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The rise and fall of traditional forest management in southern Moravia: A history of the past 700 years

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European broadleaved forests have been influenced by humans for centuries. Historical management practices are related to environmental conditions but the role of socio-economic factors is also important. For the successful restoration of traditional management for conservation purposes, detailed knowledge on management history and on the driving forces of historical forest changes is necessary. In order to reconstruct long-term spatio-temporal dynamics in forest management, we chose the Pálava Protected Landscape Area, Czech Republic and analyzed archival sources spanning the past seven centuries. Forests in the study area comprise two relatively large woods (Děvín and Milovice) with different environmental conditions. Historical forest management in both woods was coppicing. The coppice cycle was lengthened from 7 years (14th century) to more than 30 years (19th century) with a fluctuating density of standards. After WWII, coppicing was completely abandoned. This led to pronounced changes in forest age structure accompanied by stand unification indicated by a sharp decrease in the Shannon index of age diversity. To study local attributes responsible for spatial patterns in coppice abandonment, we constructed a regression model with the date of abandonment as a dependent variable and three groups of explanatory variables: (i) remoteness of forest parcels, (ii) morphometric environmental factors and (iii) site productivity. In Děvín Wood, coppicing was abandoned gradually with the pattern of abandonment related significantly to slope steepness and forest productivity. Poorly accessible upper slopes and low productive forest sites were abandoned earlier. By contrast, in Milovice Wood, where no clear topographic gradient is present, the abandonment of coppicing was not related to any of the variables we studied. Our study brings insights into the history and consequences of past management practices, and can be used in current attempts to re-establish coppice management for conservation purposes and as a source of sustainable energy.

1. Introduction

Forest management practices depend not only on environmental factors but also on changing socio-economic conditions (Johann, 2007). In pre-industrial times, in densely populated and mostly deforested European lowlands the demand for firewood and construction timber was high, and so was the pressure on the remaining forests. As a result, coppicing – an intensive type of management – was common for centuries in most European lowland forests (Rackham, 2006). In coppice forests, shoots re-sprout from dormant buds on the stumps (coppice stools) or from the root system and are felled repeatedly at short intervals, providing a regular supply of firewood. If combined with standard trees (single-stemmed trees left to grow among coppice stools; coppice-with-standards management) such woodlands provide building material as well (Buckley, 1992; Peterken, 1996; Rackham, 2003; Gimmi et al., 2008; Szabó, 2010a). In the past, coppice forests yielded further products, such as leaf fodder, pasture (usually 4–7 years after coppice harvest to protect young shoots), and pannage (domestic pigs fed on acorns and beechmast in autumn and winter) (Rackham, 2003; Szabó, 2013).

Coppicing was commonly practiced on easily re-sprouting oak, lime, hazel, ash, hornbeam, maple, alder, willow, sweet-chestnut, beech, and later on black locust (Peterken, 1996; Rackham, 2003; Matula et al., 2012). Traditionally, the composition of the underwood (i.e. coppice stools and shoots) was not directly influenced by humans, although the actual mixture was sometimes improved by removing unwanted species or encouraging valuable species by

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natural regeneration, layering, plashing or planting (Peterken, 1993; Tack et al., 1993). By contrast, standard tree species were carefully selected, and usually oak was favoured (Buckley, 1992).

Historical coppice management represented a flexible and diverse system as well as a good source of income that could be adjusted in response to almost annual changes in labour availability and demands for timber, wood and pasture (Peterken, 1993). The extent and importance of coppicing was changing over time. By the second half of the 20th century, coppicing virtually disappeared from many parts of Europe, mostly due to the substitution of firewood by fossil fuels (Sieferle, 2001) and changes in silvicultural practices (transition to modern forestry, including plantations and high-forest management) (Rackham, 2008). Nonetheless, in some European countries (notably in the Mediterranean) coppicing (and coppicing with standards) still represents an important form of management; for example in Albania (55%), France (47%), Greece (68%), Hungary (29%), Italy (56%), Portugal (37%) (all data based on UN/ECE-FAO, 2000), Bulgaria (48%, State Forest Agency, 2008), Croatia (22%, Croatian Forests Ltd. 2006), and Macedonia (60%, State Statistical Office of Macedonia, 2004). In other parts of Europe, most coppice woods have been transformed into high-forests or left to overgrow (Peterken, 1996; Logli and Joffre, 2001; Rackham, 2008; Van Calster et al., 2008a). Coppiced trees were often reduced to one or two large trunks ('singled out'), felling cycles were prolonged and canopy structure became more uniform (Buckley, 1992).

Coppicing provided high temporal resource heterogeneity and enabled the co-existence of species with contrasting strategies (light and shade tolerant species). By contrast, in high-forests those plant and animal species that prefer open habitats have disappeared (Rackham, 2003; Beneš et al., 2006; Hermy and Verheyen, 2007; Spitzer et al., 2008; Van Calster et al., 2008b; Hédl et al., 2010; Kopecký et al., 2013; Fartmann et al., 2013). The abandonment of traditional forest management techniques has resulted in the gradual closure of formerly open lowland forests, which has led to taxonomic impoverishment and a homogenization of woodland ecosystems (Strandberg et al., 2005; Spitzer et al., 2008). Ancient coppice stools and woodland-related archaeological features also represent a part of cultural heritage (Hermy and Verheyen, 2007; Rackham, 2008; Szabó, 2010b) and thus enhance the value of traditional management.

Recently there is growing interest in coppice re-establishment in Europe for both ecological and economic purposes (as part of nature conservation and as a source of sustainable energy) (Rydberg, 2000; Jansen and Kuiper, 2004; Coppini and Hermanin, 2007; Roedl, 2010; Merckx et al., 2012; Vild et al., 2013). However, the beneficial effects of restoration coppicing are not guaranteed in all cases. When reintroduced to long-neglected sites, coppicing can pose threats to biodiversity by enhancing the spread of ruderal species of native origin and even the invasion of aliens (Radtke et al., 2013; Vild et al., 2013). Problems partly arise from environmental changes concurrent with but independent from the abandonment of coppicing in the 20th century (Verheyen et al., 2012), and partly from insufficient knowledge on coppicing itself. There are few empirical data available on the details of historical coppice management, such as the density of standards, rotation length, the size and position of coppice compartments, and the spatial pattern of coppice abandonment or transition to other types of management. All these factors are likely to have influenced canopy closure, shrub density, the vigour of coppice re-growth, and the extent and duration of canopy cover (Joys et al., 2004). For conservation to be successful, it is necessary to study and preserve traditional forms of management that shaped forest composition and therefore the distribution and abundance of many rare species for centuries (Hermy and Verheyen, 2007). In order to protect diversity in the long run, deeper knowledge on the spatio-temporal dynamics of individual species and disturbance regimes is indispensable, and information on land-use legacies must be obtained and processed (Bengtsson et al., 2000; Rotherham, 2011; Navarro-González et al., 2013).

For the present study, we selected the Pálava Protected Landscape Area (southeastern part of the Czech Republic). This area contains the last remnants of lowland forests in an otherwise agricultural landscape inhabited since the Palaeolithic. Being among the few sources of wood in the region, these forests were intensively coppiced since at least the Middle Ages. The abandonment of coppicing in the region around the middle of the 20th century was connected not only to the substitution of wood by fossil fuels but possibly also to the expulsion of local German-speaking inhabitants and the subsequent confiscation of private lands by the Communist regime. Despite more than eight decades of neglect and non-intervention management in parts of the Pálava PLA, the remnants of former coppices are still clearly visible. In our study, we aimed to reconstruct the long-term history of the forests in the area in order to answer the following questions: (i) Were there any significant changes in forest cover?; (ii) How did management and age structure change in the study area over the past seven centuries?; (iii) Are there any detectable spatial patterns in the abandonment of traditional management that could help interpret the forces driving this process?

2. Material and methods

2.1. Study area

The Pálava Protected Landscape Area (PLA; Fig. 1) (8017 ha) is located in the northwestern corner of the Pannonian Lowland, southern Moravia, Czech Republic. This region represents the warmest and driest part of the Czech Republic with an average annual temperature of 9.6 °C, average annual precipitation of 524 mm, and large seasonal variability. This ancient cultural landscape has been continuously occupied since the Palaeolithic. The dense network of settlements has changed little since the 14th century. From the Middle Ages to the 20th century, the entire area of the PLA belonged to the estate of Mikulov, which was

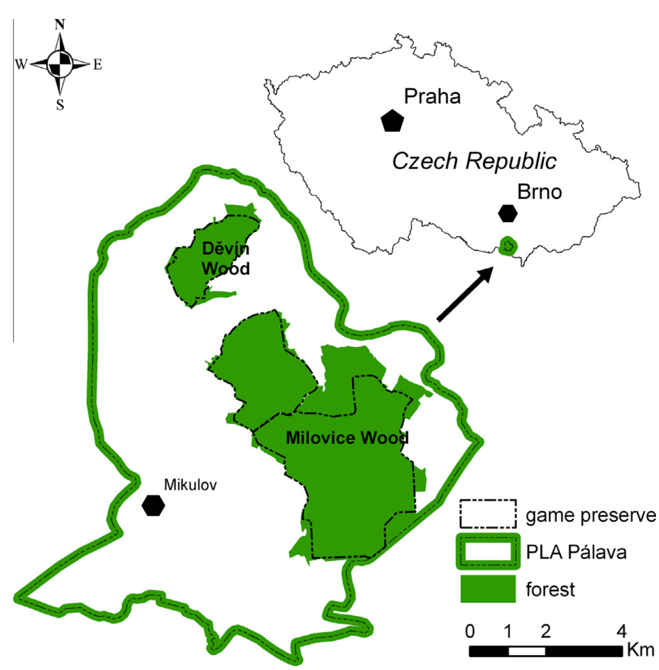

Fig. 1. Map of the study area.

owned by the Lichtenstein family until the 16th century, followed by the Ditrichstein family, who possessed the estate until the formation of Czechoslovakia in the early 20th century.

The intensively cultivated landscape of the region is formed by arable land (40%), vineyards (10%), urban areas (5%), semi-natural to natural grasslands (1.5%), and forests (30%). There are two larger forests in the Pálava PLA: Děvín Wood (400 ha covering most of Děvín Hill, 260 to 549 m a.s.l.) and Milovice Wood (2500 ha, 180 to 324 m a.s.l.). The limestone slopes of Děvín Hill represent a sharp environmental gradient. The northwestern slopes are covered by deep and fertile luvisols and leptosols and are overgrown by thermophilous to mesophilous oak-hornbeam and ravine lime forests. The top and southeastern slopes are exposed to the sun and wind and have poorly developed soils supporting dry grassland and small patches of ravine forests and thermophilous oak forests (Hédl and Rejšek, 2007). The gently undulating loess plateau of Milovice Wood is covered mostly by luvisols that support subcontinental oak forests and small-scale plantations of non-native black pine (Hédl et al., 2010).

Several game preserves were established in the region, some of which are still active. The first game preserve was established in Děvín Wood in 1885 to breed deer and wild boar, and later mouflons (introduced in 1911) and Bezoar goats (introduced in 1953, Fig. 1). After WWII, two additional game preserves covering ca. 80% of Milovice Wood (Fig. 1) were set up in 1965 and 1966 (Bulhary, 1200 ha, red and fallow deer; and Klentnice, 500 ha, fallow deer and mouflons). High numbers of ungulates (0.5, 1.23, and 0.26 animals per hectare in Bulhary, Klentnice and Pálava, respectively, in 1990; Pálava PLA Management Plan 2006) and the resulting problems of overgrazing, trampling and soil erosion facilitated conservation efforts, which led to the abolition of the game preserve in Děvín Wood in 1996, and the reduction of high game densities in Klentnice to 0.72 in 1994 and 0.54 in 2003 (Pálava PLA Management Plan 2006).

The high conservation value of the area, which hosts many endangered species (92 plant, 3 fungi and 159 animal species), resulted in protection measures as early as in 1946, when the Děvín nature reserve (184.6 ha) was established. This area was enlarged and further protected in 1976 as the Pálava PLA (8017 ha, Fig. 1), in 1986 as the Pálava UNESCO Biosphere Reserve, in 2003 as the Lower Morava Biosphere Reserve (354 km^2, including also the neighbouring Lednice-Valtice area and the floodplain forests at the confluence of Dyje and Morava rivers), and in 2005 as a Natura 2000 locality (eight Sites of Community Importance).

2.2. Data sources, processing and analyses

2.2.1. Historical changes in forest extent, age structure and management

We compiled a comprehensive dataset of archival information from the 14th to the 20th century (Fig. 2, Table 1, henceforth numbers in brackets in the text refer to individual sources in Table 1). We used the following types of sources: forest maps, topographical and cadastral maps, *urbaria*, estate conscriptions, forest surveys, management instructions for foresters, forest management plans (FMP) and account books (Table 1). In order to assess forest changes, historical maps were scanned, georeferenced, digitized and analyzed in a GIS environment using ArcMap 10.0 (ESRI, 2006). Archival written sources differed markedly in extent, quality, accuracy, scale and information content. The first written archival record comes from 1384 (Bretholz, 1930), the earliest large scale map from 1675 [5]. Some historical maps were difficult to rectify and interpret due to geometrical distortions, discoloration and other deteriorations. On the other hand, large scale forest maps contained precise information on forest extent and age, and the accompanying FMPs and surveys described forest structure and management. Already the first survey of woodland (1384; Bretholz, 1930 [1]) included names, prices and coppice cycles for most woods in the PLA. The second survey (1692 [9]) listed management (including coppice cycles) for each wood. Highly informative were the forest maps and FMP of 1807/8 [16, 17], which recorded not only the age of underwood for each stand, but also included data on more than 50,000 standards trees that were apparently individually counted. A series a FMPs from the late 19th century (1885 [25], 1901 [27], 1905 [28], 1921–1925 [29], 1933–1936 [30], 1948 [33], 1971 [36] and 2010 [42]) described the age structure of forests in great detail. FMPs from 1885 [25], 1901 [27] and 1933–1936 [30] dealt only with underwood, while the 1948 [33], and 1971 [36], FMPs contained data on both standards and coppice underwood. In the latest source (2010 FMP [41]) standards and underwood were treated together. For the spatial analysis of the information included in FMPs, the accompanying forest maps were used.

In addition to FMPs, three detailed surveys of woodland areas were compiled in 1750 [12], 1789 [15] and 1813 [18]. Further details on management were gleaned from a series of management instructions that were written for local foresters from the late 17th century onwards (1672 [5], 1689 [8], and 1741 [11]). These instructions contained information on for example wood-cutting methods, pasturing in woodlands or haymaking. Unfortunately not all sources covered the entire study area (Table 1). Děvín Wood was covered by all sources, but, as far as more detailed sources are concerned, Milovice Wood was covered partly (ca. 2/3 of the area) by the 1807/8 FMP [17] and entirely only by the most recent sources (1971 [36], and 2010 [42] FMPs).

Archival sources came from the Moravian Archives in Brno, and the Internet – the geoportal INSPIRE of the Czech Environmental Information Agency (CENIA, available from http://geoportal.gov.cz/), and the geoportal of Czech Office for Surveying, Mapping and Cadastre (available from http://archivnimapy.cuzk.cz/). Source references are summarized in Table 1. Recent forest changes were derived from forest maps and management plans kept at the Forest Management Institute in Brno (1990 and 2006), as well as from aerial imagery (1938 to 1990 provided by the Military Geographic and Hydrometeorologic Office in Dobruška; 2006 by CENIA).

2.2.2. Local attributes responsible for spatial patterns in coppice abandonment

We constructed a regression model with the date of abandonment (date of last coppicing) as a dependent variable and three groups of explanatory variables: (i) remoteness of forest parcels expressed by the distance of forest parcel centroids from roads and villages; (ii) morphometric environmental factors derived from a digital elevation model based on the ASTER Global Digital Elevation Model (METI/NASA, 2011) – slope, solar radiation and topographic wetness index (Böhner and Selige, 2006; computed in SAGA GIS version 2.1; SAGA Development Team, 2011) expressed by average values within each parcel, and (iii) site productivity expressed by two parameters (average values within each parcel): (a) price of forest property in 2008 (Supplement No 22 to Regulation 3/2008 Sb) – more valuable property was considered to be more productive for forestry because the evaluation was based on estimated pedological-ecological units; (b) forest productivity ("bonitas") described in the 1885 FMP [25], ranging between 1 and 4 from least to most productive forests. These variables were chosen to characterize site conditions (e.g. solar radiation was taken into account to include the environmental gradient of shaded vs. sun-exposed slopes). The species composition of the coppice layer was very stable along the coppice abandonment gradient and was therefore not used in the analysis. Prior to the analysis, we tested the multicollinearity of the

Fig. 2. Examples of historical maps depicting Děvín Wood (1675, 1807/8, 1883 and 1947; for source references, see Table 1).

explanatory variables using the inflation factor analysis (VIF) where none of the variables was over 3, therefore they were all used in the models. The above mentioned environmental (predictor) variables were tested with respect to the time of coppice abandonment (dependent variable) using a generalized linear model with a Gaussian error distribution and an identity link function. Univariate models for each explanatory variable, a multivariate model for all the variables, and combinations of variables were tested to determine the best explanatory model for coppice abandonment using Akaike's Information Criterion (Akaike, 1973; Johnson and Omland, 2004). The variables were calculated and morphometric parameters extracted using ArcMap 10.0 (ESRI, 2006) and Geospatial Modelling Environment (Beyer, 2010). Variable testing and modelling were done using the software R version 2.14.2 (R Development Core Team, 2012).

3. Results

3.1. Dynamics of forest cover

The first source describing the study area comes from 1384 (Bretholz, 1930) [1]. It lists 26 individual woodlots in the whole study area, usually with their names. Although precise identification in most cases is problematic, the route the surveyors apparently followed indicates that woodland cover was similar to later times. The 1675 map [6] clearly shows that the size of forests in the study area was practically identical to that in the 19th century, although due to problems with georeferencing it was impossible to measure woodland cover precisely. The first detailed forest map, covering most of Děvín Wood, dates from 1786 [14] and shows the wood basically as it stood in the 19th century. During the 19th century forest cover was stable. At the turn of the 19th and 20th centuries Děvín Wood was enlarged by ca 9% (former pastures forested mostly by black pine), and ca. 10% of Milovice Wood dominated mostly by Scots pine was transformed into arable fields. Since 1946, most of Děvín Hill has been under strict protection with non-intervention management. Pasture, previously commonly practiced mainly on the top and SE slopes, ceased after WWII, and these dry grasslands started to overgrow mainly with shrubs. The process speeded up after 1990, probably due to the abolition of the game preserve and a large reduction of ungulates feeding on these grasslands inside Děvín Wood. These shrubby areas have the potential to be invaded by trees and turn into woodland within a few decades. Apart from these smaller changes, woodland cover in the Pálava PLA has been stable from at least the late 17th century and probably earlier.

3.2. Changes and stability in forest management

Woods in the study area were traditionally managed as coppices. Standard trees were also present albeit in highly variable numbers. The first evidence of coppicing comes from 1384 (Bretholz, 1930) [1]. At this point the coppice cycle was 7 years and apparently there were no standards. Such a short cycle signifies a high demand for firewood. Later on the management became more heterogeneous. The coppice cycle was gradually lengthened and the density of standards grew. At the end of the 17th century, the coppice cycle was 11–13 years and there were ca. 1175

Table 1
Main archival sources (AP – aerial photography, FM – forest map; FMP – forest management plan; FS – forest survey; MGHO – Military Geographic and Hydrometeorological Office in Dobruška; MZA – Moravian Archives, letters and numbers refer to archival shelfmarks).

Year	Type of source	Reference, archival shelfmark or internet access	Area covered		Description	Reference in the text
			Děvín Wood	Milovice Wood		
1414	*Urbarium* of Mikulov estate	Bretholz (1930)	Entirely	Entirely	List of every wood on the estate including age at the time of survey, planned coppice cycle and market price. The woodland survey was completed in 1384 and copied into the later *urbarium*.	[1]
1560	*Urbaria* of Mikulov estate and town	MZA F 18 inv. č. 6792–6793	Entirely	Entirely	Data on woodland related incomes	[2]
1590	*Urbarium* of Mikulov estate	MZA F 18 karton 1250	Entirely	Entirely	Data on woodland related incomes	[3]
1629	*Urbarium* of Mikulov estate	MZA F 18 karton 1250	Entirely	Entirely	Data on woodland related incomes	[4]
1672	Management instructions for foresters	MZA F 18 inv. č. 7679	N/A	N/A	Instructions for local foresters issued by the central estate authorities	[5]
1675	Map of Mikulov estate	MZA F 18 mapa 12	Entirely	Entirely	Copy from 1802	[6]
1685–1885	Forest account books	MZA F 18 inv. č. 10362–10598, F 72 inv. č. 3353–3429	Entirely	c.2/3	Yearly accounts of harvest and sale of coppice underwood and timber	[7]
1689	Management instructions for foresters	MZA F 18 inv. č. 7679	N/A	N/A	Instructions for local foresters issued by the central estate authorities	[8]
1692	FS	MZA F 18 inv.č. 7679	Entirely	Entirely	Survey of each wood on the estate including age at the time of survey, coppice cycle, number and species of standard trees	[9]
17th cent[a]	FS	MZA F 18 inv. č. 7679	Entirely	Partly	Short list of woodlands in demesne including tree species composition	[10]
1741	Management instructions for foresters	MZA F 18 inv. č. 7679	N/A	N/A	Instructions for local foresters issued by the central estate authorities	[11]
1750	FS	MZA F 18 inv.č. 7607	Almost entirely	c. 1/3	Survey of woodland areas	[12]
1764–1768	1st Military Mapping	Oldmaps.geolab.cz	Entirely	Entirely	Mapping of the Czech, Moravian and Silezian parts of the Habsburg empire by the Army	[13]
1786	FM	MZA F 18 mapa 51	Entirely	None		[14]
1789	FS	MZA F 18 inv. č. 7615	Entirely	Entirely	Survey of woodland areas	[15]
1807–1808	FM	MZA F 18 mapa 27–31	Entirely	c.2/3		[16]
1807–1808	FMP	MZA F 72 karton 1124–1125	Entirely	c.2/3	Species composition, woodland area, number of standards, age of stands	[17]
1813	FS	MZA F 18 inv. č. 7615	Entirely	c.2/3	Survey of woodland areas	[18]
1825–1826	Stable Cadastre Maps	Archivnimapy.cuzk.cz	Entirely	Entirely	Maps accompanying the taxation survey of the Czech Lands	[19]
1837–1838	2nd Military Mapping	Oldmaps.geolab.cz	Entirely	Entirely	Mapping of the Czech, Moravian and Silezian parts of the Habsburg empire by the Army	[20]
1882	3rd Military Mapping	Kontaminace.cenia.cz	Entirely	Entirely	Mapping of the Czech, Moravian and Silezian parts of the Habsburg empire by the Army	[21]
1847	FM	MZA F 72 mapa 27, 45	Entirely	Partly		[22]
1861	FM	MZA F 72 mapa 44	Entirely	None		[23]
1883	FM	MZA F 72 mapa 22	Entirely	Partly		[24]
1885	FMP	MZA F 72 karton 1127–1129	Entirely	c.2/3	Age, species composition and area by individual stands	[25]
1901	FM	MZA F 72 mapa 25	Entirely			[26]
1901	FMP	MZA F 72 karton 1128–1129	Entirely	c.2/3	Age, species composition and area by individual stands	[27]
1905	FMP	MZA F 72 karton 1128–1129	Entirely	c.2/3	Age, species composition and area by individual stands	[28]
1921–1925	FMP	MZA F 72 kniha 113	Entirely	c.2/3	Age, species composition and area by individual stands	[29]
1933–1936	FMP	MZA F 72 kniha 114–117	entirely	c.2/3	Age, species composition and area by individual stands	[30]
1938	AP	MGHO	Entirely	entirely		[31]

1947	FM	Kouřil M (1955) Reconstruction of forest development based on preserved archival material (in Czech). Diploma Thesis. Original map lost.	Entirely	none		[32]
1948	FMP	MZA F 121 kniha 5–9	Entirely	Entirely	Age, species composition and area by individual stands	[33]
1953	AP	MGHO	Entirely	Entirely		[34]
1971	FM	Forest Management Institute	Entirely	Entirely		[35]
1971	FMP	MZA F 121 kniha 30–31	Entirely	Entirely	Age, species composition and area by individual stands	[36]
1976	AP	MGHO	Entirely	Entirely		[37]
1990	FM	Forest Management Institute	Entirely	Entirely		[38]
1990	AP	MGHO	Entirely	Entirely		[39]
2006	AP	GEODIS Prague	Entirely	Entirely		[40]
2010	FM	Forest Management Institute				[41]
2010	FMP	Forest Management Institute	Entirely	Entirely	Age, species composition and area by individual stands	[42]

[a] Precise dating not available.

standards on ca. 1700 ha of woodland (i.e. 0.7 standards per hectare [8]). Many parcels were managed as simple coppices and had no standards at all. Coeval management instructions recorded pasturing and hay-cutting as well. Pasturing was forbidden in freshly cut coppice compartments for three years and hay cutting for four years (so that coppice shoots are not cut accidentally together with grass). Nonetheless, the main product of these forests was firewood. Firewood production was carefully monitored and documented from the late 17th century onwards. Yearly harvest data (Fig. 3) showed long-term temporal stability with considerable year-to-year variation (see also Fig. 4). Until the mid-19th century, on average ca. 1600 fathoms (Klafter) of coppice underwood (ca. 4 m^3 per hectare) were harvested yearly on the Mikulov estate. This amount increased suddenly to ca. 4000 fathoms (ca. 10.5 m^3 per hectare) in ca. 1850.

Whereas in the Middle Ages coppice firewood represented a significant source of income, later on the economic value of woodland products drastically fell (Fig. 5). As a result, some time in the 16th century the right to underwood in most of the woodland was leased to local peasants for a fixed yearly sum and only a limited number of woods remained in demesne (that is, in the direct management of the estate). The estate owners kept the right to standard trees in all forests, which probably led to a rise in their numbers. Already in the 17th century the practice of singling out coppice stools (cutting each shoot except for the strongest and straightest to grow pseudo high-forests) was recorded in management instructions. In 1807/8 [16] the study area was managed as coppice-with-standards with a maximum cycle of 35 years and a varying density of 1–49 standards per hectare (average 30).

To increase the income from forests, the first game preserve was established in Děvín Wood in 1885 (Fig. 1). Because of the resulting increased grazing pressure, the coppice cycle was extended up to 40 years in 1948 [33]. The length of the coppice cycle differed according to parcel position (longer on the drier southeastern slopes, Fig. 6). Forest management plans included clear instructions on the length of the coppice cycle and the area to be harvested each year, but in reality such plans were not followed too rigidly. In Děvín Wood, the annual sum of harvested area differed significantly year by year (Fig. 4). However, the average sums over longer time periods were close to the planned ideal.

After the study area became protected (1946 for Děvín Hill and 1976 for the whole area including Milovice Wood), a double structure in priorities was formed. While nature conservation bodies preferred non-intervention, foresters aimed to replace coppices with high-forests. Coppices were left to overgrow and were often transformed into high-forest by singling out or destroying the stools. In spite of the formally compulsory non-intervention management, 23% of Děvín and 13% of Milovice Wood was felled after protection had been enacted. In addition, game keeping continued in Děvín Wood until the 1990s, and the two game preserves established in Milovice Wood in the 1960s still exist, covering over 69% of forests in the Pálava PLA (Fig. 1). Management in game preserves is driven by game keeping, therefore in the 1960s and 1970s some woods were turned to pastures, and fructiferous trees, such as horse chestnut, were planted.

3.3. Coppice abandonment: patterns and consequences

While in the 19th century all forests were coppiced, in the 20th century this management gradually lost its importance. Most of the coppices were abandoned in the 1920s–1940s, but some compartments, especially in Děvín Wood, were left already at the end of the 19th century (Fig. 7a). Most of the compartments where coppicing was abandoned already in the 19th century were located on sites with low productivity and/or on the steep NW upper slopes of Děvín Hill. After WWII, coppicing was completely

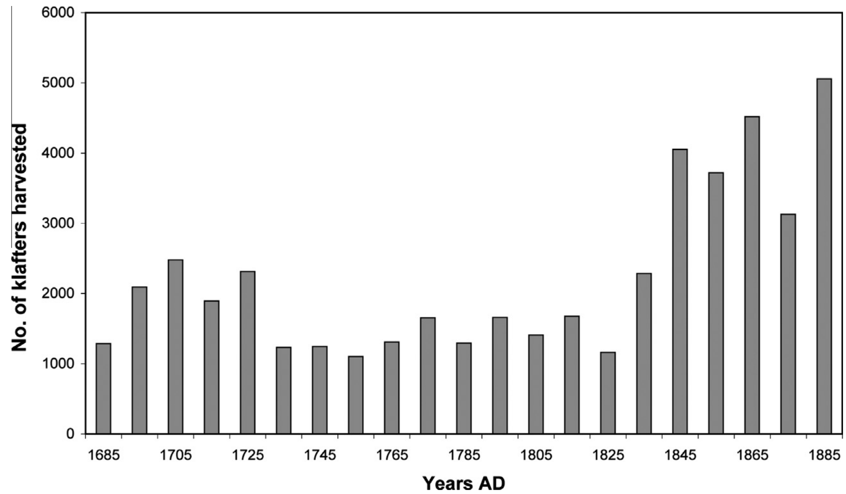

Fig. 3. Firewood production on the Mikulov estate through two centuries. Every tenth year was sampled. Klafter (English fathom) is ca 3.4 m^3.

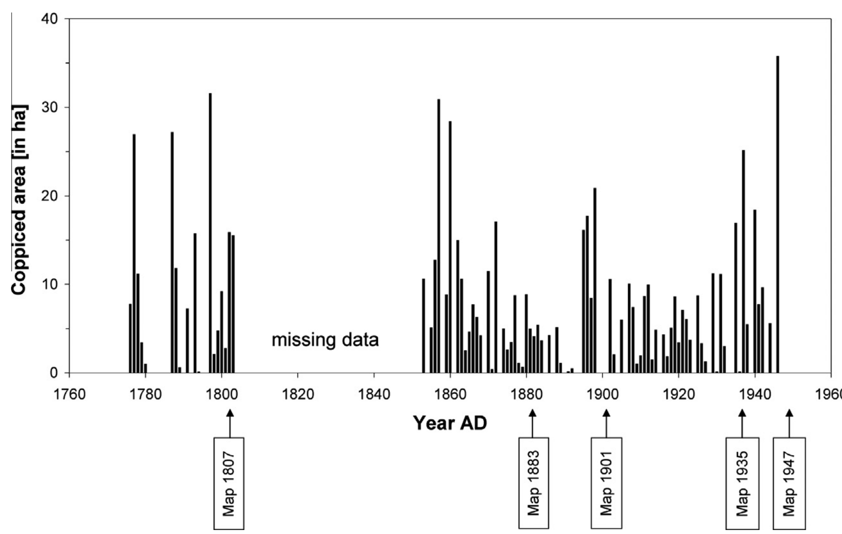

Fig. 4. Percentage of woodland-based income in the overall income of the Mikulov estate.

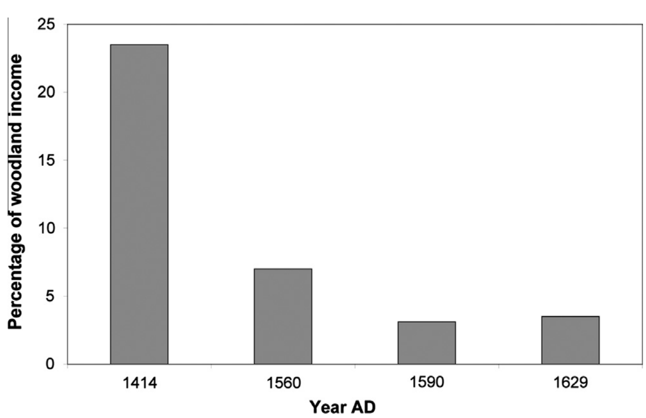

Fig. 5. Aging of Děvín Wood throughout 200 years.

abandoned (Fig. 4). In 1947/8 [33] as much as 35% of Děvín Wood was already labelled as high-forest. These stands were relatively young (on average 39 years old) and consisted of either broadleaved forests at unproductive sites, such as rocks, steep slopes and sites under high grazing pressure, or black pine plantations. The rest was divided between coppice-with-standards (47%) and coppice (18%). The average age of standards in 1948 [33] was 64 years ranging from 45 to 90, and the density, calculated from a 1938 aerial photograph, was 10 standards per hectare.

The pattern of coppice abandonment was different in the two woods – whereas in Děvín Wood poorly accessible, steep and rocky slopes were abandoned earlier compared to productive or better accessible sites, in rather uniform Milovice Wood such a relationship could not be demonstrated (Fig. 7b and c). In Děvín Wood, the pattern was significantly related to solar radiation and slope in both uni- and multivariate models, and to the forest productivity expressed by the price of the forest property in multivariate models (Table 2). The other examined variables were insignificant. In Milovice Wood, none of the explanatory variables showed a significant relationship to coppice abandonment.

The extension of the coppice cycle and the final abandonment of intensive management caused substantial changes in forest age and structure. Young forest stages almost disappeared and the proportion of older stages grew (Fig. 8a). While in active coppices young stages on average constituted more than half of all forests (31% for 1–10 years and 22% for 11–20 years in 1807/8 [16]), after the abandonment of coppicing these values fell to 1% and 4%,

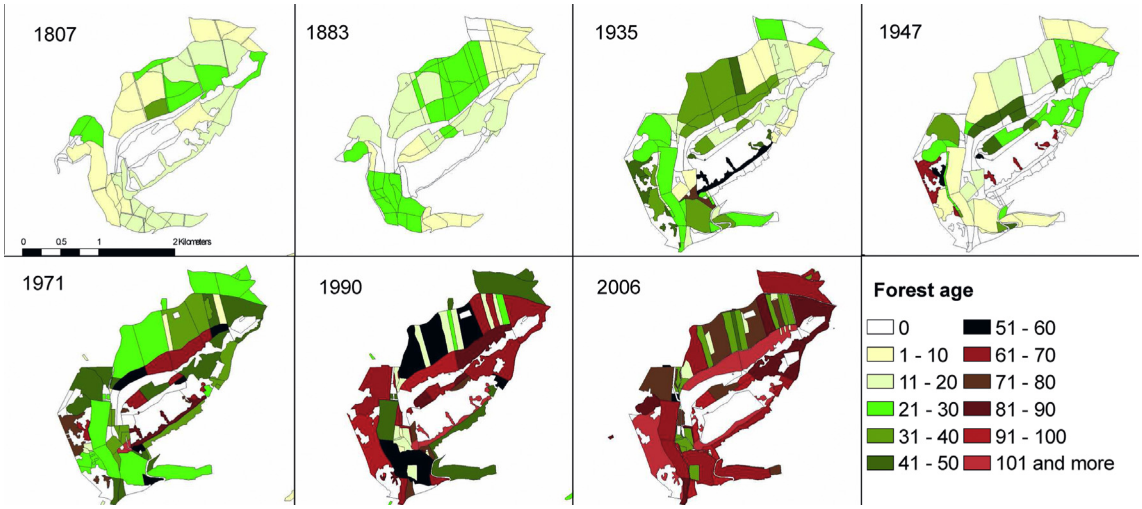

Fig. 6. Changes in coppiced area in time. Annual sum of harvest in Děvín Wood (map sources of information is marked).

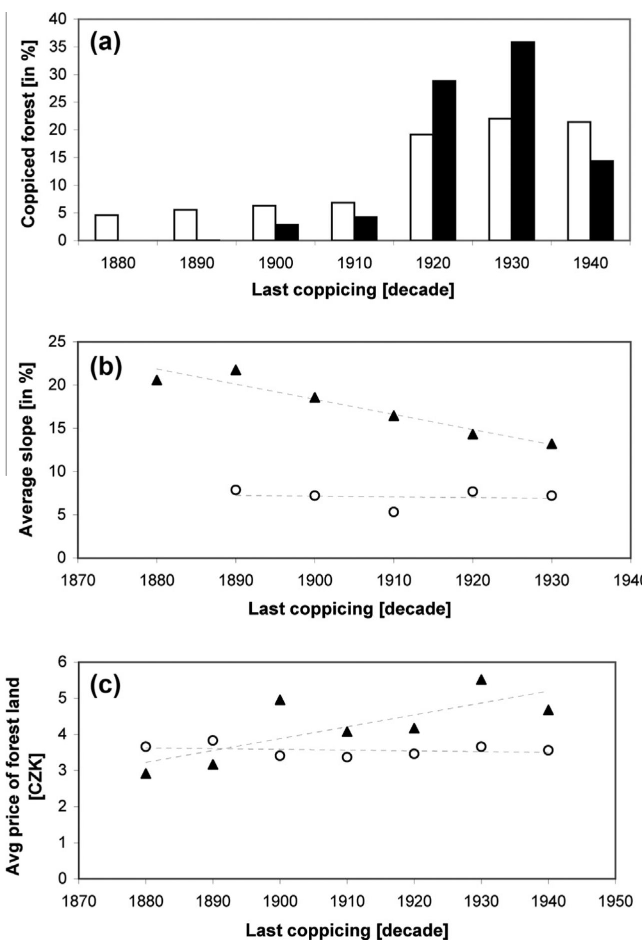

Fig. 7. Pattern of coppice abandonment. Differences between Děvín (empty symbols, circles) and Milovice Wood (filled symbols, triangles): (a) amount of abandoned coppice (percent of the total forest area), (b) relation of coppice abandonment to slope, and (c) to average price of forest land in 2008 based on estimated pedological-ecological units (Supplement No 22 to the Regulation 3/2008 Sb). Dashed lines show linear trend.

respectively. Older stands (over 40 years) were absent until 1883/5 [25] but constituted 15% in 1948 [33], 48% in 1971 [36], and 77% in 2006 [40]. Today, 26% of Děvín Wood is covered by forests older than 100 years, compared to 8% of such forests in Milovice Wood. The original fast-changing mosaic of open and dense coppice stands has shifted towards the post-abandonment closed-canopy structure of old forests. Open habitats have drastically decreased. This tendency towards uniformity is indicated by a sharp decrease in the Shannon index of age diversity. Based on Brown and Parker (1994), stands over 50 years were interpreted as closed-canopy forest and were therefore merged into one class (Fig. 8b).

4. Discussion

4.1. Forest cover

Forest cover in the study area was stable throughout the centuries and only small changes occurred. Dynamic processes in usage and access, such as abandoning direct management and leasing out the majority of forests to tenants in the 16th century, did not lead to loss of woodland. Generally speaking, the stability of woodland cover in the study area is similar to other long-settled and little wooded lowland regions in Europe (Rackham, 2003; Tack et al., 1993; Bürgi, 1999). In such regions, woodland has been valued as a limited resource since the Middle Ages. The Mikulov estate (which included the study area) was ca. 21% wooded. This apparently represented a 'minimum' value in the region, over which the benefits of further woodland clearance in feeding the steadily growing population could not compensate for the loss in firewood supply (Szabó and Hédl, 2013). A similar minimum percentage of woodland cover was observed to have repeatedly occurred over several centuries in neighbouring Hungary as well (Szabó, 2008).

4.2. Forest management

Forest management in the region was stable from at least the 14th century until WWII, even though forests experienced shifts in structure and dynamics as the coppice cycle was extended and the density of standards changed (Szabó, 2010a; Altman et al., 2013). An important difference between changes in the coppice cycle and in the density of standards is that the former was regular (the cycle gradually became longer) while the latter was irregular (the number of standards showed no clear trend over longer periods and could drastically change following major harvests). Nonetheless, in the coppice system underwood was always the major product, and standards were allowed to grow only to the extent so as not to compromise coppice regrowth (Matthews, 1989). Underwood harvest was planned and regular, while

Table 2
The coppice abandonment as a function of environmental variables in both Děvín (37 parcels) and Milovice Wood (69 parcels). Significance was tested in generalized linear models of univariate and multivariate type using software R version 2.14.2 (R Development Core Team, 2012). The best fitted model was determined by the lowest Akaike Information Criterion value. Univariate models are shown only for significant explanatory variables.

All variable model	AIC: 556.19			
	Estimate	Std. Error	*t* value	Pr(>|*t*|)
Milovice Wood				
(Intercept)	1.92E+03	2.49E+01	77.164	<2e−16***
Solar radiation	−3.43E+00	6.07E+00	−0.565	0.574
Wetness Index	7.55E−01	1.32E+00	0.573	0.569
Slope	−9.62E−01	7.37E−01	−1.305	0.197
Price	−2.51E−01	1.76E+00	−0.143	0.887
Forest bonity	2.88E+00	3.32E+00	0.869	0.388
Road distance	2.42E−02	3.12E−02	0.775	0.442
Distance from the village	2.14E−03	3.47E−03	0.617	0.54
Univariate model for solar radiation	AIC: 322.59			
	Estimate	Std. Error	*t* value	Pr(>|*t*|)
Děvín Wood				
(Intercept)	1945.87	11.1	175.333	<2e−16***
Solar radiation	−11.17	3.9	−2.865	0.00701**
Univariate model for slope	AIC: 324.38			
	Estimate	Std. Error	*t* value	Pr(>|*t*|)
(Intercept)	1933.0604	7.7957	247.964	<2e−16***
Slope	−1.1516	0.4638	−2.483	0.018*
All variable model	AIC: 312.31			
	Estimate	Std. Error	*t* value	Pr(>|*t*|)
(Intercept)	2.03E+03	3.64E+01	55.615	<2e−16***
Slope	−1.27E+00	3.82E−01	−3.32	0.00244**
Solar radiation	−1.04E+01	3.75E+00	−2.786	0.00932**
Wetness Index	−5.39E+00	3.20E+00	−1.685	0.10268
Price	−4.50E+00	1.93E+00	−2.333	0.02681*
Forest productivity	1.28E+00	3.69E+00	0.346	0.73161
Road distance	7.60E−03	4.76E−02	0.16	0.87422
Distance from the village	−4.05E−03	8.05E−03	−0.503	0.61878
Best fitted model	AIC: 303.87			
	Estimate	Std. Error	*t* value	Pr(>|*t*|)
(Intercept)	2070.0942	29.448	70.297	<2e−16***
Slope	−3.3557	1.061	−3.163	0.00349**
Solar radiation	−27.2469	8.2822	−3.29	0.00250**
Wetness Index	−5.5016	2.7455	−2.004	0.05389 .
Price	−4.8842	1.4008	−3.487	0.00149**
Slope:Solar radiation	0.7961	0.3767	2.113	0.04272*

Signif. codes are 0‘***’, 0.001‘**’, 0.01‘*’, 0.05‘.’, 0.1‘ ’.

standards were cut occasionally, controlled by local building activities. Therefore the irregularly changing number of standards in the study area was part of the system, and the only real change was the extension of the coppice cycle from the medieval 7 years to several decades in the 19th-20th centuries. This trend was not particular to the study area, in fact it was observed throughout Europe (e.g. Rackham, 2003). Why this happened is presently unknown, reasons might include for example the appearance of chimneys and fireplaces, the declining fertility of forest soils or the growing costs of labour. Another change is visible in Fig. 3. This did not concern the form of management, rather its intensity. Providing that the sudden increase in firewood production reflects a real change (and not for example a change in the volume of the local fathom), it can be arguably connected to the introduction of scientific forestry on the Mikulov estate. It may have resulted from better planning or from increased harvests as part of the effort to transform coppices into high-forests.

The reasons behind stability in woodland management varied over time. Coppice firewood, a major source of income for the estate in the Middle Ages, lost its economic importance in the Early Modern Period, but local society still depended on it (Szabó, 2010a). At the end of the 19th century fossil fuels became available, and high-forests started to replace coppices. Nonetheless, until WWII coppicing was active in most of the study area except unproductive sites on shallow rocky soils and steep slopes that were difficult to harvest.

4.3. Coppice abandonment

The extension of the coppice cycle and the abandonment of coppicing after WWII had a strong impact on forest characteristics. While the fact that many coppices were abandoned in Europe in this period is well-known (e.g. Bürgi and Russell, 2001; Gondard et al., 2001; Tack et al., 1993; Peterken, 1993; Molnár, 1998), practically no information exists to describe the process of abandonment. A particularly intriguing aspect is the spatial pattern of coppice abandonment and the driving forces behind this pattern. Modern forestry in general can be characterized as a highly planned and organized activity (Matthews, 1989; Puettmann et al., 2009; Lowood, 1990). From the late 19th century onwards, it tried to enforce rigorous wood harvesting regimes, which were unusual in earlier times. By contrast, our results suggest that coppice abandonment in the mid-20th century was an unregulated process. Any discernable spatial pattern was observed only in

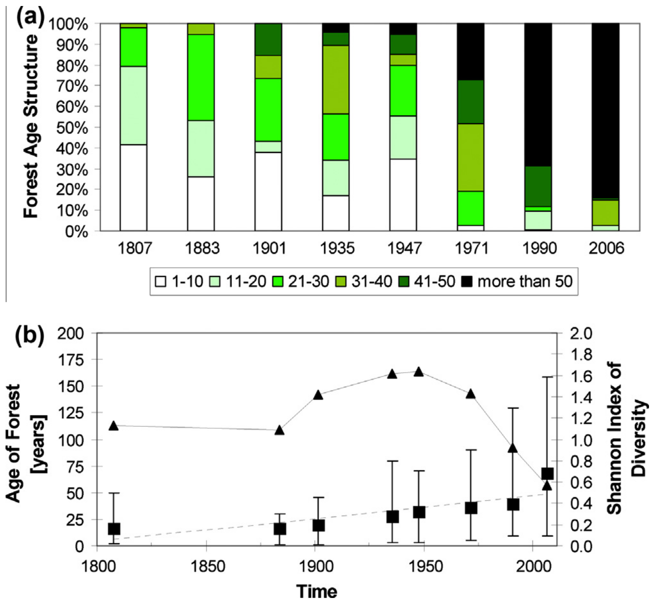

Fig. 8. Coppicing abandonment caused changes in forest structure. Increase in average forest age (a) and sharp decrease in age diversity of forest patches (b) expressed by Shannon Index of diversity (triangle; the same age categories as for the Figure A, i.e. stands over 50 years are considered as one class). Average age of forest (square) is shown together with age minimum and maximum, and the linear regression line. Results are from the Děvín Wood where data on forest age were more abundant.

Děvín Wood, where we found a significant relationship between the time of coppice abandonment and slope and solar radiation, and a less obvious relationship between time of abandonment and forest productivity. In Milovice Wood, no factors we studied were significantly related to the time of abandonment. This could be explained by differences in environmental conditions. The gradient of elevation and site productivity in Milovice Wood is less pronounced than in Děvín Wood. The latter is steeper, 64% of the area has slopes over 12° compared to only 16% in Milovice Wood. This means that first those coppice compartments were abandoned that were steep, in simple terms those places where it was difficult to harvest. Soil fertility was far less important. If no such places existed (as in Milovice Wood), no pattern could be detected. The length of the abandonment period could also differ. Poorly accessible places in Děvín Wood began to be neglected already in the 19th century, but most of Milovice Wood was abandoned during a relatively short interval (1920s–1940s).

We conclude that there was little planning in coppice abandonment, coppices were in fact left behind in an unregulated manner. Not even income mattered: in Milovice Wood, productive sites were just as likely to be abandoned as infertile ones. It is especially remarkable from this perspective that the remoteness of compartments from roads did not affect their time of abandonment. If the slightest effort had been made to abandon coppices in an organized manner, surely the compartments closest to roads (and therefore harvestable in the most cost-effective manner) would have been abandoned last. The only pattern detected in coppice abandonment indicates that the process was not driven by economic factors (as in the principles of coeval forestry) but rather by down-to-earth considerations to avoid difficult working conditions. The decisions about where not to coppice are likely to have been brought by local foresters rather than the central planning office in Mikulov. In this sense, coppice abandonment was not entirely random but at the same time, when compared to forestry standards, it was not planned, either.

5. Conclusions and implications for conservation

Pálava is an ancient landscape that has been co-formed by humans for millennia. The forests in the Pálava PLA demonstrated a high degree of stability for centuries. Both woodland cover and management appear to have changed very little from the Middle Ages to the 20th century. Coppice management was abandoned shortly after WWII, which completely altered the age structure of the forests from young to old, a pattern never experienced in the known history of the Pálava forests. This and the isolation of the remaining few patches of young forest stages have led to drastic changes in vascular plants species composition, which indicate the replacement of thermophilous oakwoods by mesic forests (Hédl et al., 2010; Kopecký et al., 2013). Nonetheless, signs of previous coppice management, such as coppice stools and standards are still recognizable in most of Děvín Wood and in some parts of Milovice Wood. Although the history of the two forests is almost identical, the existence of the game preserves in Milovice Wood creates a situation rather different from strictly protected Děvín Wood. The re-introduction of coppicing would be pointless in the heavily grazed parts of Milovice Wood, but at the same time artificially high numbers of ungulates appear to have held up succession, so that some changes may be more reversible here than in Děvín Wood (Hédl et al., 2010).

Generally speaking, forests in the study area can be viewed as typical for densely settled European lowland regions north of the Alps. In such regions, woodland is often the most conservative landscape element both in extent and management. Similarly to our study region, most European coppice woods were abandoned in the 20th century. A so far unknown element in the abandonment of coppices is the spatial pattern the process followed. In our study region, abandonment appears to have been unregulated. As a result, the current spatial pattern of forest age structure can only be connected to topographic conditions. Based on the general similarities among lowland regions described above, we hypothesize that coppice abandonment was a similarly irregular process in other areas as well.

The haphazard fashion in which coppices were abandoned could have far-reaching consequences for their protection and restoration as well. For example, predicting the distribution patterns for rare and endangered plant species should be approached with caution. Under traditional management, young forest stages dominated in coppices and provided excellent opportunities for the occurrence of light-demanding species (Beneš et al., 2006; Spitzer et al., 2008; Van Calster et al., 2008a; Vodka and Čížek, 2013). However, the precise distribution of species was determined by many other factors, which makes the distribution to a certain extent unpredictable. If, for example, the effect of ungulate grazing produced a spatially heterogeneous pattern (Adler et al., 2001), plant species sensitive to such a disturbance could have been structured following grazing intensity rather than historically relatively homogeneous coppice management. If accidentally heavily grazed parts had been abandoned last, the entire wood would be evaluated as poorer in such species than if an ungrazed part had been managed longest.

Attempts to reintroduce coppice management for conservation purposes should take into account the pattern of abandonment. At present, three models exist for coppice reintroduction. (i) If the entire forest is to be coppiced, it is divided into compartments that are successively cut. This is in fact a complete imitation of the traditional system (e.g. Hauberg Fellinghausen, Germany – Fasel, 2007) (ii) If only part of the forest is planned for coppicing, this may be done in a regular geometric fashion starting from some point (e.g. Hayley Wood, England – Rackham, 1975) or (iii) in a scattered manner in which individual plots are not adjacent to each other, as it has been done for example on the northern slopes of Děvín Wood for the past few years. Especially in the third case, current age structure can be a strong determining factor. In Děvín Wood, 21.6 ha of overgrown coppices were harvested in 2009–2014, and further thinning is planned to reduce the density of shoots by 60% (V. Riedl, personal communication). Such decisions usually result from a combination of various conservation targets (Fuller and Warren, 1993). A deeper understanding of current age structure through the study of abandonment patterns has the potential to foster more informed decisions with regard to the spatial plan of management reintroduction and can lead to more successful restoration efforts.

The exceptional ecological value of woodlands in the Pálava PLA is partly due to human influence. Traditional management, such as coppicing, has been abandoned due to socio-economic changes as well as to previous concepts of nature protection. In the past, nature protection was defined as the protection of nature with an emphasis on avoiding human influence, now usually termed protection of processes, or non-intervention. The Pálava PLA is a perfect example of the importance of humans in maintaining ecosystem biodiversity.

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