the set of 5064 LUCAS-based points as in the original points, but in this case the forest cover information was assigned automatically on the basis of forest and non-forest polygons for each time layer (1860s, 1930s, 1970s). These automatically-assigned points enabled us to assess whether differences between original points and polygons were due to the differences in the data types (point – polygon), or due to human errors and subjective interpretation of forest cover information at the original points using the backdating approach (e.g., errors in visual assignment of land use for points close to land use boundaries). We do not show this dataset in Fig. 3, because it is very similar to the original points, and does not differ visually at the scale of the whole study area.

When we compared polygon and point data we essentially compared the entire population with a sample. That is why we



Fig. 2. An example of the backdating approach. We analysed the point position on the older map (1930s) by considering the location of the point on the newest map (1970s).

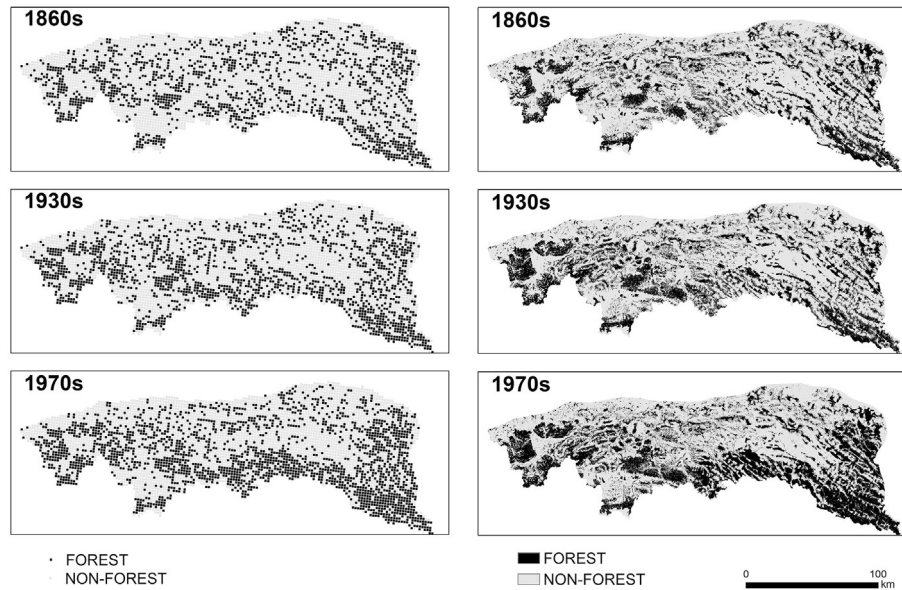


Fig. 3. Forest cover in the study areas in original points (left) and polygons (right).

started the analysis with the assessment of the sampling error (se). We calculated sampling error according to the transformed formula for sample size estimation (Eq. (1)):

$$se = \sqrt{\frac{z^2 \sigma^2 \left(\frac{N}{N-1} \right)}{n} - \frac{z^2 \sigma^2}{N-1}} \quad (1)$$

where n is the sample size (5064 points), N is the population size (202,708,528 pixels at 10-m resolution), z is the standard score (for confidence level = 99%), and σ^2 is the variance. Because the variance for a regular sample cannot be calculated using the formulae for a simple random sample (Koop, 1971), we divided the sample points into 1299 non-overlapping squares (local strata, each consisting of four neighbouring points (up to four on the study area peripheries), and calculated the variance in each of them. Regular sample variance (ReV) was a mean of the variance values of all the strata (Aune-Lundberg & Strand, 2014). In this way, we were able to estimate the margin of error of the regular sample for each map comparison.

One possible limitation of systematic samples is that some structures in the landscape can bias results. For instance, when the distance between points in a systematic sample accidentally corresponds to regular valley and ridge patterns a substantial overestimation of specific land use types may appear in the sample. The same might be true if there are chessboard-like landscape structures (Aune-Lundberg & Strand, 2014; Fattorini, Marcheselli, & Pisani, 2006). To verify whether such a situation affected our results, we shifted the automatically-assigned points by 100 m in both x and y direction, repeated this process twenty times, and compared results from these 40 new point grids (hereafter 'shifted grid points') with those from the original points and polygons. A shifting value of 100 m was chosen as appropriate in relation to the Carpathian landscape structure, where the distances between parallel valleys are typically several kilometres. Taking into account 100 m increments, shifting the points twenty times in both directions covered 10% of all possible locations of 2-km point grid in the landscape.

To assess how different reconstructions reflected forest cover changes over time we compared forest cover trajectories for all

reconstructions. Specifically, we calculated the proportions of pixels or points representing specific change for eight possible trajectories: 0-0-0, 0-0-1, 0-1-0, 0-1-1, 1-0-0, 1-0-1, 1-1-0, 1-1-1, where 0 means non-forest and 1 is forest. For instance, 0-0-1 indicates non-forest for 1860s and 1930s and forest cover for 1970s. Such comparison can serve as an important test if errors of specific reconstructions do not propagate significantly into related forest cover change products.

2.2. Datasets comparison at the local level

The comparison on the level of the whole territory of the Polish Carpathians provides the most robust results, but at this scale it is not possible to explore the effects of contextual factors, such as landscape pattern, on the accuracy of our systematic sample. Therefore we also analysed the differences among datasets at the level of communes (LAU 2). We analysed all 186 communes that were completely contained within the Polish Carpathians, and calculated the difference between the two forest cover reconstructions in two ways. First, we compared the original points and polygons for each commune. However, the number of original points in the communes differed substantially (ranging from 5 to 120). That is why we also compared polygons with regular grid points created for each commune separately (hereafter 'commune grid points'), for which we assigned automatically forest or non-forest attributes based on the existing polygons. The spacing between commune grid points for each commune was obtained by calculating the square root of the commune area divided by 5064 (number of points covering the entire Polish Carpathians) resulting in sample size varying between 5029 and 5216 depending on the commune. The sample size was chosen so that the sampling error was similar to that in the regional-scale analysis for the entire Polish Carpathians.

We hypothesised that differences among datasets may vary depending on landscape spatial patterns (e.g., points may better represent big and compact forest patches than small or complex ones) or on the size of the reference unit (e.g., points may capture larger units better than smaller ones). That is why we selected three contextual variables that could be associated with the absolute differences between forest cover in different datasets (original

points vs. polygons, and commune grid points vs. polygons): 1) forest cover (in %) in the commune, 2) area of the commune, and 3) forest edge-to-core ratio in the commune. We were concerned about collinearity among these variables in a multivariate model, but their correlation coefficient was never higher than 0.7. To identify the association between the absolute differences of forest cover and contextual variables, we parameterized generalised linear models (GLM). Regression models were built separately for each time period (1860s, 1930s and 1970s).

3. Results

3.1. Differences at the regional level

The results for the entire Polish Carpathians showed that original points had slightly higher forest cover estimates than both polygons and automatically-assigned points (Fig. 4). Over-estimation occurred in each time period, but it was highest for the 1930s (3.24% difference, compared to 1.87% for the 1860s, and 1.01% for the 1970s; Fig. 4). Differences between polygons and automatically-assigned points did not exceed 0.5 percentage points of forest cover at any time period.

The sampling error (calculated according to Eq. (1)) did not exceed 1.5% for any time period (1.37% for the 1860s, and 1.42% for the 1930s and 1970s). Only for the 1970s the differences between the original points and polygons for the whole territory of the Polish Carpathians were lower than the sampling error.

The comparison of forest cover among the shifted grid points showed that differences among 40 datasets for 1970s were higher (2.28%) than for the 1930s (1.58%), and 1860s (1.74%; Fig. 5). In all cases the differences exceeded the sampling error values.

When we compared the forest cover change trajectories among our reconstructions, differences were minor. We found the highest differences for constant stable forest cover trajectory (1-1-1), which was 24% based on the original points, compared to 21% for the other datasets (Table 2). Only in two other trajectory categories, 0-0-1 and 1-0-1, were the differences higher than 1%. For the latter, however, polygon reconstruction yielded almost twice as many occurrences as the reconstruction based on original points. In these cases, the highest proportions were recorded for polygons and the lowest for original points. In all the other trajectories, the differences among datasets did not exceed 0.7%.

Comparison of the time efficiency between the methods employed for the regional forest cover change analysis showed that we needed around eight times more time to obtain forest

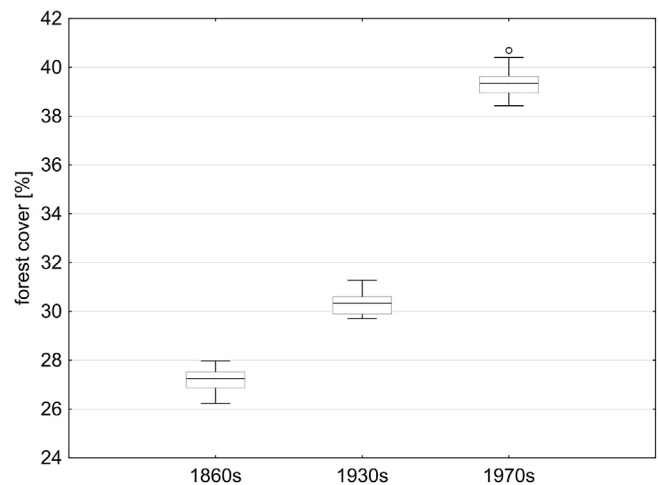


Fig. 5. Forest cover estimate variation depending on the location of the sample point grids; $n = 40$ for each period.

Table 2

Trajectory analysis of forest cover change among different datasets (1 – forest, 0 – non-forest).

Trajectory (1860s–1930s–1970s)	Original points [%]	Polygons [%]	Automatically- assigned points [%]
0-0-0	54.84	55.31	55.46
1-1-1	24.29	21.23	21.43
0-0-1	8.00	9.44	9.31
0-1-1	6.60	5.92	6.18
1-0-0	2.43	2.37	2.35
0-1-0	1.58	1.96	1.89
1-0-1	1.52	3.01	2.54
1-1-0	0.75	0.75	0.84

information via a wall-to-wall mapping than by assigning land use manually to 2-km point grid. This is an average estimation for the whole territory of our study area, and the time differences differed within the region due to variety of landscape patterns. On average, time needed to assign land use information to one grid point was 80–90 s, once the maps were scanned and georeferenced.

3.2. Differences at the local level

The differences between original points and polygons varied substantially among communes (min – 0.01%, max – 33.7%, median <6% for each period). The results of the linear regression models showed that the commune area was the only statistically significant variable ($p < 0.0001$ for 1860s and 1930s, $p < 0.001$ for 1970s), regardless of the period (Table 3). The other variables were either statistically insignificant (edge-to-core ratio) or significant at the level of $p = 0.1$ (forest cover proportion).

When we compared forest cover differences between polygons and dense commune grid points, where the number of points was higher than 5000 for each of the 186 Carpathian communes, we found differences of less than 1% in all cases and the median value for each of the three time periods lower than 0.15% (Fig. 6).

The results of the linear regression models, parameterized to explain the role of different factors, showed some differences among periods and variables (Table 4), but in general the responses of the independent variables were similar among time periods, both in terms of direction and magnitude (when statistically significant). Models for 1930s and for 1970s explained only slightly more than 10% of the variance of forest cover differences.

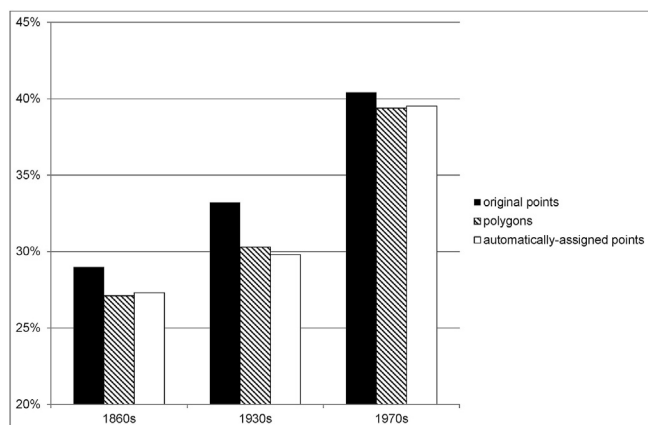


Fig. 4. Forest cover proportions in the Polish Carpathians according to different datasets.

Table 3

Association between percent forest cover differences and contextual factors for original points and polygons: multiple linear regression model, $n = 186$ (significance – * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$, **** $p < 0.001$).

Variables			
1860s			
Model R ²	0.09****		
Unit		β	T
Forest cover*	%	0.16	1.73
Commune area****	ha	–0.29	–4.03
Edge-to-core ratio	–	0.09	0.04
1930s			
Model R ²	0.13****		
Unit		β	T
Forest cover**	%	0.29	3.09
Commune area****	ha	–0.31	–4.44
Edge-to-core ratio	–	0.13	1.39
1970s			
Model R ²	0.08***		
Unit		β	T
Forest cover*	%	0.20	1.89
Commune area****	ha	–0.31	–3.92
Edge-to-core ratio	–	0.10	0.98

Table 4

Association between percent forest cover differences and contextual factors for commune point grids and polygons: multiple linear regression model, $n = 186$ (significance – * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$, **** $p < 0.001$).

Variables			
1860s			
Model R ²	0.03		
Unit		β	T
Forest cover	%	0.09	0.92
Commune area	ha	0.08	1.02
Edge-to-core ratio*	–	0.21	2.27
1930s			
Model R ²	0.10****		
Unit		β	T
Forest cover**	%	0.22	2.37
Commune area****	ha	0.26	3.67
Edge-to-core ratio**	–	0.20	2.18
1970s			
Model R ²	0.13****		
Unit		β	T
Forest cover**	%	0.25	2.36
Commune area****	ha	0.28	3.49
Edge-to-core ratio**	–	0.21	2.16

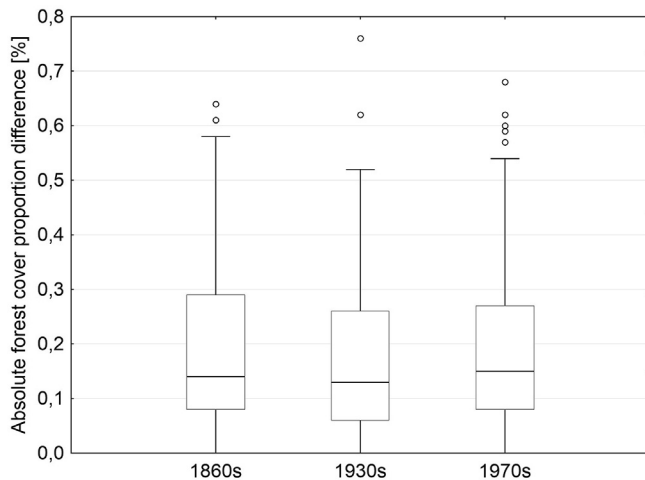


Fig. 6. Differences in percent forest cover between polygon data and point (automatically extracted) data for Carpathian communes, $n = 186$.

Nevertheless, in both these models all independent variables were statistically significant ($p < 0.05$). In 1860s model, the only significant variable was the edge-to-core ratio (Table 4).

4. Discussion

The main objective of our paper was to identify a time effective land use reconstruction method for broad-scale land change analysis. We compared regular point-based and wall-to-wall mapping reconstructions at two spatial scales (regional and local), focussing on the influence of point position, sampling error, human errors and potential contextual factors. We found that results from the point-based reconstruction did not differ substantially from wall-to-wall-mapping but required roughly one eighth of the time spent on wall-to-wall-mapping. This is important, because our methodology can be used anywhere where spatial land use information in the form of historical maps is available, allowing to extend the time scale of existing land change assessments by many decades if not centuries for many countries, especially in Europe.

In regional scale reconstructions, the differences in forest cover

proportions were the highest for the 1930s (3.24%), exceeding the sampling error value (1.42%). The relatively small differences that we found between point and polygon approaches were not propagated to forest cover trajectories analyses, highlighting the value of the point-based approach for land change assessments. The comparison of different trajectory proportions among three datasets revealed that the maximum difference did not exceed 3% for any of the major trajectories. For rare trajectories, however, relative differences could be higher. The overestimation of forest in 1930s for point-based reconstruction caused the highest differences in 1-1-1 and 1-0-1 trajectories, suggesting that manually assigned point values in 1930s were frequently forest instead of non-forest if point values were forest also in the 1860s and 1970s. This might be explained by our backdating approach, because assigning land cover value to the point according to its location on the map from 1970s (1:25,000) was particularly difficult and subjective for 1930s (1:100,000) due to the 1930s map generalisation. It shows that human error is an issue in all analyses of historical maps. Both polygon digitizing and the assignment of land use classes to the original points were done by the same group of people and based on the same map sources. However, due to differences in the quality and scale of maps, and in forest representations among maps, the visual interpretation could generate some errors.

Reliable point-based reconstructions could be derived not only via a manual assignment, but also through an automated extraction of land use information to points. Importantly, this means it is possible to use existing land use polygons to complement broader point-based databases. The automatically assigned points gave very similar results to polygons when comparing forest proportion in regional scale. However, our shifting point grid experiment showed that point position may influence the results. Forest proportion differences among shifted data were lower for datasets based on more generalised maps (1:100,000) than for the ones based on more detailed sources (1:25,000; 1:28,800).

The analysis conducted on a local level showed the importance of sampling strategy design in point-based reconstructions. While simple comparison of original points and polygons at this level showed that maximal differences were up to 34% (with median less than 6% for each period), the dense grid points for communes did not differ from polygons by more than 0.8%. In other words, if the point grid has low density, then the differences between datasets depend on the area of reference unit as showed by our regression

models. This problem is noticeable also for the smallest European countries where LUCAS network is not dense enough to reach required level of accuracy (Gallego & Delincé, 2010). If the point density is properly defined, then the differences among datasets depended on other factors, such as forest fragmentation. We used a 2-km point grid because it is widely used across Europe and easy to expand to surrounding areas, but the sampling size should be reconsidered for local studies. In such cases, denser point grids that are nested within the 2-km grid, would be more reliable, such as the point grids tested and verified against national inventory data in French Guyana (Eva et al., 2010). Tests conducted with LUCAS point grid by Gallego and Delincé (2010) define the exact number of points needed to capture given land use with defined coefficient of variation (1%, 2% or 5%). Answering the very basic question – what is the minimum number of points required to capture the land use for defined study area – depends on the level of accuracy that is required (e.g. less than 1000 points for 5% coefficient of variation).

Using regular point grids is also effective to minimize spatial autocorrelation problem (Flores, Martinez, & Ferrer, 2003). However, regular point grids can be problematic when many land use classes are present, because regular sample may under- or overestimate rare classes (Gallego & Delincé, 2010). The decision about appropriate representation of rare classes – the detectability problem (Strand, 2013) – should be made before starting a land survey. However, our study was not affected by this issue, because we analysed only two land cover categories. In Switzerland the land use catalogue contains 74 classes, but the point density is 100 m (SFSO, 2001). In Norway, where 57 land cover categories are recorded, the problem of rare classes occurrence was solved by implying additional Primary Statistical Units (PSU, 1500 × 600 m) around each of the 18-km grid point. The area of PSU is where a wall-to-wall inventory is conducted, and that increasing the likelihood of the occurrence of rare classes (Strand, 2013). Last but not least, using regular point grid instead of wall-to-wall mapping, does not allow to conduct detailed landscape pattern analysis, which is a drawback of the method.

Time efficiency between our two reconstruction approaches differed slightly depending on the archival map quality. In our analyses, assigning manually land use information to points was at least eight times faster than wall-to-wall digitizing, based on a 2-km point grid, diverse Carpathian landscape pattern, and quality of maps. One alternative that we did not compare here for all the maps is automatic feature extraction from scanned paper maps, based on colour separation and morphological processing. Such approaches can be very fast (Ostafin et al., submitted for publication). However, the accuracy of the automatic feature extraction is comparable to the manual vectorisation only when high quality map sheets are available, being substantially lower for old archival maps due to e.g. variable cartographic representation or degradation of original colour prints (Ostafin et al., submitted for publication). Furthermore, automatic procedures are usually prepared for one, dedicated land use class. That is why point-based reconstructions are more effective when analysing diverse cartographic sources from different periods or several different land use classes at the same time.

Our research showed that 80–90 s were needed to assign land use to one LUCAS point based on historical maps provided they are scanned and georeferenced. Taking into account the total number of LUCAS points for the European Union (990,000), we estimate an approximate time frame to assign historical land use to the whole point grid for one time period as 135–155 person months (Table 5). Many historical topographic and military maps of European countries are already scanned and even available in georeferenced form (Table 1), and this means that the main problem now is how to analyse them efficiently. Our analysis showed that the point-based

Table 5

Estimation of time needed to assign historical land use to 2-km LUCAS grid for EU.

	Time requirements
Time needed for one point	80–90 s
The Polish Carpathians (5064 points)	110–130 h
LUCAS network (990,000 points)	135–155 person months

reconstruction might be an appropriate solution also at the Pan-European scale. As the Carpathian landscape is diverse, we suppose that it was more difficult to conduct our research in this mountain region compared to many of the less complex European lowlands. In other words, our successful test in the mountains is promising for most European landscapes. Additionally, available local studies that provide historical polygon land use maps could be easily used to extract the land use attributes to the LUCAS points. For territories where no such layers are available, the analysis could be done by manually assigning past land use information to points. A potential Pan-European historical land use reconstruction initiative based on LUCAS grid requires thus only a commonly defined land use reporting scheme, assuring the semantic comparability. Crowdsourcing may offer a cost-effective solution to complete such a dataset (Fritz et al., 2009).

So far, available land use reconstructions for large areas have been based on statistical data modelling. This is the most common solution for global reconstructions (Klein Goldewijk et al., 2010; Ramankutty & Foley, 1999), and this approach has also been used at continental scales (Fuchs, Herold, Verburg, & Clevers, 2013; Kaplan, Krumhardt, & Zimmermann, 2009). At regional scale, where the use of historical maps is possible, the reconstructions based on actual spatial land cover data rather than environmental proxies are much more reliable (Fuchs et al., 2015). The point-based reconstruction that we propose could serve as a valuable validation data for existing global datasets and many global land use reconstructions could benefit from a detailed European historical land use map. Our research was based on existing LUCAS network, which provides harmonised, current land use information for all EU-28 countries, and area of just under 4.5 million square kilometres. The value of spatially explicit, historical land use database for all of Europe over the last 200 years is, in our opinion, well worth the effort.

5. Conclusions

Historical land use reconstructions are important for climate, carbon or biodiversity assessments (Fuchs et al., 2013; Gimmi et al., 2011; Ramankutty & Foley, 1999). They can be based on various data sources influencing the temporal and spatial extent of the analysis (Bürgi, Hersperger, Hall, Southgate, & Schneeberger, 2007; Yang et al., 2014; Ye, Wei, Li, & Fang, 2015). Historical maps have one important advantage over land use statistics in that they show exact boundaries of various land use types. There are several problems when using historical maps for land use reconstructions over large areas, including map availability, accurate georeferencing, and – finally – the time consuming step of map vectorisation. Fortunately, the availability of high resolution scans of historical maps has been rapidly growing in both libraries and online collections, especially in Europe. Some of these maps cover large areas and are already available in a georeferenced form (Timár et al., 2010). There are also initiatives focused on using the power of crowdsourcing in georeferencing extensive maps collections (Kowal & Prídál, 2012). In this context, our analysis answers the question how to digitize the content. We showed that a regular point grid can serve as a basis for historical land use database with a

level of accuracy equivalent to standard polygon land use layers, and demonstrated time effectiveness of point-based reconstructions as compared to the much more time consuming digitizing of polygons for large areas.

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References

- Affek, A. (2011). Landscape continuity versus landscape transformation: a case study in the Wiar River catchment, Polish Carpathians (1780–2000). *The Problems of Landscape Ecology*, 30, 147–155.
- Allan, E., Bosdorf, O., Dormann, C. F., Prati, D., Gossner, M. M., Tscharrntke, T., et al. (2014). Interannual variation in land-use intensity enhances grassland multi-diversity. *Proceedings of the National Academy of Sciences of the United States of America*, 111(1), 308–313. <http://dx.doi.org/10.1073/pnas.1312213111>.
- Aune-Lundberg, L., & Strand, G.-H. (2014). Comparison of variance estimation methods for use with two-dimensional systematic sampling of land use/land cover data. *Environmental Modelling and Software*, 61, 87–97. <http://dx.doi.org/10.1016/j.envsoft.2014.07.001>.
- Axelsson, A.-L., Östlund, L., & Hellberg, E. (2002). Changes in mixed deciduous forests of boreal Sweden 1866–1999 based on interpretation of historical records. *Landscape Ecology*, 17(5), 403–418. <http://dx.doi.org/10.1023/A:1021226600159>.
- Balon, J., German, K., Kozak, J., Malara, H., Widacki, W., & Ziaja, W. (1995). Regiony fizycznogeograficzne Polskich Karpat. In J. Warszyńska (Ed.), *Karpaty Polskie* (pp. 117–130).
- Belward, A. S., & Skoien, J. O. (2014). Who launched what, when and why; trends in global land-cover observation capacity from civilian earth observation satellites. *ISPRS Journal of Photogrammetry and Remote Sensing*, 103, 115–128. <http://dx.doi.org/10.1016/j.isprsjprs.2014.03.009>.
- Böhme, R. (1989). *Inventory of world topographic mapping Vol. 1 Western Europe, North America and Australasia* (p. 196). Elsevier Applied Science Publishers.
- Brown, I., Castellazzi, M., & Feliciano, D. (2014). Comparing path dependence and spatial targeting of land use in implementing climate change responses. *Land*, 3, 850–873. <http://dx.doi.org/10.3390/land3030850>.
- Bürgi, M., Hersperger, A. M., Hall, M., (Russel) Southgate, E. W. B., & Schneeberger, N. (2007). Using the past to understand the present land use and land cover. In F. Kienast, O. Wildi, & S. Ghosh (Eds.), *A changing world. Challenges for landscape research* (pp. 133–144). Springer Netherlands. http://dx.doi.org/10.1007/978-1-4020-4436-6_9.
- Bürgi, M., Hersperger, A. M., & Schneeberger, N. (2005). Driving forces of landscape change – current and new directions. *Landscape Ecology*, 19, 857–868. <http://dx.doi.org/10.1007/s10980-005-0245-3>.
- Bürgi, M., Salzmann, D., & Gimmi, U. (2015). 264 years of change and persistence in an agrarian landscape: a case study from the Swiss lowlands. *Landscape Ecology*, 30(7), 1321–1333. <http://dx.doi.org/10.1007/s10980-015-0189-1>.
- Chavez, A. B., & Perz, S. G. (2013). Path dependency and contingent causation in policy adoption and land use plans: the case of Southeastern Peru. *Geoforum*, 50, 138–148. <http://dx.doi.org/10.1016/j.geoforum.2013.09.003>.
- Depuydt, F. (1975). The large scale mapping of Belgium, 1800–1850. *Imago Mundi: The International Journal for the History of Cartography*, 27(1), 23–26. <http://dx.doi.org/10.1080/03085697508592404>.
- Eurostat. (2003). *The Lucas survey. Luxembourg: European Statisticians Monitor Territory*.
- Eva, H., Carboni, S., Achard, F., Stach, N., Durieux, L., Faure, J.-F., et al. (2010). Monitoring forest areas from continental to territorial levels using a sample of medium spatial resolution satellite imagery. *ISPRS Journal of Photogrammetry and Remote Sensing*, 65(2), 191–197. <http://dx.doi.org/10.1016/j.isprsjprs.2009.10.008>.
- FAO. (2010). *Global forest resources assessment 2010-main report – FAO forestry paper 163*.
- Fattorini, L., Marcheselli, M., & Pisani, C. (2006). A three-phase sampling strategy for large-scale multiresource forest inventories. *Journal of Agricultural, Biological, and Environmental Statistics*, 11(3), 296–316. <http://dx.doi.org/10.1198/108571106X130548>.
- Feranec, J., Hazeu, G., Christensen, S., & Jaffrain, G. (2007). Corine land cover change detection in Europe (case studies of the Netherlands and Slovakia). *Land Use Policy*, 24(1), 234–247. <http://dx.doi.org/10.1016/j.landusepol.2006.02.002>.
- Flores, L. A., Martinez, I. L., & Ferrer, M. C. (2003). Systematic sample design for the estimation of spatial means. *Environmetrics*, 14(1), 45–61. <http://dx.doi.org/10.1002/env.564>.
- Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative Inquiry*, 12(2), 219–245. <http://dx.doi.org/10.1177/1077800405284363>.
- Foley, J. A., Defries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., et al. (2005). Global consequences of land use. *Science*, 309(5734), 570–574. <http://dx.doi.org/10.1126/science.1111772>.
- Foster, D., Swanson, F., Aber, J., Burke, I., Brokaw, N., Tilman, D., et al. (2003). The importance of land-use legacies to ecology and conservation. *BioScience*, 53(1), 77. [http://dx.doi.org/10.1641/0006-3568\(2003\)053\[0077:TOLUL\]2.0.CO;2](http://dx.doi.org/10.1641/0006-3568(2003)053[0077:TOLUL]2.0.CO;2).
- Fritz, S., McCallum, I., Schill, C., Perger, C., Grillmayer, R., Achard, F., et al. (2009). Geo-Wiki.org: the use of crowdsourcing to improve global land cover. *Remote Sensing*, 1(3), 345–354. <http://dx.doi.org/10.3390/rs1030345>.
- Fuchs, R., Herold, M., Verburg, P. H., & Clevers, J. G. P. W. (2013). A high-resolution and harmonized model approach for reconstructing and analysing historic land changes in Europe. *Biogeosciences*, 10, 1543–1559. <http://dx.doi.org/10.5194/bg-10-1543-2013>.
- Fuchs, R., Verburg, P. H., Clevers, J. G. P. W., & Herold, M. (2015). The potential of old maps and encyclopaedias for reconstructing historic European land cover/use change. *Applied Geography*, 59, 43–55. <http://dx.doi.org/10.1016/j.apgeog.2015.02.013>.
- Gallego, J., & Delincé, J. (2010). The European land use and cover area-frame statistical survey. *Agricultural Survey Methods*, 168, 149–168. <http://dx.doi.org/10.1002/9780470665480.ch10>.
- Gerard, F., Petit, S., Smith, G., Thomson, A., Brown, N., Manchester, S., et al. (2010). Land cover change in Europe between 1950 and 2000 determined employing aerial photography. *Progress in Physical Geography*, 34(2), 183–205. <http://dx.doi.org/10.1177/0309133309360141>.
- Gimmi, U., Lachat, T., & Bürgi, M. (2011). Reconstructing the collapse of wetland networks in the Swiss lowlands 1850–2000. *Landscape Ecology*, 26(8), 1071–1083. <http://dx.doi.org/10.1007/s10980-011-9633-z>.
- Given, M. (2002). Maps, Fields, and boundary Cairns: demarcation and resistance in Colonial Cyprus. *International Journal of Historical Archaeology*, 6(1), 1–22. <http://dx.doi.org/10.1023/A:1014862155523>.
- Godet, L., & Thomas, A. (2013). Three centuries of land cover changes in the largest French Atlantic wetland provide new insights for wetland conservation. *Applied Geography*, 42, 133–139. <http://dx.doi.org/10.1016/j.apgeog.2013.05.011>.
- Griffiths, P., Kuemmerle, T., Baumann, M., Radeloff, V. C., Abrudan, I. V., Lieskovsky, J., et al. (2014). Forest disturbances, forest recovery, and changes in forest types across the Carpathian ecoregion from 1985 to 2010 based on Landsat image composites. *Remote Sensing of Environment*, 151, 72–88. <http://dx.doi.org/10.1016/j.rse.2013.04.022>.
- Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., et al. (2013). High-resolution global maps of 21st-century forest cover change. *Science*, 342(6160), 850–853. <http://dx.doi.org/10.1126/science.1244693>.
- Heald, C. L., & Spracklen, D. V. (2015). Land use change impacts on air quality and climate. *Chemical Reviews*, 115(10), 4476–4496. <http://dx.doi.org/10.1021/cr500446g>.
- Iwanowski, M., & Kozak, J. (2012). Automatic detection of forest regions on scanned old maps. *Przegląd Elektrotechniczny*, 88(4), 249–252.
- Jepsen, M. R., Reenberg, A., Kümmerle, T., Müller, D., Erb, K., Haberl, H., et al. (2013). *Visions of land use transitions in Europe. Technological, institutional and economic drivers of land use change* (p. 226).
- Kaim, D., Kozak, J., Ostafin, K., Dobosz, M., Ostapowicz, K., Kolecka, N., et al. (2014). Uncertainty in historical land-use reconstructions with topographic maps. *Quaestiones Geographicae*, 33(3), 55–63. <http://dx.doi.org/10.2478/quageo-2014-0029>.
- Kaplan, J. O., Krumhardt, K. M., & Zimmermann, N. (2009). The prehistoric and preindustrial deforestation of Europe. *Quaternary Science Reviews*, 28(27–28), 3016–3034. <http://dx.doi.org/10.1016/j.quascirev.2009.09.028>.
- Klein Goldewijk, K., Beusen, A., & Janssen, P. (2010). Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1. *The Holocene*, 20(4), 565–573. <http://dx.doi.org/10.1177/0959683609356587>.
- Konvitz, J. (1987). *Cartography in France, 1660–1848: Science, engineering, and statecraft* (p. 194). University of Chicago Press.
- Koop, J. C. (1971). On Splitting a systematic sample for variance estimation. *The Annals of Mathematical Statistics*, 42(3), 1084–1087.
- Kowal, K. C., & Pridal, P. (2012). Online georeferencing for libraries: the British Library implementation of georeferencer for spatial metadata enhancement and public engagement. *Journal of Map & Geography Libraries*, 8(3), 276–289. <http://dx.doi.org/10.1080/15420353.2012.700914>.
- Kozak, J. (2003). Forest cover change in the western Carpathians in the past 180 years. *Mountain Research and Development*. [http://dx.doi.org/10.1659/0276-4741\(2003\)023\[0369:FCCITW\]2.0.CO;2](http://dx.doi.org/10.1659/0276-4741(2003)023[0369:FCCITW]2.0.CO;2).
- Krassowski, B. (1974). *Polska kartografia wojskowa w latach 1918–1945*. Warszawa: Wydawnictwo MON.
- Lambin, E. F., Geist, H., & Rindfuss, R. R. (2006). Introduction: local processes with global impacts. In E. F. Lambin, & H. Geist (Eds.), *Land-use and land-cover change local processes and global impacts* (pp. 1–8). Springer Berlin Heidelberg. http://dx.doi.org/10.1007/3-540-32202-7_1.

- Lambin, E. F., & Meyfroidt, P. (2010). Land use transitions: socio-ecological feedback versus socio-economic change. *Land Use Policy*, 27(2), 108–118. <http://dx.doi.org/10.1016/j.landusepol.2009.09.003>.
- Lawler, J. J., Lewis, D. J., Nelson, E., Plantinga, A. J., Polasky, S., Withey, J. C., et al. (2014). Projected land-use change impacts on ecosystem services in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, 111(20), 7492–7497. <http://dx.doi.org/10.1073/pnas.1405557111>.
- Legendre, P. (1993). Spatial autocorrelation: trouble or new Paradigm? *Ecology*, 74(6), 1659–1673.
- Leyk, S., Boesch, R., & Weibel, R. (2005). A conceptual framework for uncertainty investigation in map-based land cover change modelling. *Transactions in GIS*, 9(3), 291–322. <http://dx.doi.org/10.1111/j.1467-9671.2005.00220.x>.
- Loran, C., Ginzler, C., & Bürgi, M. (2015). Evaluating forest transition based on a multi-scale approach: forest area dynamics in Switzerland 1850–2000. *Regional Environmental Change* (accepted).
- Meyfroidt, P., Lambin, E. F., Erb, K.-H., & Hertel, T. W. (2013). Globalization of land use: distant drivers of land change and geographic displacement of land use. *Current Opinion in Environmental Sustainability*, 5(5), 438–444. <http://dx.doi.org/10.1016/j.cosust.2013.04.003>.
- Mikusinska, A., Zawadzka, B., Samojlik, T., Jędrzejewska, B., & Mikusiński, G. (2013). Quantifying landscape change during the last two centuries in Białowieża Primeval Forest. *Applied Vegetation Science*, 16(2), 217–226. <http://dx.doi.org/10.1111/j.1654-109X.2012.01220.x>.
- Munteanu, C., Kuemmerle, T., Boltziar, M., Butsic, V., Gimmi, U., Lúboš, H., et al. (2014). Forest and agricultural land change in the Carpathian region-A meta-analysis of long-term patterns and drivers of change. *Land Use Policy*, 38, 685–697. <http://dx.doi.org/10.1016/j.landusepol.2014.01.012>.
- Munteanu, C., Kuemmerle, T., Keuler, N. S., Müller, D., Balázs, P., Dobosz, M., et al. (2015). Legacies of 19th century land use shape contemporary forest cover. *Global Environmental Change*, 34, 83–94. <http://dx.doi.org/10.1016/j.gloenvcha.2015.06.015>.
- Newbold, T., Hudson, L. N., Hill, S. L. L., Contu, S., Lysenko, I., Senior, R. A., et al. (2015). Global effects of land use on local terrestrial biodiversity. *Nature*, 520(7545), 45–50. <http://dx.doi.org/10.1038/nature14324>.
- Nordrhein-Westfalen. (1967). *Kartenaufnahme der Rheinlande durch Tranchot und von Müffling 1803-1820. Bonn*.
- Ostafin, K., Iwanowski, M., Cacko, A., Kozak, J., Gimmi, U., Kaim, D., et al. (2015). Detection of forest cover on historical topographic maps based on colour segmentation and morphological image processing (in revision).
- Plewe, B. (2002). The nature of uncertainty in historical geographic information. *Transactions in GIS*, 6(4), 431–456. <http://dx.doi.org/10.1111/1467-9671.00121>.
- Plieninger, T., Schaich, H., & Kizos, T. (2010). Land-use legacies in the forest structure of silvopastoral oak woodlands in the Eastern Mediterranean. *Regional Environmental Change*, 11(3), 603–615. <http://dx.doi.org/10.1007/s10113-010-0192-7>.
- Pongratz, J., Reick, C., Raddatz, T., & Claussen, M. (2008). A reconstruction of global agricultural areas and land cover for the last millennium. *Global Biogeochemical Cycles*, 22(April), GB3018. <http://dx.doi.org/10.1029/2007GB003153>.
- Potapov, P., Hansen, M. C., Gerrand, A. M., Lindquist, E. J., Pittman, K., Turubanova, S., et al. (2011). The global landsat imagery database for the FAO FRA remote sensing survey. *International Journal of Digital Earth*, 4(1), 2–21. <http://dx.doi.org/10.1080/17538947.2010.492244>.
- Ramankutty, N., & Foley, J. A. (1999). Estimating historical changes in global land cover: croplands from 1700 to 1992. *Global Biogeochemical Cycles*, 13(4), 997–1027. <http://dx.doi.org/10.1029/1999GB900046>.
- Rudel, T. K. (2008). Meta-analyses of case studies: a method for studying regional and global environmental change. *Global Environmental Change*, 18, 18–25. <http://dx.doi.org/10.1016/j.gloenvcha.2007.06.001>.
- SFSO. (2001). *The changing face of land-use: Land use statistics of Switzerland* (p. 31). Neuchâtel.
- Shandra, O., Weisberg, P., & Martazinova, V. (2013). Influences of climate and land use history on Forest and timberline dynamics in the Carpathian mountains during the Twentieth Century. In J. Kozak, K. Ostapowicz, A. Bytnerowicz, & B. Wyżga (Eds.), *The Carpathians: integrating nature and society towards sustainability* (pp. 209–223). Springer.
- Sitko, I., & Troll, M. (2008). Timberline changes in relation to Summer farming in the western Chornohora (Ukrainian Carpathians). *Mountain Research and Development*, 28(3/4), 263–271. <http://dx.doi.org/10.1659/mrd.0963>.
- Skaloš, J., Weber, M., Lipský, Z., Trpáková, I., Šantrůčková, M., Uhlířová, L., et al. (2011). Using old military survey maps and orthophotograph maps to analyse long-term land cover changes – case study (Czech Republic). *Applied Geography*, 31(2), 426–438. <http://dx.doi.org/10.1016/j.apgeog.2010.10.004>.
- Song, D.-X., Huang, C., Sexton, J. O., Channan, S., Feng, M., & Townshend, J. R. (2015). Use of Landsat and Corona data for mapping forest cover change from the mid-1960s to 2000s: case studies from the Eastern United States and Central Brazil. *ISPRS Journal of Photogrammetry and Remote Sensing*, 103, 81–92. <http://dx.doi.org/10.1016/j.isprsjprs.2014.09.005>.
- Stehman, S. V. (2009). Sampling designs for accuracy assessment of land cover. *International Journal of Remote Sensing*, 30(20), 5243–5272. <http://dx.doi.org/10.1080/01431160903131000>.
- Stocker, B. D., Feissli, F., Strassmann, K. M., Spahni, R., & Joos, F. (2014). Past and future carbon fluxes from land use change, shifting cultivation and wood harvest. *Tellus B*, 66. <http://dx.doi.org/10.3402/tellusb.v66.23188>.
- Strand, G.-H. (2013). The Norwegian area frame survey of land cover and outfield land resources. *Norsk Geografisk Tidsskrift – Norwegian Journal of Geography*, 67(1), 24–35. <http://dx.doi.org/10.1080/00291951.2012.760001>.
- Tee, M. (2007). Historical maps in internet gis solutions quiz: an example of community-based web-gis. In *Proceedings of the XXIII International Cartographic Conference* (pp. 233–237). Moscow.
- Timár, G., Biszak, S., Székely, B., & Molnár, G. (2010). Digitized maps of the Habsburg military surveys – overview of the project of ARCANUM Ltd. (Hungary). *Preservation in Digital Cartography*, 273–283. <http://dx.doi.org/10.1007/978-3-642-12733-5>.
- Van Asselen, S., Verburg, P. H., Vermaat, J. E., & Janse, J. H. (2013). Drivers of wetland conversion: a global meta-analysis. *PLoS One*, 8(11), e81292. <http://dx.doi.org/10.1371/journal.pone.0081292>.
- Wulf, M., & Rujner, H. (2010). A GIS-based method for the reconstruction of the late eighteenth century forest vegetation in the Prignitz region (NE Germany). *Landscape Ecology*, 26(2), 153–168. <http://dx.doi.org/10.1007/s10980-010-9555-1>.
- Yang, Y., Zhang, S., Yang, J., Chang, L., Bu, K., & Xing, X. (2014). A review of historical reconstruction methods of land use/land cover. *Journal of Geographical Sciences*, 24(4), 746–766. <http://dx.doi.org/10.1007/s11442-014-1117-z>.
- Ye, Y., Wei, X., Li, F., & Fang, X. (2015). Reconstruction of cropland cover changes in the Shandong Province over the past 300 years. *Scientific Reports*, 5, 13642. <http://dx.doi.org/10.1038/srep13642>.

Web references

- <http://easteurotopo.org/indices/s84/>. Accessed 23.10.15.
- <http://download.kortforsyningen.dk/>. Accessed 23.10.15.
- <http://geoportal.cuzk.cz/>. Accessed 23.10.15.
- <http://greif.uni-greifswald.de>. Accessed 23.10.15.
- <http://gso.gbv.de/>. Accessed 23.10.15.
- <http://hgis.cartomatic.pl>. Accessed 23.10.15.
- <http://mapire.eu/en/>. Accessed 23.10.15.
- <http://maps.nls.uk/>. Accessed 23.10.15.
- <http://maps.osi.ie/publicviewer>. Accessed 23.10.15.
- <http://maps.geoportal.gov.pl>. Accessed 23.10.15.
- <http://observe-fp7.eu/NR/Bulgaria.pdf>. Accessed 23.10.15.
- <http://studenten.tudelft.nl/en/students/faculty-specific/architecture/facilities/tu-delfts-map-room/map-room-collection/digital-data/tmk-digital/>. Accessed 23.10.15.
- http://www.swisstopo.admin.ch/internet/swisstopo/en/home/products/maps/hist/dufour_digital.html. Accessed 23.10.15.
- <http://www.arcanum.hu>. Accessed 23.10.15.
- <http://www.british-history.ac.uk/>. Accessed 23.10.15.
- <http://www.deutschefotothek.de/db/apsisa.dll/ete?action=viewPage&page=kartenforum-sachsen-messtischblaetter.xm>. Accessed 23.10.15.
- <http://www.igmi.org/>. Accessed 23.10.15.
- <http://www.geoportail.gouv.fr/>. Accessed 23.10.15.
- <http://www.lantmateriet.se/>. Accessed 23.10.15.