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What are the transitions of woodlands at the landscape level? Change trajectories of forest, non-forest and reclamation woody vegetation elements in a mining landscape in North-western Czech Republic

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ABSTRACT

This study answers the following research questions: 1) What are the change trajectories of woody vegetation elements at the landscape level? 2) What are the differences in change trajectories amongst the various categories of forest, non-forest and reclamation woody vegetation? 3) How do the change trajectories differ in mining and non-mining landscapes? The study area, measuring 209.6 km^2, is located in the north-western part of the Czech Republic and may be broken down into 76.8 km^2 of mining landscape and 132.8 km^2 of non-mining landscape. Brown coal mining began in this region during the second half of the 18th century and led to the radical transformation of the landscape, including woodlands, during the second half of the 20th century. The source data for this study was obtained from the original stable cadastre maps (1842) and the landscape field mapping performed in 2010. The various woody vegetation elements (forest, non-forest, and reclamation woody plants) and land use/cover (LULC) categories were identified. The GIS symmetrical difference tool was subsequently used to perform an overlay analysis for the individual woody vegetation elements in order to study the change trajectories and to obtain information about the woodlands that have remained unchanged (continuous), the ones that have disappeared (extinct), and the ones that have newly appeared in the landscape (recent). In the case of the non-mining landscape, the total proportion of woodlands has increased (from 17 to 32%), but there has been a decline in the overall volume of forest woody plants found in these areas (from 93 to 74%). As far as the mining landscape is concerned, there has also been an increase in the area covered by woodlands (from 10 to 20%), however, the proportion of forest woody plants has decreased to a much greater extent (from 90 to 31%). From the perspective of extinct woody vegetation, 23.3% of all types of woodlands in the mining landscape may be classified as such, as compared to 10.8% in the non-mining landscape. The primary causes of this decline are mining activities and newly built-up areas. More continuous woody vegetation may be found in the non-mining landscape (42.1%) as compared to the mining landscape (15.4%). Recent woody vegetation, which has primarily replaced grasslands and partially arable land, prevails in both the mining (61.3%) as well as the non-mining (47.1%) landscapes. Different categories of woodlands (forest, non-forest, and reclamation woody vegetation elements) exhibit various change dynamics due to their different structure and the functions they serve. At the most basic level, there has been an overall increase in the occurrence of woodlands in the studied areas. However, once GIS spatial analysis is applied it is possible to see more complex processes in the development of woodland areas as characterised by gains and losses, and it is possible to identify mining and agricultural extensification as the two most significant factors behind the historical changes. Mining leads to a direct decrease in the area of woodlands; conversely, the spontaneous succession of vegetation resulting from agricultural extensification and forest reclamation facilitates woodland recovery. Forest reclamation and reforestation are essential on order to ensure the time continuity of woodlands in both

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types of landscape, i.e. mining and non-mining. The study presented in this paper proves that it is relevant to analyse the changes occurring in different woodland categories separately. The same methodology may be applied when studying the change dynamics of other important landscape elements, such as wood pastures and wetlands.

Introduction

Woodlands refer to ecologically (Le Coeur, Baundry, Burel, & Thenail, 2002; Orlowski and Nowak, 2007) and historically (Rackham, 2007) significant landscape segments that are heterogeneous in their structures (Forman & Godron, 1986; Lafortezza, Chen, Sanesi, & Crow, 2008) and in their functions (Skaloš et al., 2014). Not only are woodlands used for wood production, they also fulfil a wide range of non-production related functions in the landscape, e.g. aesthetic, land-forming, and eco-stabilizing (McCollin, 2000). Non-forest woody vegetation elements (solitary trees, small woodlots, tree alleys, etc.) play a key ecological role, particularly in heavily exploited landscapes (Bulíř & Škorpík, 1987). In addition, these elements provide information about the historical utilization of the landscape, including the extensive use of trees for various purposes by traditional society (Krčmářová, 2012), and they play a key role from the perspective of landscape memory and heritage (e.g. Schama, 1995).

The landscape, including woodlands, underwent radical transformation in most European countries during the Holocene period as a result of anthropogenic pressure and changes in natural conditions (Bender, 2005; Brůna, Wild, Svoboda, Heurich, & Müllerová, 2013; Bürgi and Russell, 2001; Bürgi & Schuler, 2003; Hooke & Kain, 1982; Ihse, 1995; Lipský, 1995; Ohlson & Tryterud, 1999; Pelorosso, Leone, & Boccia, 2009; Schulte, Liebman, Asbjornsen, & Crow, 2006; Sklenička, Janovská, Šálek, Vlasák, Molnarová, 2014; Sklenička, Molnarová, Pixová, Šálek, 2013; Sklenička, Šímová, Hrdinová, Šálek, 2014). There are only a relatively few modern studies that focus on the development of woodlands in the Czech Republic and elsewhere in Central Europe. These include, for example, interdisciplinary papers combining different research fields, e.g. ecology, landscape ecology, history, and forestry (Bürgi, Gimmi, & Stuber, 2013; Müllerová, Szabó, & Hédl, 2014; Szabó, 2010, 2012; Szabó & Hédl, 2013), and single-subject works, such as the landscape-focused studies published by Plieninger, Schleyer, Mantel, and Hostert (2012), and Skaloš, Engstová, Trpáková, Šantrůčková, and Podrázský (2012). The work published by Plieninger et al. (2012) provides an outstanding analysis of the long-term change trajectories of woody vegetation in an agricultural landscape in eastern Germany. However, this study monitored only trees outside of forests and over a limited time span (1964–2008). Patru-Stupariu, Angelstam, Elbakidze, Huzui, and Andersson (2013) employed the forest history perspective and spatial pattern analysis to identify potential high conservation value forests in Romania, but their study focused only on forest woody vegetation. The composition of forest vegetation species in relation to long- and short-term forest changes were analysed by e.g. Jamrichová et al. (2013), Vild, Roleček, Hédl, Kopecký, and Utínek (2013), and Plieninger and Schaich (2014). In addition, comprehensive works applying a historical research perspective have been published covering some Central European countries. These include the synthesis published by Agnoletti (2000); Woitsch (2010) in the Czech Republic; Broda (2000) in Austria; Weinberger (2001) in Germany, and Koller (1975) in Poland.

Despite relatively advanced forest history research and other works focussing on the analysis of spatial changes in the landscape (e.g. Huzui, Călin, & Pătru-Stupariu, 2012; Khromykh and Khromykh, 2014; Seabrook, McAlpine, & Fensham, 2007; Spanò & Pellegrino, 2013), the studies that have been published do not fully apply spatial change analysis to woodland trajectories at the level of the individual woody vegetation elements, which would help to understand the long-term dynamics of woody vegetation within the overall landscape context. In addition, the existing studies do not consistently and systematically distinguish between the different categories of woody vegetation (forest, non-forest, and reclamation woody plants). This may in fact be viewed as a research challenge, because these elements are diverse in their structure, the functions they serve, and their historic dynamics (Forman & Godron, 1986; Lafortezza et al., 2008; McCollin, 2000). Consequently, this study aims to fill this existing research gap by expanding the current methodological approach to include an analysis of the detailed change trajectories of woodlands through using old maps, field surveys, and GIS. As woodlands do reflect historical actuality, we believe that we must become familiar with the change trajectories of the past in order to understand their long-term dynamics. This information may become a source of inspiration for future forest and landscape management.

To meet this overall aim, the study will answer the following specific research questions:

1) What are the change trajectories of woody vegetation elements at the landscape level?
2) What are the differences in the change trajectories amongst the various forest, non-forest and reclamation woody vegetation elements?
3) How do the change trajectories differ in mining and non-mining landscapes?

Materials and methods

Study area

The study area of 209.62 square kilometres is located in the Sokolov district, in the north-western part of the Czech Republic, close to the border with Germany (Fig. 1). It consists of 49 historic cadastral territories, in which all major types of extant woody vegetation and other types of LULC may be found. This area includes landscapes that have been extremely exploited by brown coal surface mining (76.77 km^2, or 36.6%) as well as those that have not been directly affected by mining at all (132.85 km^2, or 63.4%). Brown coal mining began in the Sokolov district during the second half of the 18th century. Deep opencast mining became the prevalent method in the mid-1900s and led to the consequent radical transformation of all existing landscape elements, including woodlands (Majer & Matějček, 1985; Matějček, 1984).

Source data

The old Stable Cadastre Maps (SALSC, 2010), drawn using a scale of 1:2,880, were used to identify the characteristics of the historical landscape. These were the first geodetically objective maps made of the Czech territory and provide information about land use/cover

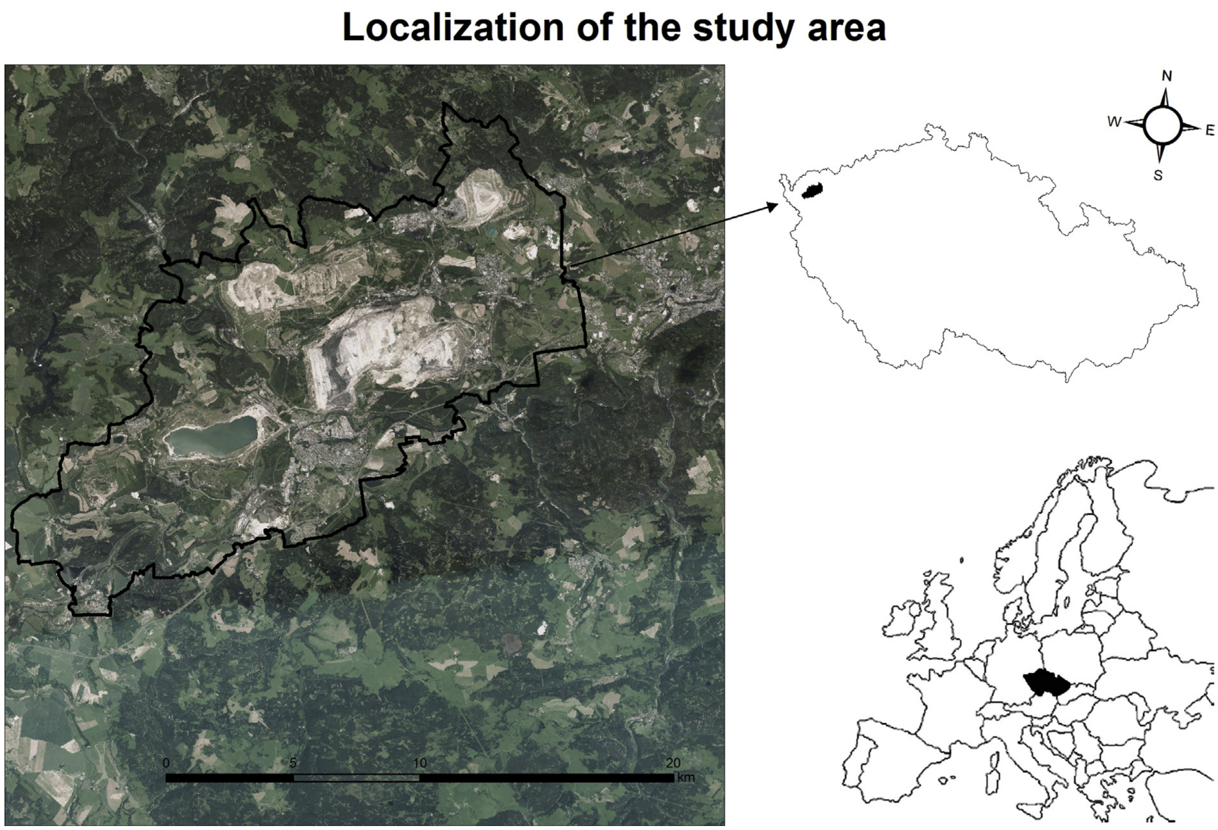

Fig. 1. Localization of the study area.

and ownership structure (Semotanová, 2002). As a result, GIS may be used to analyse these maps and the spatial changes in the LULC and woodlands areas. The stable cadastre maps (imperial prints) were obtained as digital data in raster format with a high resolution of 300 dpi, which made it possible to interpret them in detail. The ArcGIS 10 (ESRI) software was used to georeference the maps to the S-JTSK (Krovak East North) coordinate system on the basis of the orthophotomap of the Czech Republic (SALSC, 2010). An affine transformation was applied, and the distortion of angles and lengths was minimized. The maps were then aligned using rubber sheeting. The interpretation of the historic woodlands and LULC categories (Appendices 1 and 2) was performed using the legend for the georeferenced stable cadastre maps. The identified features were subsequently digitised as polygons with a LULC category assigned in ArcGIS 10 (ESRI) to create a vector-based map of the LULC for the 1842 time horizon.

The data for the LULC and woody vegetation characteristics in 2010 was obtained from the field mapping of the study area in July and August 2010, using current orthophotomaps in combination with the classification keys (Appendices 1 and 2). The field mapping was carried out at a scale of 1:2000 (close to the 1:2880 used for the stable cadastre maps). Polygon landscape elements were identified according to the criteria for LULC and woody vegetation types (Appendices 1 and 2). These features were then visually digitised using the orthophotomaps to create a vector-based map for the 2010 time horizon.

The interpreted features contained in the database were updated to include the attributes of the woody vegetation and LULC elements, i.e. the code of the relevant LULC and woody vegetation elements according to the classification key (Appendices 1 and 2), including area sizes stated in hectares. All elements were interpreted as polygon features, regardless of whether they were enclaves or corridors in the landscape (Forman & Godron, 1986). However, tree alleys and riparian vegetation were not analysed, as they are shown only schematically on the stable cadastral maps. Consequently, it is not possible to objectively define them as polygons, which is necessary for GIS spatial analysis. The next step consisted of the verification and correction of the data captured in the GIS. In order to minimize spatial inaccuracies, all polygons smaller than 30 m^2 were deleted (e.g. Skaloš and Engstová, 2010).

Interpretation of woody vegetation elements and LULC categories

We approached the topic from the landscape ecology perspective. LULC categories and woody vegetation elements are understood to be the segments that form the landscape structure (Forman & Godron, 1986). Only polygon features of woody vegetation (e.g. forests and landscape woodlots) are taken into account.

Woody vegetation elements

For the purposes of this study, woodlands are defined as land that is mostly covered with dense stands of trees and shrubs (Merriam-Webster, 2013). Woodlands are strictly differentiated into forest, non-forest (spontaneous succession of woody plants), and reclamation woody vegetation (see Appendix 1). In the landscape unaffected by mining, what we generally term reclamation woody vegetation refers to the new young forests established through afforestation. The woody vegetation elements included on the stable cadastre maps are delimited using the map key, which distinguishes between forest and non-forest woody vegetation (landscape woodlots and thickets). During the field mapping, the functional criteria of the vegetation as well as stand height and age were taken into account in order to distinguish between forest, non-forest, and reclamation woody vegetation elements. The differentiation was not based on the official classification according to the Land Cadastre of the Czech Republic, and no area size criteria were applied. The study focused only on woody vegetation elements in the open landscape with regard to their importance for landscape and nature conservation, forestry, and the reclamation of land affected by mining. Consequently, urban non-forest woody vegetation (gardens and parks) and orchards were not monitored. Historic and current woody vegetation categories have been unified so that it was possible to analyse changes between similar categories (Appendix 1).

Other LULC categories

Other types of LULC were monitored to analyse the change trajectories of woodlands at the landscape level (Appendix 2). Change trajectories provide information about the LULC categories that have replaced extinct woodlands and about those that have been supplanted by recent woodlands. For this reason, the study area landscape was also delineated into individual elements according to LULC type. These elements were delimited either by land plot borders according to the Stable Cadastre Map (1842), or by the actual borders of the landscape elements identified during the field observation (2010). Historic and current LULC categories have been unified to enable the analysis of changes in similar categories (Appendix 2).

Spatio-temporal analysis in GIS

The objective of the GIS spatial analysis (e.g. Huzui et al., 2012; Khromykh and Khromykh, 2014; Seabrook et al., 2007; Spanò & Pellegrino, 2013) was to analyse the spatio-temporal change trajectories of woodlands between 1842 and 2010. Change trajectories provide information on spatial-temporal transitions in woody vegetation elements and other types of land use/cover in the landscape. The bi-temporal analysis was performed using ESRI's ArcGIS 10.2 software suite (Arc Toolbox functions). All of the woody vegetation elements were categorised according to their spatio-temporal dynamics into continuous (present in both 1842 and 2010), extinct (present in 1842, but transformed into another type of LULC by 2010), and recent (newly established woodlands, i.e. a different type of LULC existing in 1842 and transformed into forest woody vegetation by 2010). The transitory changes that occurred between these two points in time were not studied. The outputs comprise the vector-based maps showing the extent of continuous, extinct, and recent woody vegetation elements, and the database tables containing the information about the woody vegetation segments (their type according to spatio-temporal dynamics, i.e. continuous, extinct or recent; the type of LULC in 1842 and the type in 2010, and the size of the relevant area in hectares). This database information makes it possible to analyse the spatio-temporal changes in woody vegetation at the level of the individual landscape elements.

The output from the source data interpretation (see Sections Source data and Interpretation of woody vegetation elements and LULC categories.) was used to generate ESRI shapefiles (.shp) for the woody vegetation elements existing in 1842 and in 2010. An overlay analysis was performed using ESRI's ArcGIS 10.2 software (Overlay Arc Toolbox – Analysis Tools – Intersect), and the shapefiles were generated for the woody vegetation polygon layers from both time horizons, i.e. 1842 and 2010. These overlapping polygons represent continuous elements. Based on the detailed woody vegetation classification system (Appendix 1), it is possible to determine the changes that occurred in the continuous woody vegetation elements in the woodland sub-categories between 1842 and 2010.

The non-overlapping woody vegetation elements were analysed using the same procedure in GIS, but, in this case, the symmetrical difference tool (Arc Toolbox – Analysis Tools – Overlay) was used to delimit extinct and recent woody vegetation elements. At the same time, the LULC categories which replaced extinct woody vegetation and those that were supplanted by recent woodlands were identified (Fig. 2).

Data computation and statistical analysis

The data set was divided into two parts according to the landscape affected by mining (76.8 km^2) and the landscape not affected by mining (132.9 km^2), and the parts were analysed separately. The percentage cover was calculated for each category of woody elements, i.e. continuous, extinct and recent, and the dynamics of the individual categories were compared. The areas of replaced and replacing LULC categories were determined for extinct and recent woody elements, respectively.

The comparison of the areas of continuous, extinct and recent woody elements was examined using two-way repeated measure analysis of variance (ANOVA) without interactions, where mining, point in time (1842 and 2010), and the type of woody element were used as factors, and the area size of the elements, adjusted through logarithmic transformation, was used as the response. The interactions between the factors were excluded from the analysis, as they had previously been found to be insignificant. After the completion of the aforementioned ANOVA, Tukey's HSD test for multiple comparisons was performed. The area sizes of elements of a particular type, with respect to both the point in time and trajectory changes, were compared using contingency tables and the chi-square test. The analysis was performed using the original data (areas were measured in hectares).

Results

Overall changes in woodlands

The woodlands located in the study area underwent quite dramatic transformations with regard to both areal and spatial changes (Fig. 3). An increase in the overall proportion of woodlands may be seen both in the non-mining landscape (from 17 to 32% of the total area) as well as in the landscape affected by coal mining (from 10 to 20% of the total area; chi-square = 8220.5, df = 1, p-value < 10^{-6}). In the non-mining landscape, while the proportion of the total area comprising forest woody vegetation has increased (from 16 to 24%, chi-square = 308.5, df = 1, p-value < 10^{-3}), the proportion of forest woody vegetation in all types of woodland areas has decreased from 93 to 74%. A similar trend may be seen in the mining landscape with regard to the total proportion of forest woody vegetation in all types of woodland areas, which has dropped substantially from 90 to 31%. This may be explained by the fact that, in both types of landscape, the occurrence of forest, non-forest (spontaneous succession of woody plants), and reclamation woody vegetation has increased due to “communicating vessels”. However, as far as the mining landscape is concerned, the overall proportion of forest woody vegetation has decreased from 9 to 6% of the total area (chi-square = 89.9, df = 1, p-value < 10^{-3}). In the landscape affected by mining, the representation of non-forest woody vegetation (spontaneous succession of woody plants) has increased from 10 to 29% in all types of woodland areas and from 1 to 6% in relation to the total area. An increase is seen for this category in the non-mining landscape as well, where the non-forest woody vegetation cover has increased from 7 to 13% in all types of woodland areas and

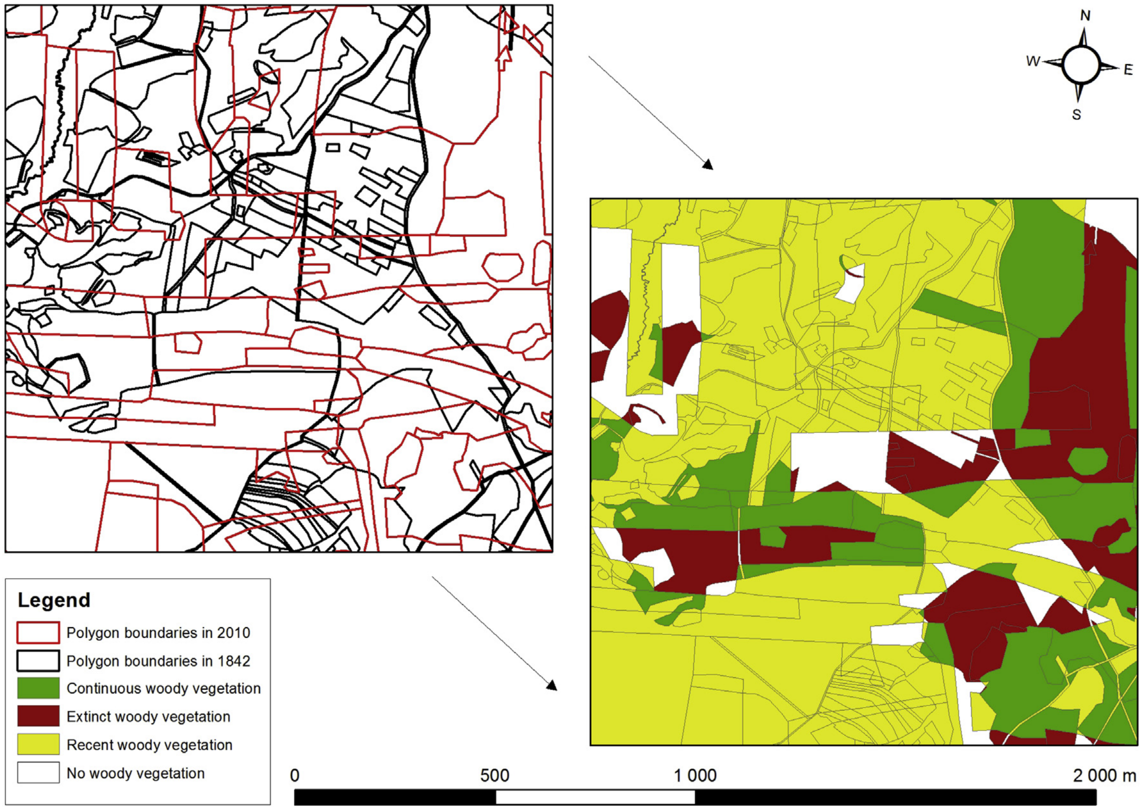

Fig. 2. Graphical abstract showing the results of the spatial analysis procedure in GIS at the level of individual polygons.

from 1 to 4% in relation to the total area (chi-square = 29.2, df = 1, p-value = 0.0062). Currently, in the mining landscape, the proportion of forest reclamation elements is 41% in all types of woodland areas and 8% of the total area. As far as the present-day non-mining landscape is concerned, the proportion of forest reclamation elements, formed mostly by new young forest stands resulting from afforestation, is 13% in all types of woodland areas and 4% of the total area.

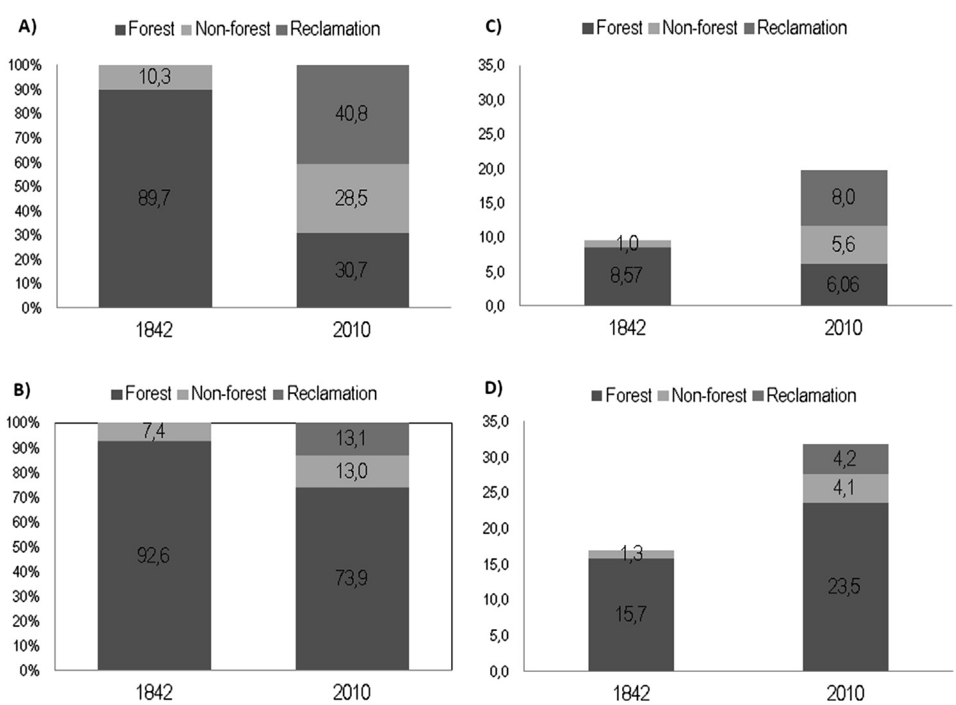

Fig. 3. Changes in the proportion of different categories of woodlands between 1842 and 2010: A) in the mining landscape, in relation to the total area of woodlands; B) in the non-mining landscape, in relation to the total area of woodlands; C) in the mining landscape, in relation to the total area; D) in the non-mining landscape, in relation to the total area.

Spatio-temporal changes in the different woody vegetation categories

In the areas unaffected by mining, there is a significantly higher proportion of continuous woody vegetation, specifically 42.1% of all types of woodland areas, as compared to only 15.4% in the mining landscape (chi-square = 1162.6, df = 1, p-value < 10^{-6}). Conversely, the proportion of extinct woody vegetation in the non-mining landscape is lower than in the mining landscape (10.8% as compared to 23.3%; chi-square = 927.3328, df = 1, p-value < 10^{-6}). The same applies to recent woodlands (47.1% versus 61.3% in the non-mining and mining landscapes respectively; chi-square = 8.6266, df = 1, p-value = 0.003) (Fig. 4, Table 1).

The patches of continuous forests in the non-mining landscape (no change in LULC between 1842 and 2010) are substantially larger than those patches with a different type of change trajectory (ANOVA, $F_{(2, 1342)} = 291.2$, $p < 10^{-6}$). In the landscape affected by mining, the newly established forest cover is significantly smaller than the patches of continuous and extinct woody elements. This is because areas where larger forest stands were located in the past started to be reforested only after the mining activities were terminated (Fig. 4).

Continuous woody vegetation

In the landscape unaffected by mining the vast majority of continuous woody vegetation elements have remained unchanged and consist of forest woody plants (87%). Forest woody vegetation has been transformed to reclamation woody plants (mostly young forest stands) to a much lesser extent (5%). Woodland continuity represented by changes from non-forest to forest woody vegetation (3%) and vice versa (3%) rarely occurs. Transformations from one non-forest type of vegetation to another are even less frequent (1%). In contrast, the continuity of woodlands in the landscape disturbed by surface coal mining has, for the most part, occurred through the transformation of forest woody vegetation either to reclamation woody plants (33%) or to non-forest woody vegetation (28%). As far as the individual continuous woody vegetation elements are concerned, the original forest woody vegetation has remained unchanged to a lesser extent (24%) in the mining landscape than in the non-mining landscape (87%; chi-square = 1861.146, df = 1, p-value < 10^{-6}). Non-forest woody vegetation has either remained constant (6%) or changed into reclamation vegetation (7%). Forests have supplanted non-forest woody vegetation to a comparable extent as in the landscape unaffected by mining (2%). The comparison of original areas of particular trajectories shows highly significant differences for both mining and non-mining landscapes (mining areas: chi-square = 13.1, df = 2, p-value = 0.0014; non-mining areas: chi-square = 161.2, df = 2, p-value < 10^{-6}). (Tables 2 and 3).

Table 1
Proportion of different categories of woodlands in the mining and non-mining landscapes (based on the spatial analysis performed using GIS).

Category	Mining landscape			Non-mining landscape		
	Number of elements	Area (hectares)	%	Number of elements	Area (hectares)	%
Continuous	702	690,3	15.4	1275	2665,3	42.1
Extinct	835	1045,9	23.3	1181	683,7	10.8
Recent	8168	2755,1	61.3	9761	2977,5	47.1
Total	9705	4491,3	100.0	12,217	6326,6	100.0

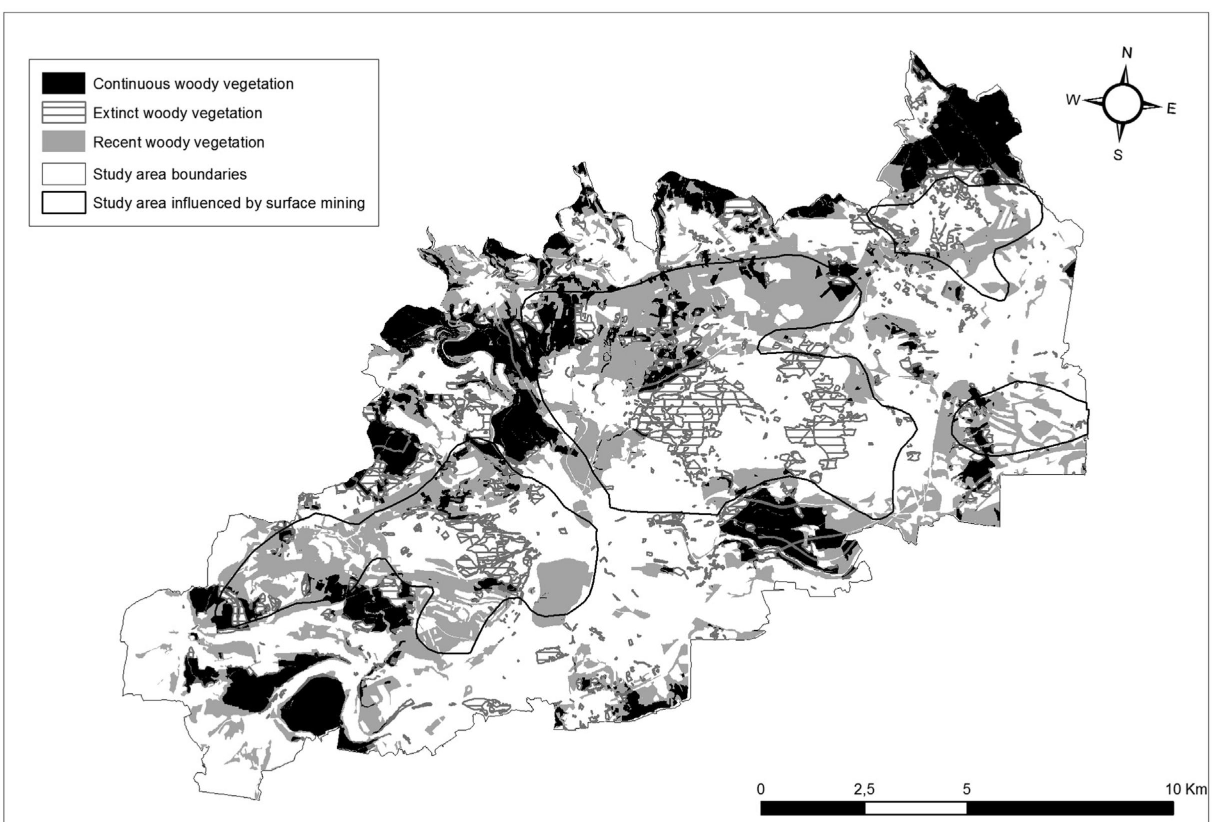

Fig. 4. Occurrence of continuous, extinct, and recent woody vegetation in the study area.

Table 2
Change trajectories amongst the different categories of woody vegetation elements (forest, non-forest, and reclamation woody vegetation) in continuous woodland areas in the mining landscape (as a percentage of continuous woodlands).

Type of the change	Hectares	%
Forest 1842 – Reclamation 2010	230,0	33.3
Forest 1842 – Non-forest 2010	193,8	28.1
Forest 1842 – Forest 2010	166,4	24.1
Non-forest 1842 – Reclamation 2010	48,9	7.1
Non-forest 1842 – Non-forest 2010	40,0	5.8
Non-forest 1842 – Forest 2010	11,1	1.6
Total	690,3	100.0

Table 3
Change trajectories amongst the different categories of woody vegetation elements (forest, non-forest, and reclamation woody vegetation) in continuous woodland areas in the non-mining landscape (as a percentage of continuous woodlands).

Type of the change	Hectares	%
Forest 1842 – Forest 2010	2315,8	86.9
Forest 1842 – Reclamation 2010	128,6	4.8
Non-forest 1842 – Forest 2010	89,9	3.4
Forest 1842 – Non-forest 2010	77,5	2.9
Non-forest 1842 – Non-forest 2010	31,5	1.2
Non-forest 1842 – Reclamation 2010	22,0	0.8
Total	2665,3	100.0

Extinct woody vegetation

Extinct woody vegetation refers to woodlands that disappeared from the landscape between 1842 and 2010. In the landscape unaffected by mining, forests have primarily been replaced by built-up areas (36% of the extinct woody vegetation), arable land (13%), mining areas (12%), permanent grassland (9%), and barren land (9%). The disappearance of non-forest woody vegetation is also due to built-up areas (7%). The frequency of other types of changes is negligible. In the landscape affected by mining, forests have, for the most part, given way to mining areas (54% of the extinct woody vegetation), barren land to a lesser extent (15%), bodies of water (6%), and permanent grassland (6%). The frequency of other types of changes is negligible. The comparison of original areas of particular trajectories shows highly significant differences for both mining and non-mining landscapes (mining area: chi-square = 87.9, df = 6, p-value $\leq 10^{-6}$; non-mining areas: chi-square = 79.4, df = 6, p-value $< 10^{-6}$).

Recent woody vegetation

The occurrence of woodlands in the mining and non-mining study areas has increased overall since 1842, with the largest increase recorded for reclamation woody plants and a lower increase in the case of non-forest woody vegetation. Forest woody vegetation increased only in the landscape undisturbed by mining. However, the GIS spatial analysis reveals the complexity of these changes and provides more detailed information about recent woody vegetation. In the non-mining landscape, forests, reclamation woody plants (mostly new young forest stands resulting from afforestation), and forest woody vegetation have increased primarily at the expense of grasslands (50%, 48%, and 47% of the total area of recent woodlands, respectively), and arable land (44%, 44%, and 43%). In the landscape disturbed by mining, reclamation woody plants and forest woody vegetation have mostly supplanted grasslands (49% and 52% of the total area of recent woodlands respectively), and arable land (43% and 37%). In contrast to the non-mining landscape, non-forest woody vegetation elements have replaced arable land (48%) and grasslands (45%). The comparison of original areas of particular trajectories shows highly significant differences for both mining and non-mining landscapes (mining area: chi-square = 78.9, df = 6, p-value $\leq 10^{-6}$; non-mining areas: chi-square = 82.6, df = 6, p-value $< 10^{-6}$).

Discussion

The changing face of the Sokolov landscape

Surface brown coal mining has played a significant role in shaping the landscape in the study area since the 1950s (Frouz, Pöpperl, Přikryl, & Štrudl, 2007; Richter & Pecharová, 2013). This influence, together with land recovery and landscape revitalization, have been studied by, for example, Häge (1996), Menegaki and Kaliampakos (2012), Sklenička and Charvátová (2003), Svobodová, Sklenička, Molnárová, and Šálek (2011), Toomik and Kaljuvee (1994), Skaloš and Kašparová (2012), Brom, Nedbal, Procházka, Pecharová, et al. (2012). The increase in extraction sites and reclamation areas, mainly at the expense of former arable land and grasslands, is only one of the effects of the surface coal mining activities (Skaloš et al., 2014). Woodlands have always been an important part of the studied landscape, and, as such, they have also been seriously affected by mining activities. Forest management and land use extensification are two other factors that have had an impact on the occurrence of different categories of woodlands. As far as the non-mining landscape is concerned, the size of the woodland areas has increased due to a higher proportion of forest woody vegetation cover. In the case of the mining landscape the woodland areas have become larger as a result of the expansion of reclamation woody vegetation and the spontaneous succession of woody plants. Although mining activities were indeed a direct cause leading the decrease in the size of the woodland areas, subsequent reclamation activities have led to the recovery of woodlands. This reclamation, performed after the termination of coal extraction activities, also changed the structure of the woodlands (i.e. the proportions of the various vegetation categories) thanks to the reduced areas of forest, reclamation, and non-forest woody vegetation elements.

Gains and losses in woodlands

It is apparent that the overall occurrence of woodlands has increased in both the mining as well as the non-mining landscapes. However, upon further investigation, the detailed GIS analysis reveals that complex trends exist with regard to the transformations that have taken place in all woodland categories (i.e. forest, non-forest, and reclamation vegetation elements). The same level of complexity may be seen in the spatio-temporal change trajectories of woodlands at the landscape level. GIS-based spatial analysis may thus be used to shed more light on the complex change processes that occur in woodlands, rather than only referring to the simple bi-temporal changes in a particular woodland area. The comprehensive history of the woodlands in the studied landscape reveals contradictory trends, characterized by gains and losses in the area covered by woodlands and their spatial distribution, due to the effects of different driving forces. Overall, gains prevail in the study area, as the occurrence of woodlands has increased from 10 to 20% in the mining landscape, and from 17 to 32% in the non-mining landscape. Also, recent woodlands occupy 61.3%, and 47.1% of all woodlands in the mining and non-mining landscapes respectively. In spite of the mining and thanks to forest reclamation activities, the spontaneous succession of woody plants, and reforestation, the overall balance in the area covered by woodlands is positive. Gains are represented by emerging recent woody vegetation elements, which have, for the most part, supplanted arable land and sites formerly covered by permanent grassland in 1842. In the non-mining landscape, the majority of these elements consist of forest land (69.2%), which is an indication that forest management and reforestation are important driving forces behind the increase in woody vegetation. However, as 46.8% of the recent woodlands in the mining landscape consist of reclamation woody elements, it is apparent that primarily mining activities, followed by forest reclamation, have definitely played a role in the shaping of the woodlands in this landscape. Thanks to forest reclamation, there are 2560 ha of newly occurring reclamation woody vegetation elements in the study area landscape (of which 1687 ha are in the mining landscape and 874 ha in the non-mining landscape, primarily due to inaccuracies in the delimitation of the mining areas). This type of reclamation is one of the most frequently applied methods for revitalizing land that has been disturbed by surface coal mining (apart from agro-technical measures and other types of land restoration). This figure agrees with the area of 1800 ha of new forest reclamation elements reported for the Sokolov region by Frouz et al. (2007). In addition, as non-forest woody vegetation (resulting from the spontaneous succession of woody plants) is the second most prevalent woody vegetation type in the mining and the non-mining landscapes (making up 29.7% and 16.9% of the total area of recent woodlands in the two landscape types respectively), it is possible to say that the expulsion of the German population (Beranová Vaicová, 2005; Mikšíček, 2006) and agricultural extensification (Lipský & Kukla, 2012), which leads to the landscape being overgrown as a result of the spontaneous succession of woody plants, are also important factors behind the woodland changes. Losses, on the other hand, are represented by extinct woody vegetation elements, which have been determined to correspond to 23.3% of the mining landscape and 10.8% of the non-mining landscape in the study area. To a large extent, the extinct woodlands were identified in locations affected by mining (Fig. 4). The largest losses of woodland areas are a direct result of mining activities and urbanization (in the mining and non-mining landscapes respectively), as, in both cases, primarily woodlands were replaced. These processes occur in conjunction with the relative spatio-temporal stability of continuous woody vegetation (which makes up 15.4% and 42.1% of all woodland types in the mining and non-mining landscapes respectively). Continuous woodlands consist primarily of managed forests in the non-mining landscape, and reclamation woody vegetation elements in the mining landscape, where they are an important stabilizing factor. For the most part, continuous woodlands are located at the outer edges of the non-mining landscape, which has helped to support the time stability of continuous woodlands.

In 2010, the occurrences of woodlands in both the non-mining landscape (30%) as well as the mining landscape (20%) are less than the figure for forest land in the Czech Republic as a whole (33.5%, CSO, 2013). However, the area of real forest cover could be even smaller, as, according to the Land Registry, forest cover includes only forest vegetation, while in the study area all types of woodlands are included in this category, including areas of non-forest woody vegetation (the spontaneous succession of woody plants), reclamation vegetation, and forest woody vegetation. Reclamation woody elements up to 10 years of age are not included in the area of forest land (CSO, 2013). For this reason, this category was not included in either the forest or the non-forest woody vegetation.

Differences in change between forest, non-forest and reclamation woody vegetation elements

As they vary in their structures, functions, and consequently in the way they are managed, forest, non-forest and reclamation woody vegetation elements have been found to have different change trajectories (Forman & Godron, 1986; Lafortezza et al., 2008; Skaloš et al., 2014). The different roles played by woodlands in the landscape, i.e. production, environmental, erosion control, and aesthetic functions, (Bulíř & Škorpík, 1987) substantially influence the nature of the management regime that is applied. As a result, different woodland areas have various change dynamics.

Differences between the mining and the non-mining landscapes

Generally speaking, surface mining reduces the area of woodlands found in the landscape. In addition, it tends to increase the occurrence of non-forest woody vegetation (resulting mainly from the spontaneous succession of woody plants) and reclamation woody vegetation in all types of woodlands at the expense of forest land. In both the mining as well as the non-mining landscape, new woodlands have occurred primarily at locations, which, in 1842, were used as grassland, and, to a lesser degree, arable land. Only non-forest woody vegetation has newly appeared in the mining landscape, mainly supplanting what was arable land in 1842.

An increase in the occurrence of reclamation woody vegetation is also partially apparent in the non-mining landscape for two main reasons: 1) the boundaries of the mining area were taken from the landscape typology published by CENIA (2013), which may have resulted in certain inaccuracies in the delimitation of the mining area. As a result, mining areas, with all of the typical consequences, may have also existed even outside of the defined boundaries of the mining landscape; and 2) some confusion may arise when differentiating between newly established forest elements and forest reclamation elements, as some are very similar. Given that these two types of vegetation cannot be clearly distinguished, we have included young forest elements from the non-mining landscape together with the reclamation woody plants from the mining landscape as "reclamation" woody vegetation. This category in the landscape unaffected by mining primarily consists of the newly established young forests resulting from afforestation.

Summary of driving forces

Apart from the classical concept presented by Forman and Godron (1986), land change may also be understood as the land's response to variously classified driving forces, i.e. socioeconomic, political, technological, natural, cultural, direct, and indirect (Bičík & Kupková, 2013; Brandt, Primdahl, & Reenberg, 1999; Bürgi, Hersperger, & Schneeberger, 2004; Hersperger, Gennaio, Verburg, & Bürgi, 2010). In this study, driving forces have been divided into large-scale driving forces (affecting the landscape from the international or national perspective), and small-scale driving forces (which are very explicit and, for the most part, area-specific) (Milanova, Himiyama, & Bičík, 2005).

Large-scale (general) driving forces

As the investigated period was not divided into shorter time periods, the large-scale driving forces may generally be characterized as those processes that change the relationship between mankind and the landscape from the determinative level (the dependence of mankind on nature and landscape structures) to the competitive level (mankind, or more specifically, society as a key factor in the transformation of the landscape). These processes have been in play in central Europe since the second half of the 19th century and primarily consist of the following: industrialization, urbanization, agricultural intensification, and the associated decreases in agricultural land (Bičík, Jeleček, & Štěpánek, 2001). Their consequences include the gradual depopulation of rural areas, the growth of urban settlements, the formation of large-scale industrially-urban landscape structures, and the general tendency of the non-urban landscape to be transformed into areas of woody vegetation that occur primarily due to the spontaneous succession of woody plants. During the second half of the 20th century, some of these processes were even significantly intensified as a result of the socio-economic circumstances in totalitarian Czechoslovakia and the other Socialist states. The collectivisation of agriculture, which led to centralised mass production, did not significantly affect the area covered by this study, however, the focus on metallurgy, heavy machinery industries, and brown coal energy, which was promoted by the Council for Mutual Economic Assistance (COMECON), had a major impact (Jeleček, 2002).

Small-scale (local) driving forces

The small-scale driving forces are identified at the level of regional and natural and cultural landscape structures, particularly with regard to significant historical, economic and social characteristics of the study area. In general, they intensify the effects of the large-scale driving forces, sometimes to an extreme degree. For the purpose of this study, the most significant small-scale driving forces are associated with the large reserves of brown coal in the study area, and its extraction, processing and use in the energy sector. Underground coal mining was identified as the main cause of urbanization and industrialization in the region during the 19th century, and surface coal mining as the main cause of large-scale landscape changes after 1950. Within the context of historical and socio-economic driving forces, we should mention: 1) the relatively good forest management (Nožička, 1962) implemented by the major forest owners in the region until the 1920s (the Nostic-Rieneck aristocratic family); and 2) the expulsion of the local German-speaking population (Sudeten Germans) after World War II, which had a crucial impact on the region's development during the second half of the 20th century. The study area was inhabited primarily by ethnic Germans until 1946 (about 94% of the population). During the 1946-1947 period, approximately 46,000 people were forced to leave the region, while only about 15,000 new settlers arrived, primarily in the larger towns (Nosková, 1991; Prokop, 1994; Staněk, 1991). The result of this massive population exchange led to the final extreme depopulation of the area and the immediate extinction of several small villages and dozens of buildings in the late 1940s and early 1950s (Beranová Vaicová, 2005; Mikšíček, 2006). The subsequent extensification of land use resulted in an increase in the spontaneous succession of woody plants and vegetation cover. In addition, the aforementioned events facilitated large-scale land use changes, particularly with regard to creating vast opencast mines and large industrial complexes, as it was not necessary to resolve any issues concerning land purchases and the relocation of the population.

Discussion about the methodology

The results from this study have been largely influenced by the different nature of the source data, i.e. the old stable cadastre maps, which show the ownership of the individual plots of land, versus the orthophotomaps of the Czech Republic, which display the actual segments existing in the landscape and are used to monitor the current landscape. This same issue has been described and discussed in previous studies (e.g. Skaloš and Engstová, 2010; Skaloš et al., 2012; Plieninger et al., 2012).

The LULC and woody vegetation categories from the stable cadastre map legend must be made compatible with those used for current landscape monitoring (see Section Interpretation of woody vegetation elements and LULC categories), as this is a key prerequisite for analysing the changes in identical categories of LULC and woodlands. Since the LULC categories in the current landscape are interpreted at a much higher level of detail as compared to the relatively unrefined LULC categories used for the stable cadastre maps (Semotanová, 2002), the data for the study had to be simplified to a certain extent. It must also be noted that the study is not comprehensive, as its scope is reduced by focussing only on polygonal woodland elements (i.e. forests, small landscape woodlots, and spontaneous succession involving woody plants) and it does not include woody vegetation corridor features (riparian forests, tree alleys, etc.). The reason for this is that the stable cadastre maps record woody vegetation corridor elements only schematically, and this makes it impossible to perform the quantitative spatial analysis in GIS.

The study results were also partially influenced by the inclusion of scattered woody vegetation elements, which usually fall into the category of non-forest woody vegetation (e.g. small landscape woodlots), under forest stands. This was due to the fact that the main criterion for the classification of woody vegetation elements in this paper was the physiognomy of the vegetation, not the size or location of individual elements. The classification of woodlands may significantly influence the results of similar studies and future research should attempt to quantify this effect.

The use of different source data (the old stable cadastre maps on the one hand, and the mapping of the current state of landscape on the other), combined with the subsequent unification of the classification legend result in the fact that certain monitored categories of woodlands may be “hidden” in other unmonitored categories of LULC. For example, whereas in the current landscape it is possible to distinguish elements of spontaneous woody vegetation succession, on the old stable cadastre maps this category is not explicitly specified in the map key and, if spontaneous woody vegetation succession did occur in any area, it was most likely included under barren land. This uncertainty makes it impossible to objectively monitor the spontaneous succession category on the stable cadastre maps. As the barren land category includes other types of LULC in addition to woodlands, the monitoring of it as a land use category would introduce too many errors into the study.

Only two time horizons (1842 and 2010) were used to analyse the spatio-temporal change trajectories of woodlands. Therefore, the results from the study provide information only on the absolute long-term dynamics of woodlands between 1842 and 2010, rather than on the detailed dynamics of the transitory changes that occurred between the two time horizons. If the term “change dynamics” is used, it refers to the dynamics of the transformations between different types of woody vegetation and other LULC elements, not between the time horizons. In order to come closer to determining the “temporal change dynamics” of woodlands, more source data from multiple time horizons must be used in future research. It will also be necessary to use the same type of source materials (only aerial photos, only maps, etc.) for obtaining LULC and woodlands data that are more compatible.

Given that surface coal mining began in the Sokolov region during the second half of the 20th century, the use of existing historic aerial images (i.e. from the 1960s and 1980s) would be the most relevant for completing a multi-temporal study providing a detailed evaluation of the dynamics of the landscapes and woody vegetation disturbed by surface coal mining in the area (rather than the old stable cadastre maps and orthophotos). The authors of the study presented in this paper are currently performing this type of research and the use of the aforementioned historical aerial photos is included in their research plan. The results will be published in the near future.

Despite the existence of several important works dealing with the analysis of spatial changes in the landscape (e.g. Khromykh and Khromykh, 2014; Spanò & Pellegrino, 2013; Huzui et al., 2012; Seabrook et al., 2007), the studies published to date have not fully utilized spatial change analysis for woodland trajectories at the level of the individual woody vegetation elements. The methodology proposed in this study makes it possible to perform a relatively efficient detailed analysis of spatial-temporal woodland changes in the landscape. However, the core part of the methodology, with only a few minor adjustments, may be applied in the same way to other important landscape elements, such as built-up areas, grasslands, wetlands, etc. The proposed methodological procedure should also be verified by applying it under the diverse natural and cultural conditions existing in the different types of landscape found in the Czech Republic. Another challenge will be to use additional methods to differentiate forest and non-forest vegetation (e.g. the official classification used by the Land Cadastre of the Czech Republic and GIS methods) and not only the visual criteria used for this study.

Conclusions

The landscape in the study area underwent radical transformations between 1842 and 2010. The same may be said regarding the changes in the extent and the spatial distribution of the woodlands as a result of different, often conflicting, driving forces and factors. The occurrence of woodlands increased overall – both in the landscape affected by mining as well as in the areas where no mining activities were carried out. In the case of the former, the primary reason may be found in the proliferation of reclamation woody elements and the spontaneous succession of woody plants as a result of surface coal mining activities. In the latter, the area with woodland cover expanded mainly thanks to afforestation.

However, the study results show that, in addition to the absolute areal changes, it is also important to analyse the spatio-temporal changes at the landscape level, as these transitions (change trajectories) may shed new light on the complex history of woodland areas. Surface coal mining, the extensification of landscape use, and the acceleration of urbanization have all played a key role in shaping the landscape, including woodlands. Newly established (recent) forests and areas covered by self-seeded woody plants have mostly replaced the grassland areas that existed in 1842. Forest reclamation, carried out after the termination of mining activities, is a key factor that has essentially ensured the continuity of woodland development in the mining landscape. In the areas unaffected by mining, this function continues to be fulfilled by forests and through forest management. The causes leading to the reduced occurrence of woodland vegetation also differ between the mining and the non-mining landscapes. Whilst in the case of the former, coal extraction is the major factor, in the latter this role is played by urbanization. Different categories of woodlands (forest, non-forest, and reclamation woody vegetation elements) exhibit various change dynamics due to their different structures and the functions they perform. The study has proved that it is relevant to analyse changes in the different woodland categories separately, and this same process may, at a general level, be applied to the study of other landscape types. It is equally important to monitor the development of woodlands in mining and non-mining landscapes separately, as mining activities play a key role in determining the occurrence and prevalence of woodlands.

The main benefit of this study lies in the fact that it has proven that GIS analysis tools may be effectively used to reveal that what at first appears to be the seemingly clear development of woodland areas may in fact be more complex and variable with regard to the spatial transitions (change trajectories) of woodlands, the occurrence of forest, non-forest and reclamation woody vegetation elements, and difference between the mining and non-mining landscapes. Change trajectories help us to understand woodland dynamics at the landscape level. The method used for this study may be applied to any other important landscape elements whose dynamics in the landscape are of interest (e. g. water bodies, wetlands). The methodology may also be used to monitor the success of reclamation activities and all other types of ecosystem restoration. These findings are of great value if we want to obtain a deeper understanding of woodland dynamics at the landscape level, including knowledge about the processes of change and stability, which will lead to a better understanding of the human-landscape system and its dynamics.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2015.02.003.

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