Long-term land-cover/use change in a traditional farming landscape in Romania inferred from pollen data, historical maps, and satellite images

Short running head: **Land-use effects on traditional farming landscapes**

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Abstract

Traditional farming landscapes in the temperate zone that have persisted for millennia, can be exceptionally species-rich, and are therefore key conservation targets. In contrast to Europe's West, Eastern Europe harbours widespread traditional farming landscapes, but drastic socio-economic and political changes in the 20th century are likely to have impacted these landscapes profoundly. We reconstructed long-term land-use/cover and biodiversity changes over the last 150 years in a traditional farming landscape of outstanding species diversity in Transylvania. We used the Regional Estimates of Vegetation Abundance from Large Sites (REVEALS) model applied to a pollen record from the Transylvanian Plain and a suite of historical and satellite-based maps. We documented widespread changes in the extent and location of grassland and cropland, a loss of wood pastures as well as a gradual increase in forest extent. Land management in the socialist period (1947-1989) led to grassland expansion, but grassland diversity decreased due to intensive production. Land-use intensity has declined since the collapse of socialism in 1989, resulting in widespread cropland abandonment and conversion to grassland. However, these trends may be temporary, due to both ongoing woody encroachment as well as grassland management intensification in productive areas. Remarkably, only 8% of all grasslands existed throughout the entire time period (1860 and 2010), highlighting the importance of land-use history when identifying target areas for conservation, given that old-growth grasslands are most valuable in terms of biodiversity. Combining datasets from different disciplines can yield important additional insights into dynamic landscape and biodiversity changes, informing conservation actions to maintain these species-rich landscapes in the longer term.

Keywords: semi-natural grasslands; biodiversity; woody pastures; forest regeneration; farmland abandonment; conservation; socio-economic change; central-eastern Europe

Introduction

Human land-use has transformed much of the Earth's terrestrial surface with less than a quarter remaining as wildlands (Ellis et al. 2008). Land-use change is considered the greatest cause of biodiversity decline via habitat loss and fragmentation (Foley et al. 2005). Yet, many species can persist in, or even critically depend on, human-dominated landscapes (Fischer et al. 2012). Europe's traditional farming landscapes are a typical example of high conservation value ecosystems that depend on low-intensity farming practices. These landscapes, and especially the semi-natural grasslands they contain, harbour unique farmland biodiversity and are among the most species-rich vegetation communities in the world (Wilson et al. 2012; Dengler et al. 2014). They also provide an array of ecosystem services, including provisioning, regulating, supporting, and cultural services (Akeroyd and Page 2011; Bakker 1989; Poschlod and Wallis de Vries, 2002). Together this makes Europe's traditional farming landscapes and their semi-natural grasslands key targets for biodiversity conservation.

While historical land-use change, especially in the 18th and 19th century, fostered the creation and maintenance of semi-natural grasslands, land-use change in the 20th and 21st centuries has threatened traditionally managed farming landscapes and their grasslands. Particularly in Western Europe, the extent and diversity of semi-natural grasslands has declined markedly since the late 19th century, mainly due to the rise of industrialised agriculture. This process has led to an intensification and concentration of agriculture in the most productive regions, and the abandonment of more marginal sites, which, in turn, has resulted in the expansion of forest on many of these sites (Jepsen et al. 2015). In addition, semi-natural grasslands have been lost to the spread of settlement and infrastructure (Poschlod and Wallis de Vries 2002; Stoate et al. 2009). In contrast, grasslands of conservation value have persisted longer in Central and Eastern (CE) Europe, as agricultural intensification and concentration in the most fertile area was delayed in comparison to Western Europe (Jepsen et al. 2015; Hajnalova and Dreslerová 2010).

Nevertheless, a number of marked changes in CE Europe's institutional, socio-economic and political structures over the recent past have markedly affected land

management in this region. In the late 18th and early 19th century, many countries experienced a period of agricultural expansion, especially into more accessible, fertile areas such as along major rivers. The socialist period (1947-1989) brought the transfer of land ownership to the state with the rise of highly mechanised, large-scale and state-subsidised agriculture in many areas (Sârbu et al. 2004). The breakdown of the socialist system in 1989 reversed some of these trends, bringing about farmland abandonment due to a combination of lower agriculture profitability (due to the loss of agricultural subsidies and formerly guaranteed markets) and tenure insecurity (due to the privatisation and restitution of farmland) (Hartvigsen 2014), as well as widespread rural outmigration and the consequent loss of agricultural labour (Kuemmerle et al. 2009; Stoate et al. 2009). Furthermore, a marked de-intensification of farming occurred as agrochemical use declined drastically (FAO, 2012). After 2004, another phase of socioeconomic and institutional transformation began with the accession of many CE European countries to the European Union (EU). This resulted in the introduction of the Common Agricultural Policy (CAP) framework, potentially re-enforcing the two-fold trend of abandonment of marginal areas alongside agricultural intensification of more favorable sites (Levers et al. in press; Kuemmerle et al. 2006). At the same time an increasing number of sites were designated as Natura 2000 sites and CE Europe's farmers now have access to EU subsidies aimed at supporting environmentally-friendly agriculture and maintaining traditional farming practices. However, how these different and sometimes diverging trends affected the extent and dynamics in semi-natural grasslands of conservation value remains poorly understood.

A range of data sources have been employed to reconstruct land-cover and land-use changes in Europe, including pollen records (Gaillard et al. 2010; Trondman et al. 2015), historical maps (Munteanu et al. 2014; 2015) and satellite images (Kuemmerle et al. 2009; 2010; Griffith et al. 2013). Each of these data sources has its own strengths and weaknesses. Fossil pollen records provide a deep insight into vegetation composition and dynamics, and models of pollen-vegetation relationships can correct for biases in pollen productivity and the different dispersal characteristics of taxa, basin size and characteristics

(Sugita 2007). Yet, pollen-based reconstructions often lack spatial detail and can only provide indirect information on land-cover and land-use patterns, although this limitation may potentially be overcome by modeling using the Multiple Scenario Approach (Bunting and Middleton 2009). Another established way to assessing land-cover and land-use changes is through time series of satellite images, which can provide detailed insights into spatial patterns of land-cover / use change. However, satellite-based reconstructions can only reach back to the 1970s, precluding more long-term analyse (Kuemmerle et al. 2009; Griffiths et al. 2013). A third source of information on land-cover/use change are historical maps, and recent advances in the digitisation and harmonisation of historical maps allow for an understanding of land-use changes across longer time periods, although historical maps still typically provide restricted snapshots in time (Munteanu et al. 2015; Kaim et al. 2016). Combining pollen analysis, and satellite-image analyses and historical maps could make use of the strengths of all these datasets while mitigating their weaknesses, but has so far only rarely been carried out (Cui et al. 2014; Szabó et al. in press).

Here, we have assessed land-cover and land-use changes over the last 150 years in the lowlands of Transylvania, Romania; today an open landscape with significant grassland areas of high conservation value (Cremene et al. 2005; Ruprecht et al. 2009; Wilson et al. 2012). We used a harmonised set of land-cover/use maps based on historical maps and satellite images (Munteanu et al. 2014) and a pollen-based land-cover reconstruction using the Regional Estimates of Vegetation Abundance from Large Sites model (REVEALS; Sugita 2007) on a sediment profile from Lake Știucii. Our study area focussed on a 50-km circle around Lake Știucii. Specifically, we examine two main research questions:

i) How did the spatial patterns of cropland, grassland and forest change in our study area, following major socio-economic, political and institutional shifts between 1860 and 2012?

ii) How persistent and diverse have grasslands been during this period?

Methods

Study area and site

Our study was carried out at Lake Știucii (239 m a.s.l., N 46°58' 044; E 23°54' 106) located in the Transylvanian Plain, NW Romania (Fig. 1; Feurdean et al. 2013). The climate is temperate continental (mean annual temperature ca. 8-9°C, January mean temperature ca. -1°C, July 18-20°C and annual precipitation 550-650 mm). Soils are Haplic and Luvic Chernozems and Phaenozems (IUSS WRB 2006). Historical and prehistorical anthropogenic impacts have significantly altered the vegetation composition of the region so that the area presently contains a mosaic of forests, wood pastures, pastures, orchards, hay meadows and cropland. Typically, villages and arable fields occupy the valleys, pastures and hay meadows the slopes, while forests tend to be found on the hilltops (Angelstam et al. 2003). The study area underwent largely the same socio-economic, political and institutional shifts as elsewhere across the former Socialist Bloc of CE Europe (see Introduction). However, the major land reforms were not implemented until 1953, thus somewhat later than in other former socialist countries in Eastern Europe. Due to the dry climate of the study area, with frequent summer droughts, much agricultural land was designated as meadows and pastures that were grazed by sheep and cattle (David, 2008; Ruprecht et al., 2009). The breakdown of the socialist system in 1989 led to a substantial decline in livestock, especially in areas of low yielding, dry grasslands (Cremene et al. 2005, Ruprecht et al., 2009), as well as in arable agriculture.

Palaeoecological analysis

We extracted a sediment core (37 cm) using a gravity corer taken from the overlying ice in winter 2012 and sectioned the core in the field at 0.5 cm intervals. The core consists of olive brown, fine clay gyttja with a varying proportion of inorganic matter content and a distinct change in sedimentation rate between 20 and 27 cm. We established a chronology based on ^{210}Pb, ^{226}Ra, ^{137}Cs, ^{241}Am and AMS ^{14}C measurements performed on bulk sediment (see details in Feurdean et al. 2013). We analysed the pollen at intervals between 1-2 cm following the standard chemical procedures of Bennett and Willis (2001). We identified the

pollen using the pollen keys of Moore et al. (1991) and Reille et al. (1995). We counted a total of 400-800 pollen grains at each level, except for a pollen poor interval (20-216 grains) with a high minerogenic content between 20 and 25 cm depth in the core. We converted the pollen and spore counts into percentages of the terrestrial pollen sum (Fig. A1). The nomenclature for vascular plants follows Flora Europaea (Tutin et al. 1964–80).

Land-cover reconstruction from the pollen record

We used the REVEALS (Regional Estimates of Vegetation Abundance from Large Sites) model (Sugita 2007) to correct for biases due to differences between taxon-specific pollen productivities and dispersal and basin type (Fig. 2), and to provide a quantitative reconstruction of the land cover of the region surrounding Lake Știucii. Pollen productivity estimates (PPE) and the fall speed (FSP) for each of the 28 pollen types (15 woody and 13 herb taxa) were obtained from the literature (Fig. A2). A full description of the application of the REVEALS model at this site is given in Feurdean et al. (2015). The land cover reconstructed using REVEALS always adds up to 100%, which means that taxa not included in the model reconstruction, as well as non-pollen producing areas such as settlements, water and crop fields (of non-pollen producing crops) are ignored.

To determine changes in the proportion of the main land-cover types, terrestrial pollen types were classified into three major groups: (1) cropland, (2) grassland and (3) forest. We assume that each of the 28 plant taxa in the pollen record (REVEALS reconstruction) is characteristic of a single land-cover type. For a detailed list of pollen type and land-cover class attribution, as well as the harmonisation of land-cover/use classes, derived from the pollen record and the spatial sources see Fig. A2.

Land-cover/use reconstruction from historical maps and satellite images

We extracted historical and recent land-cover/use at a 50-km radius around the lake based on a combination of historical maps and satellite images covering five points in time (1860, 1930, 1960, 1985, 2010; Fig. 3). These years capture land-cover/use during periods of

distinct socio-economic and political characteristics: the Habsburg Empire (1860), the Interwar Period (1930), the early (1960) and late socialist period (1985), and finally the post-EU-accession period (2010). We used satellite-imagery-based maps for the most recent time periods because: i) these maps were of high quality, ii) the satellite-based maps and historical land-use maps are of comparable thematic detail and spatial resolution, and iii) there are, to our knowledge, no contemporary maps available. Land-cover/use reconstruction and homogenisation across the range of historical maps was based on the digitisation of four major land-cover/use classes present on all the maps (i.e., cropland, grassland, forest and other) for a regular grid of points, where the points were spaced at 2 km. Our grid conforms to the 2007 INSPIRE directive (Infrastructure for Spatial Information in the European Community) as well as the LUCAS (Land Use and Cover Area frame Survey, Gallego and Delince, 2010), which adequately captures landscape composition and structure at broad and finer spatial scales (Munteanu et al. 2015; Kaim et al. 2016). For the years 1985 and 2010, the four land-cover/use classes were automatically extracted to the point grid from Landsat TM and ETM+ satellite composites for the entire Carpathians (Griffiths et al. 2013; 2014). We reconstructed historical land cover/use for points inside 10 buffers centred on Stiucii Lake. The smallest buffer had a radius of 5-km and included a total of 20 points, whereas the largest buffer had a radius of 50-km with a total of 1,965 points. We summarised the number of points in each land-cover/use class for each of the 10 buffers, as well as the relative abundance of each land-cover/use class, based on the share of points in a class (Fig. 4). We also identified those points that were classified as grassland at least once and those points that were grassland at every time interval (Fig. 3). The latter allowed for the assessment of grassland persistence over time.

Harmonising and analysing pollen, and map-based land-cover/use reconstruction

To facilitate the comparison between pollen and map-based land-cover/use reconstructions, we calculated for the map-based reconstruction the area share of the sum of all pollen-producing land-cover/use classes. We excluded the category "other", which is made up of

non-pollen producing areas such as buildings and water. We calculated the Squared Chord Distance (SCD) between percentages of various land-cover/use classes in the pollen and maps for all 10 buffer distances (i.e., from 5-km to 50-km radius, Fig. 5), assuming that the best fit between the two provides the most appropriate scale of comparison with our pollen record (i.e., pollen source area). We used the SCD as the dissimilarity measure as this was found to offer a good signal to noise ratio for percentage data (Overpeck et al. 1985).

Numerical analysis

We assessed the overall change in the pollen-based land-cover composition between the different time periods using the Analysis of Similarity (ANOSIM) in the PRIMER v6 package (Fig. 6). REVEALS-based percentages were used to generate Bray–Curtis similarity measures. ANOSIM was carried out using 500 permutations to establish whether there were significant differences in vegetation composition between the different time periods. ANOSIM uses non-parametric permutation procedures applied to Bray–Curtis similarity matrices based on rank similarities between samples. ANOSIM produces an *R*-statistic, which gives a measure of how similar groups are. Values most commonly range from 0 to 1; the closer the *R*-value is to 1 the greater the difference between the groups (Clarke and Warwick 2001). In addition, the similarity percentage (SIMPER) procedure was used to determine which taxa were good discriminators of the differences in composition. SIMPER measures the relative contribution of each taxon to the dissimilarity between samples (Clarke and Warwick 2001).

To examine the response of grassland diversity to different degrees of land-use intensity, palynological richness was calculated by applying rarefaction analysis (Birks and Line 1992) to pollen counts of all terrestrial taxa as well as separately for herbs using the Psimpoll program (Bennett 2003). We used raw pollen data instead of REVEALS estimates in this analysis because the number of herbaceous taxa, for which PPEs are available, are limited and REVEALS estimates are therefore likely to underestimate past diversity changes. The lowest pollen count (T_{216}) was used to standardise the size of the pollen counts at each site eliminating bias in richness caused by different pollen count sizes (Fig. 7).

Results

Land-cover reconstruction from the pollen record

The ANOSIM results revealed two significant changes in the pollen profile, around 1936/1950 and 1984, which suggests important compositional differences between the three periods that these boundaries separate (Fig. 6). These boundaries roughly coincide with the timing of major shifts in the socio-economic and institutional structures in the region separating the pre-socialist period (before 1950) from the socialist period (1950-1989), and the socialist period from the post-socialist period (post-1989). It should be noted that the 1936/1950 boundary also corresponds to a shift in sediment type and accumulation rate, which makes the chronology more uncertain for this time interval. The ANOSIM analysis also provided strong support for significant differences in the composition of the vegetation communities in our study area between these three periods (global R = 0.74, p = 0.001; Fig. 6). The SIMPER analysis indicated that >60% of the difference between the pre-socialist and socialist periods was due to Poaceae (most abundant in socialist period) as well as *Fagus sylvatica* and *Quercus spp.* (most abundant in the pre-socialist period). More than 30% of the difference between the socialist and post-socialist period was due to Poaceae (most abundant in the socialist period), while *Quercus spp.* (most abundant in the post-socialist period) contributed 14% to the dissimilarity we found.

The REVEALS-based land-cover reconstruction indicates a higher proportion of open land-cover classes (grassland and cropland) than that suggested by the pollen percentages alone (Fig. 2). Specifically, in the REVEALS-based land-cover reconstruction the adjusted relative abundances of Poaceae*,* Cerealia*, Secale* and *Fagus sylvatica* were higher than their pollen percentages suggested, whereas those of *Pinus, Betula, Alnus, Corylus avellana, Artemisia*, *Rumex* and Chenopodiaceae were lower than their pollen percentages (Fig. 2). Below we summarise the land-cover changes based on REVEALS, as well as the most important changes in the untransformed pollen percentages, separated into the three time periods.

During the pre-socialist period, commencing during the Habsburg Empire (1860) to immediately following WW II, the estimated tree cover was about 50% and primarily consisted of *F. sylvatica, Quercus* and *Carpinus betulus* (Figs. 2, 4). Grassland cover (40-50%) was dominated by Poaceae (40%), whereas important forbs were Apiaceae, *Galium*, *Filipendula,* Ranunculaceae, *Artemisia,* Chenopodiaceae*, Plantago lanceolata, P. media* and *Rumex* (Figs. 2, 4, A1). The extent of cropland cover varied between 2% and 10%.

From the beginning of socialism in Romania to the final years of the socialist period (1989), the estimated tree cover dropped to 10-20%, in particular for *F. sylvatica* and *Quercus*. The grassland cover (dominated by Poaceae) increased to 60-70%, whereas cropland cover (Cerealia, *Zea, Avena*-type, *Hordeum*-type, *Triticum*-type and *Secale*) reached a maximum of 15% (Figs. 2, 4). Other herbs showing an increased abundance during this period include *Artemisia,* Chenopodiaceae, *P. lanceolata*, *P. major, Urtica,* Ranunculaceae, Apiaceae and *Cannabis,* whilst *Filipendula* declined slightly. Pollen percentages for Asteraceae Tubuliflorae, A. Liguliflorae and Brassicaceae also increased (Fig. A1).

From the end of the socialist period to 2012, the estimated tree cover increased to 40-55%, mostly *Quercus, F. sylvatica, Carpinus betulus*, *Betula*, *Corylus avellana, Salix* and *Pinus.* Grassland cover declined to 30%, in particular Poaceae, whereas the pollen percentages of forbs (Asteraceae Tubuliflorae) increased markedly (Figs. 2, A1). The cover of cropland (5-10%) also declined markedly in the post-socialist period (Fig. 4).

Pollen richness was highest between 1986 and 2012, and intermediate before 1950, whilst the lowest values were found between about 1955 and 1986 (Fig. 7). Pollen richness for herbs shows the highest values between 1990 and 2000, and 2005 to 2010.

Land land-cover/use reconstruction from historical maps and satellite images

The land-cover/use based on historical maps and satellite images showed that cropland was mostly concentrated in the southern and south-eastern part of our study region, while forests occurred predominantly in the northern and western part across all the buffers and time

periods that we considered (Fig. 3). We caution, however, that for the smaller buffer sizes (5-km, 10-km radius), the estimates of land-cover/use have greater uncertainty due to the lower number of points included in these buffers. Below we present the results for the 5-km, 25-km and 50-km buffers (see Fig. A3 for all buffers).

During the pre-socialist period, forest cover in the 5-km buffer was 21% of the landscape in 1860s and 26% in 1930s, in the 25-km buffer it was 18% in both years, and in the 50-km buffer it was 26% in 1860s and 21% in 1930s. Grasslands covered 21% in 1860s and 26% in 1930s in the 5-km buffer, 32% in 1860s and 35% in 1930s in the 25-km buffer, and 30% in 1860s and 34% in 1930s in the 50-km buffer. In 1860s and 1930s, cropland cover comprised 26%, 50%, and 44% in the 5-km, 25-km, and 50-km buffers, respectively (Fig. 4).

During the socialist period, forest cover remained roughly the same as in the previous period. Grassland cover increased considerable, especially close to the lake (5-km buffer, increased to 45% in 1960s followed by small decrease to 42% in 1980s). Cropland cover close to the lake also increased from 30% (1960s) to 42% (1985s) in the 5-km buffer, whereas cropland cover decreased further away (from 53% in 1960s to 46% in 1985s in the 25-km buffer; Fig. 4).

During the post-socialist period (2010s map), forest cover remained fairly stable, yet cropland cover decreased considerably to 6% of the landscape in the 5-km buffer, and around 13% in the 25-km and 50-km buffers. Conversely, grassland cover increased to almost 80% of the landscape (Fig. 4).

In terms of the persistence of grassland across our entire study period (1860-2010), our results indicated that only 8% of the grassland areas were continuously present from 1860s until today (permanent grasslands). As little as 21% of the 1860s grasslands still occurred in 2010 (i.e., 13% had been tilled at some point since 1860 but were again grasslands in 2010; Fig 3). Because of the potential positional accuracy errors in older maps, we also used 2010 as a comparison baseline and found that 11% of landscapes persisted as grasslands in 1930, 1960, 2000 and 2010, and only 8% in all years (1860, 1930, 2000 and

2010).

Comparison of pollen and map-based land-cover/use classes

The squared chord distance analysis showed that, over time, the best fit between the pollen-based and map-based land-cover/use reconstructions was for the most recent period (i.e., 2010; Fig. 5), whereas, the fit was weakest for the 1960s and 1930s maps. From a spatial perspective, the best fit between the pollen and map-based land-cover/use reconstructions occurred at the 5-km radius buffer (Fig. 5). The fit declined for subsequently larger buffers, but improved again beyond 25-30-km, most evidently for years 2010 and 1985. Regarding land-cover composition, there was a greater forest cover in the pollen (10-55%) than in the map-based reconstruction (14-26%) for all radius buffers (Figs. 4, A3). Grasslands cover was also greater in the pollen (33-85%) than in the map-based estimates (30-78%) for most radius buffers. Cropland cover was substantially greater in the maps (5-53%), than in the pollen-based reconstruction (2-13%) for all radius buffers, although this discrepancy was smaller for the 5-km radius.

Discussion

Understanding how and where land-cover/use change affects habitats of conservation value is important for efficient land-use and effective conservation planning. Here, we illustrate for a case study in Transylvania, Romania, how the combined use of multiple data sources (pollen, historical maps, and satellite images) can be powerful for the reconstruction of land-cover/use change over a period of 150 years. Four main outcomes can be drawn from our study. First, the major shifts in land-management that occurred in our study area with the rise and fall of socialism resulted in marked changes in land-use and vegetation cover, most importantly a waxing and waning of cropland and grassland cover, and a gradual increase in forest extent from World War II. Second, a key land-cover/use change in our study area was the widespread loss of wood pastures, a finding that would probably have been missed using any of the individual datasets in isolation. Third, only 8% of the landscape in 2010s had

retained grassland continuously from 1860s highlighting that land-use history should be considered when identifying target areas for conservation. Finally, grassland diversity decreased during socialism, but increased thereafter when fertiliser inputs and grazing pressure declined. Below, we first discuss the value and sources of uncertainties in the pollen and map-based land-cover/use classes reconstruction, then the key land-cover/use changes we detected over the past 150 years and relate them to the major shifts in land-management during that period, in order to highlight the key insights described above.

The added value and sources of uncertainties in the pollen and map-based land-cover/use classes reconstruction

The strength of the pollen record was to understand vegetation compositional aspects of land-cover, whereas of historical use/cover maps to understand the spatial patterns of land-cover/use change. However the fit between land class estimates from the two data sources varied over time, therefore below we explained sources of uncertainties in each of each of these land cover/use reconstructions that could affect the agreement of the two data sources. We identified five major sources of uncertainties in pollen-based land-cover reconstructions. First, the representation of cropland in the pollen-based land-cover reconstruction includes only cereals (Cerealia, *Zea mays, Avena*-type, *Hordeum*-type, *Triticum*-type and *Secale cereale*) for which PPEs are available, whereas other crop types (e.g. potatoes, other vegetables and legumes) are ignored, underestimating the actual cropland area (Hellman et al. 2009; Trondman et al. 2015). Second, Poaceae include taxa that can grow in several vegetation types; they dominate in grassland, but they also occur in the understory vegetation of woodland and as weeds in cropland. However, in the pollen-based land-cover reconstruction we attributed them to grasslands alone, thus potentially overestimating grassland cover. Changes in grassland management can also affect their pollen productivity and be a potential source of error in the pollen-based reconstruction of grassland cover (Broström et al. 2008). This is because all pollen-vegetation models are calibrated assuming that the relationship between pollen and composition of source

vegetation remains constant over time (Kujawa et al. 2016). Third, the use of a restricted number of pollen types (28 taxa) in REVEALS model those for which PPE and fall speed were available, together with the use of PPE from areas outside the study region (as these were not available locally), may also provide a source of uncertainties in pollen-based land cover reconstruction. Fourth, the REVEALS model is based on a series of assumptions, which only partly hold true in reality. One is that all pollen is dispersed to a site via wind above canopy level and at a constant wind speed. Other dispersal mechanisms, such as pollen carried in the trunk space of woodlands, by runoff water and by gravity from local vegetation can give a higher representation of the area surrounding the site than expected from the model (Overballe-Petersen et al. 2013). Another assumption is that the vegetation at regional scale is homogenous, i.e. that there are no ecotones or similar vegetation boundaries (Sugita 2007). In our region, as seen from the maps (Fig 3), forest is more dominant in the northwest and cropland in the south-east. When such variations are present, the vegetation reconstruction resulting from REVEALS is likely to be more impacted by the local setting than the model predicts. Fifth, chronological uncertainties increase with time and changes in sediment type, such as that from 20-25 cm, and can affect the reliability of the chronology (Hellman et al. 2009; Trondman et al. 2015), and thus the match between map and pollen based estimates.

We identified three major sources of uncertainties in the map-based land-cover/use reconstructions. The first source of uncertainty is the interpretation of historical land-cover/use maps in terms of the actual vegetation, e.g. separating grassland and cropland, and assessing the extent of trees present in the grassland category (wood pasture). For example in the 1860 map the assumption that 50% of the “uncertain” grassland/cropland points were actually grassland results in a slightly better fit to the pollen data (0.25), than assigning all as cropland land (0.27). Second, in the historical topographic maps clear-cuts in forest are shown as forest on the map, which may lead to an over-representation of the extent of forest cover, while natural succession on abandoned farmland is not captured in these maps, leading to underrepresentation of tree cover. Third, wood pastures, or pastures

with trees, are classified as grasslands in maps, overestimating the grassland extend and underestimating tree cover.

Land-cover/use changes during the pre-socialist period

Both our pollen and map land-cover/use reconstructions suggest that extensive grasslands (50%) existed in the study area in the pre-socialist period (Figs. 3, 4). Cropland cover expanded during the Habsburg Empire and Austro-Hungarian Monarchy (<1918) reflecting population increases and the rising demand for food (Munteanu et al. 2014). However, the proportion of cropland is much lower in the pollen (2-10%) than in the map-based reconstruction (25-49%). This is probably because the pollen-based reconstruction considers only the cropland area producing cereals and because the pollen signal most strongly reflects the area within a few kilometres of the lake, which, as seen on the maps (Fig. 3), has less cropland cover than the wider region. Recent studies also indicate that PPEs of cereals are difficult to estimate and differ between taxa. Wind pollinated *Secale* produces more pollen than the autogamous cereals (*Avena, Hordeum* and *Triticum*), which is reflected in the PPEs applied in the REVEALS reconstruction (3.02 for *Secale* and 1.85 for other Cerealia; Mazier et al. 2012). However, the estimate for Cerealia may still be too high, as some PPE studies have included *Secale* in the Cerealia type (Broström et al. 2008). If the PPE for Cerealia is indeed too high, the resulting cereal cover will be underestimate (Theuerkauf et al. 2016).

Our pollen record depicts a comparatively higher forest cover (50%) than that derived from the historical maps (18-26%; Fig. 4). Apart from uncertainties in pollen-based land-cover estimates, where a high tree cover can be partly the result of underestimating the cropland area, an explanation of this discrepancy may be the regional importance of so-called wood pastures (i.e., pastures with forest patches or scattered trees), that were historically widespread in our study region (Hartel et al. 2013). Documentary records from eastern Transylvania indicate that until at least the 19th century, tree removal from pastures was forbidden and that hay meadows with low manure input were highly valued and

widespread (Akeroyd and Page 2011; Molnár et al. 2015). For example, wood pastures covered about 20% of the landscape in our study area on the only map that clearly depicts this land-use class (1930, in the-5 km buffer, Fig. A2), whereas all other maps incorporate wood pastures and pastures into a single class (which is why we were unable to enumerate wood pastures separately). Thus, a substantial number of trees were not depicted in our historical maps, which may account for the higher tree cover found in the pollen record compared to that indicated by the maps. A final factor explaining this phenomenon could be that trees in small forest patches and single tress have a higher pollen productivity than in closed forest due to edge effects (Theuerkauf et al. 2015; Vera, 2000).

Land-cover/use changes during the socialist period

The pollen-based land-cover reconstruction suggests a major change sometime between 1936 and 1950, which broadly coincides with the transition in governance to socialism in Romania in 1947. Tree cover declined (10-15%), whilst grassland (60-70%) and cropland cover (10-20%) increased during this period, indicating tree loss and the expansion of meadows, pastures and croplands (Figs. 2, 4). At the same time, the historical maps do not suggest a widespread pattern of deforestation for agricultural expansion, and instead point to a conversion of grassland into cropland (Fig. 4). Two factors may explain these differences between the pollen- and map-based land-cover/use reconstructions. First, the most plausible explanation is a decline in the extent of wood pastures, that is, wood pastures previously common and valued, in the region were cleared of trees. This hypothesis is strongly supported by informal interviews with local residents during our fieldwork as well as by the literature (Hartel et al. 2013). As wood pastures were not consistently depicted in our historical maps, this loss of tree cover would only be captured by the pollen record. Although forest cover during socialism was similar in both the pollen- and map-based reconstructions, we encountered a drop in tree pollen at the beginning of the socialist period that was not present in our land-cover/use maps. Apart from wood pastures becoming cleared, two other factors may account for this phenomenon. First, forest inventories indicate that plantations of

principally *Carpinus betulus, Quercus petraea* and *Q. robur* were widespread between the 1940s and 1970s (David 2008). Saplings of these trees require about 30-40 years to produce pollen (Matthias et al. 2012), suggesting a drop of tree pollen after mature forests were cleared and plantations established. In the historical maps logging and subsequent forest recovery are not shown at all. The intensification of forestry is also indicated by the low pollen proportions of tree species such as *Tilia, Fraxinus* and *Ulmus* that grow in more natural deciduous forests (Fig. 2). Second, the reduction in tree pollen could be partially explained by oak dieback, due to insect outbreaks and drainage that occurred around 1943-1950 (Lupe et al. 1963), and which would also not be represented in our historical maps.

The herbaceous plant diversity declined, whilst the proportion of Poaceae increased during socialism according to our pollen record (Figs. 2, A1). Agricultural intensification, especially the application of artificial fertilisers, is a likely reason for this change in grassland diversity (Fig. 7). Indeed, fertiliser application is known to promote an expansion of grasses and a decline of other herbs (Akeroyd and Page 2011; Wesche et al. 2012). This pattern of cropland and grassland intensification agrees well with the general characteristics of the socio-economic system in the socialist period in Romania, including the expansion of heavily mechanised, large-scale and strongly state-subsidised agriculture in most areas of fertile land (Sarbu et al. 2004; Jepsen et al. 2015; Fig. 7). Further support for this intensification hypothesis comes from the increased slope erosion and consequent minerogenic input of sediment into the lake at this time (Hutchinson et al. 2015). The clearing of trees from wood pastures may also have contributed to lower habitat niche diversity (Bergmeier et al. 2010) and consequently the falling palynological richness of the grasslands. Finally, a reduction in the pollen of wetland taxa such as Cyperaceae (Fig A1) also implies the local intensification of agriculture, via the drainage of wetlands, to bring these areas adjacent to the lake into production.

Land-cover/use changes during the post-socialist period

Results from both the pollen and map-based land-cover/use reconstructions suggest a trend of cropland to grassland conversion and subsequent succession in the post-socialist period (Fig. 4). This was confirmed during field observations when we found extensive areas of shrubs and early-successional trees (*Crataegus, Rosa, Salix, Sambucus, Betula, Populus*) that are encroaching the grasslands. This could reflect the economic crisis triggered by the breakdown of socialism and which resulted in the reversion to more traditional, labour intensive farming practices with diminished fertiliser use and less livestock pressure (Fig. 7). This resulted in the abandonment of cropland, and managed meadows and pastures in more marginal sites (e.g., further away from villages), which has been a particularly widespread phenomenon in the Transylvanian Plain (Ruprecht 2005; 2006). For example, up to 46% of the land farmed during the last years of socialism was abandoned by the early 21st century in the Carpathian area (Griffiths et al. 2013). This explains the increase in tree cover, primarily deciduous taxa, we found in both the pollen-based and the satellite-based land-cover/use reconstructions (Figs. 2, 4). However, forest recovery following agricultural abandonment proved to be a slow process in our study region. This is not surprising, as spontaneous forest establishment via seed dispersal on abandoned cropland typically takes longer than 50 years, and the low abundance of tree propagules in the landscape will further retard forest establishment (Ruprecht 2005). This also suggests that future forest expansion could be widespread.

The pollen record also suggests that herbaceous diversity has increased in the post-socialist period compared to under socialist land management. The decreased use of fertilisers and lower grazing pressure are likely causes for this increase, although livestock type has been found to be an important factor in preserving grassland diversity, with grazing by cattle preserving a higher diversity and extend of grasslands than sheep (Tóth et al. 2016). Enhanced micro-habitat diversity, associated with the beginning of tree establishment, may also play a role, but if tree and shrub encroachment continues and dense woodland is established, the current temporary patchiness in tree cover will be lost, with negative effects on grassland diversity (Bergmeier et al. 2010). Interestingly, of the 2010s grasslands only

60% were present as grassland in 1985 and only 8% in 1860 (Fig. 3). This indicates that grassland/cropland conversions have been widespread historically. In a low nutrients input environment, as in the study region, the coexistence of mosaic of cropland, old and new meadows and pastures is possible, and this patchy landscape provides a seed bank for spontaneous grassland establishment and recolonisation after cropland abandonment. Considering that semi-natural grasslands that have persisted for long periods differ substantially in their species composition and species richness compared to those that were converted to cropland (Loos et al. 2016), identifying those grasslands that have persisted over time and prioritising them in conservation planning is therefore important.

Concluding remarks and future perspectives

We quantified changes in land-cover/use over the last 150 years in the lowlands of Transylvania, Romania; an open landscape with grasslands of outstanding species richness. A key strength of our study lies in the use of multiple data sources i.e., pollen data, harmonised historical maps, and satellite-based land-cover/use maps, which allowed us to make use of the individual strengths of these datasets, such as the value of pollen records to understand vegetation compositional aspects of land-cover, and of historical use/cover maps to understand the spatial patterns of land-cover/use change. Our study suggests that the multiple shifts in institutions, political systems that occurred with the rise and fall of socialism translated into major permutations in land-management in our study area, which in turn resulted in marked changes in land-cover and vegetation. Most importantly, we found marked waves of cropland and grassland expansion and decline, as well as a gradual increase in forest extent. These changes appear to be closely related to the increasing intensification of land-management and expansion of farmland during socialism, followed by the concentration of agricultural production on productive sites, and abandonment of others, after the breakdown of socialism. A key land-cover/use change in our study area has been the widespread loss of wood pastures, a finding that would possibly have been missed using individual datasets in isolation. Remarkably, although grasslands were widespread in our

study region at the beginning of the study period, only 8% of these grasslands persisted until 2010. Given that the oldest grasslands, having never been converted to croplands, are likely to be of the highest conservation value, our study highlights the importance land-use history when identifying areas where conservation measures to protect semi-natural grasslands should be targeted. Given, that the woody encroachment of these diverse grasslands is ongoing, and will likely accelerate in the future, we currently face a window of opportunity for conserving semi-natural grasslands that may close in the coming years.

To secure the future of high conservation value, semi-natural grasslands, maintaining and restoring more traditional land-use practices have been suggested as critical and our results support this. However, this is at odds with the current socio-economic trends in the region (e.g., rural depopulation) and the ongoing strong and accelerating tendency for land-use intensification on the one hand and abandonment on the other. Furthermore, the current toolset of agri-environmental schemes may not be adequately suited to protect CE Europe's semi-natural grasslands. Merely transferring subsidy and conservation schemes from Europe's West to the East, largely without adaptation to regional conditions, bears a considerable risk of counterintuitive and unwanted outcomes (Sutcliffe et al. 2015). Conservation policy for the region's traditional farming landscapes should instead seek to identify and strengthen links between nature and people alongside measures for development and progress (Fischer et al. 2012).

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Figure captions

Fig 1. The location of the study area in Europe and Romania (A) and photographs of the landscape around the study site showing woody encroachment (B).

Fig. 2. Temporal changes (age AD) in vegetation cover based on the REVEALS model (colour) and untransformed pollen percentages (black) for 28 taxa separated on: shrubs (upper panel), trees (middle panel) and herbs (lower panel). The numbers denoted the three major compositional changes as determined by ANOSIM.

Fig. 3. Land-use/cover classes (cropland, grassland, forest and other) extracted from historical maps and satellite images for 1860, 1930, 1960, 1985, 2010 with a buffer of 50-km radius centred on Lake Știucii. The bottom right hand panel represents the areas of grassland that have been continuously present from 1860 until the present (permanent grassland), grassland present from 1985 until today (temporary grassland) and land that has never been grassland from 1860 to 2010.

Fig. 4. Land-use/cover reconstruction based on the pollen and historical maps and satellite images for cropland, grassland and forest at three buffer sizes: 5-km (A), 25-km (B), and 50-km (C) and pollen (D). The major socio-political periods are also presented. The x scale represents age AD.

Fig. 5. Comparison based on squared chord distance (SCD) between the pollen and historical maps/satellite images-based land-use/cover reconstructions.

Fig. 6. Multidimensional scaling ordination showing differences in the composition of the vegetation in each socio-political period (Pre-socialist, Socialist and Post-socialist) based on pollen-based REVEALS estimates of plant-taxa abundance. Differences between the periods are expressed with the following R and p values: Pre-socialist and Socialist R = 0.808, p = 0.004; Socialist and Post-socialist R = 0.707, p = 0.001; Pre-socialist and Post-socialist R = 0.839, p = 0.003

Fig. 7. Summary plots showing temporal changes (age AD) in: Pollen richness for all taxa and separately for herbs; REVEALS-based landscape openness; Soil erosion content based on Ti content (Hutchinson et al. 2015); cropland, livestock and fertiliser application rates (data from FAOSTAT http://faostat3.fao.org). The orange square highlights the socialist period.

Supplementary Material

Figure A1. Full pollen diagram from Lake Știucii.

Figure A 2. Extraction and harmonisation of pollen and map-based land-use/ cover classes.

Figure A3. The land-cover/use based on historical maps and satellite images for all buffers i.e., 5-km, 10-km, 15-km, 20-km, 25-km, 30-km, 35-km, 40-km, 45-km and 50-km.

Dear Editor- in-Chief Prof. Wolfgang Cramer and the Guest Editor Dr Urs Gimmi,

Please find enclosed a revised version of our manuscript **Long-term land-cover/use change in a traditional farming landscape in Romania inferred from pollen data, historical maps, and satellite images** by Angelica Feurdean, Catalina Munteanu, Tobias Kuemmerle Anne B. Nielsen, Simon M. Hutchinson, Eszter Ruprecht, Catherine L. Parr, Aurel Persoiu, Thomas Hickler.

We apologies for remaining errors in the references list. We have crosschecked all references to eliminate additional typos and hope that the paper is now clean. We have also removed the color from the manuscript.

Yours sincerely,
Angelica Feurdean

Ref.: Ms. No. REEC-D-16-00258R1
Long-term land-cover/use change in a traditional farming landscape in Romania inferred from pollen data, historical maps, and satellite images
Regional Environmental Change

Dear Dr. Feurdean,

After careful evaluation, our guest editor Dr Urs Gimmi recommends acceptance of your paper and I agree with him. However he also notes that there are remaining errors in the reference list, so you will have to review this yourself one more time very carefully. At that stage, please also get rid of all the colour from the text.

Your revision is due by 27-10-2016.

To submit a revision, go to http://reec.edmgr.com/ and log in as an Author. You will see a menu item call Submission Needing Revision. You will find your submission record there.

Yours sincerely,

Wolfgang Cramer
Editor-in-Chief
Regional Environmental Change

Reviewers' comments:

Dear Dr Feurdean

Thank you for the careful revision of the manuscript. All points raised by the reviewers are addressed in a in a satisfactory way.
Please check again the references part of the paper. There are obviously some typing errors (e.g. Kaim et al.).

Sincerely, Urs Gimmi
Guest Editor

Figure 1

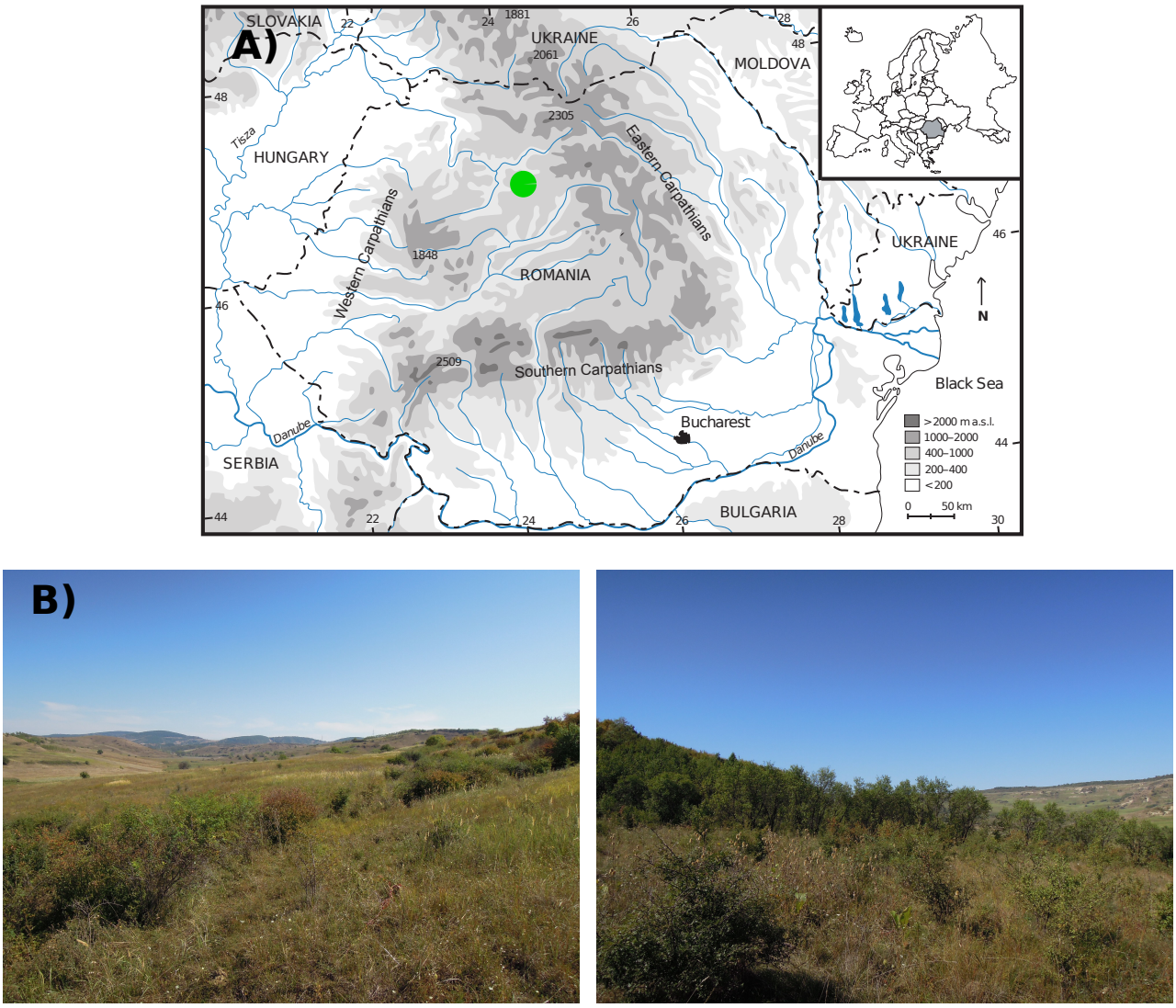

A)
SLOVAKIA
UKRAINE
MOLDOVA
HUNGARY
ROMANIA
SERBIA
BULGARIA
Tisza
Danube
Western Carpathians
Eastern Carpathians
Southern Carpathians
Bucharest
Black Sea
1881
2061
2305
1848
2509
22
24
26
28
48
46
44
30
N
>2000 m a.s.l.
1000–2000
400–1000
200–400
<200
0
50 km
B)

Figure 2

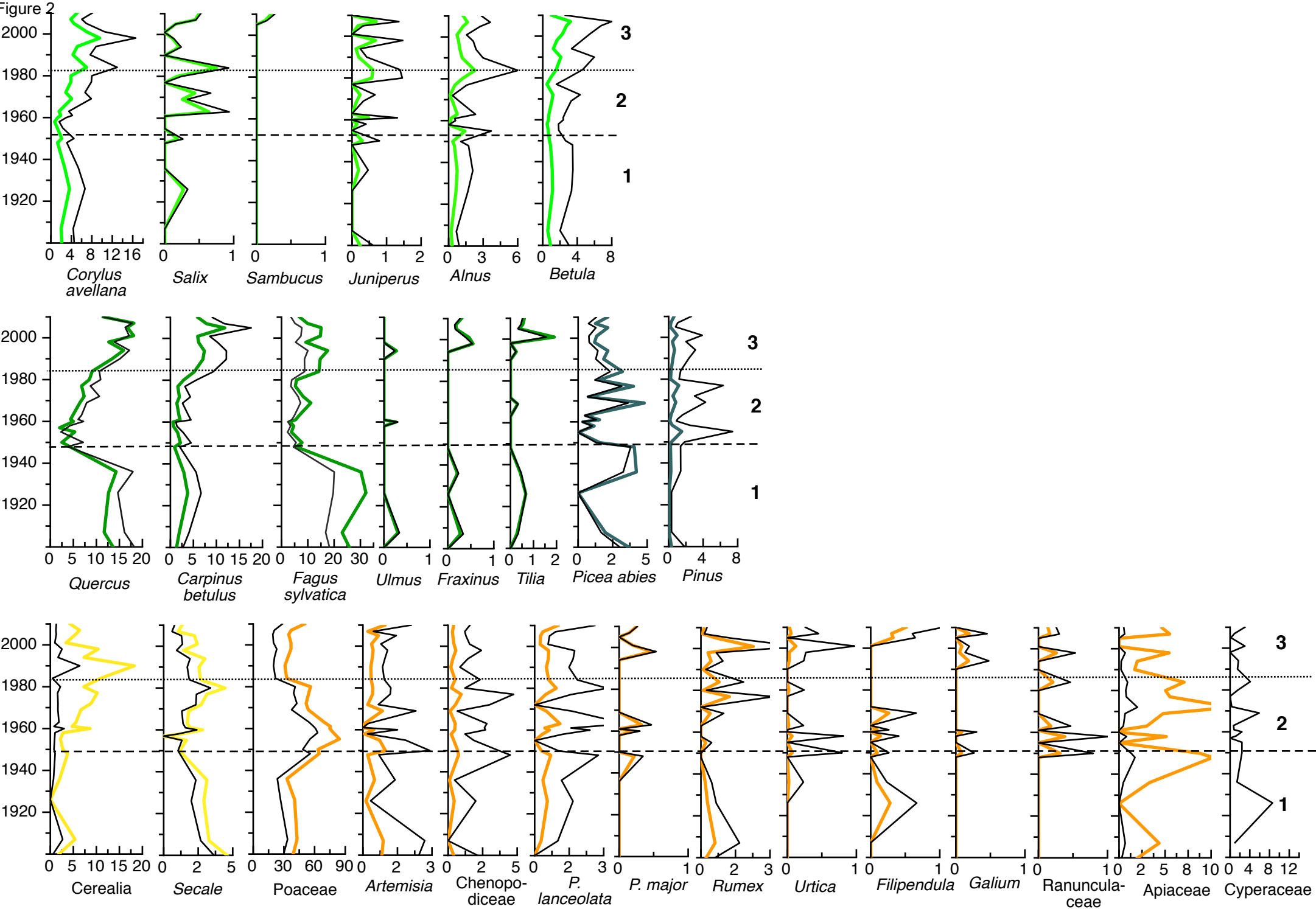
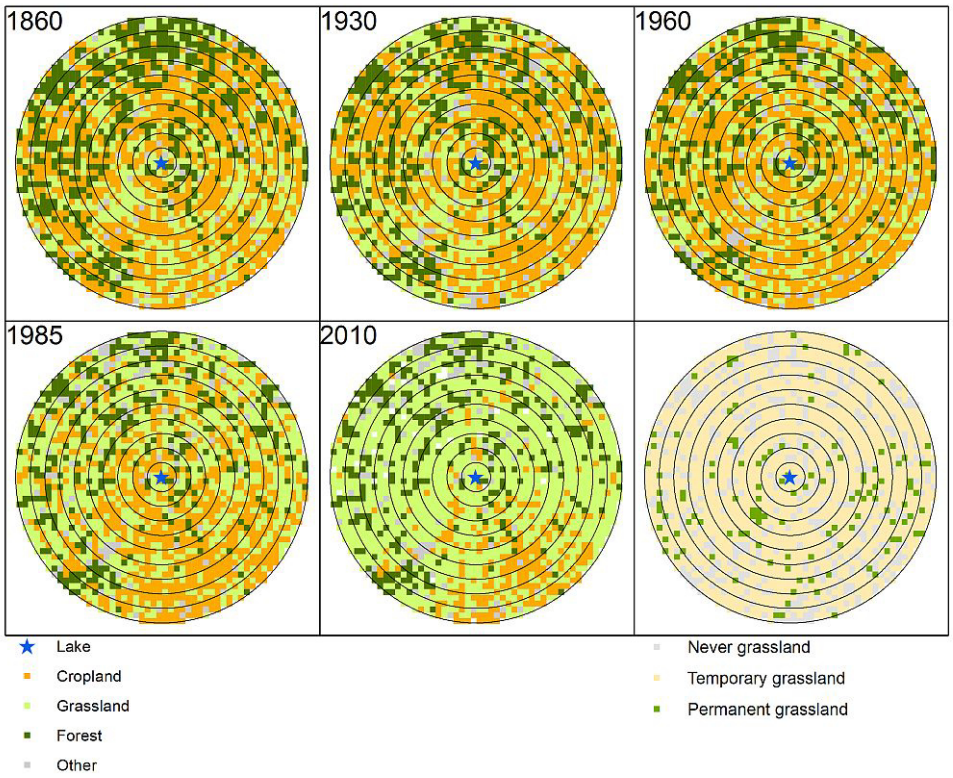

2000
1980
1960
1940
1920
3
2
1
0 4 8 12 16
Corylus avellana
0 1
Salix
0 1
Sambucus
0 1 2
Juniperus
0 3 6
Alnus
0 4 8
Betula
0 5 10 15 20
Quercus
0 5 10 15 20
Carpinus betulus
0 10 20 30
Fagus sylvatica
0 1
Ulmus
0 1
Fraxinus
0 1 2
Tilia
0 2 5
Picea abies
0 4 8
Pinus
0 5 10 15 20
Cerealia
0 2 5
Secale
0 30 60 90
Poaceae
0 2 3
Artemisia
0 2 5
Chenopo-diceae
0 2 3
P. lanceolata
0 1
P. major
0 2 3
Rumex
0 1
Urtica
0 1
Filipendula
0 1
Galium
0 1
Ranuncula-ceae
0 2 5 8 10
Apiaceae
0 4 8 12
Cyperaceae

Figure 3


1860
1930
1960
1985
2010
Lake
Cropland
Grassland
Forest
Other
Never grassland
Temporary grassland
Permanent grassland

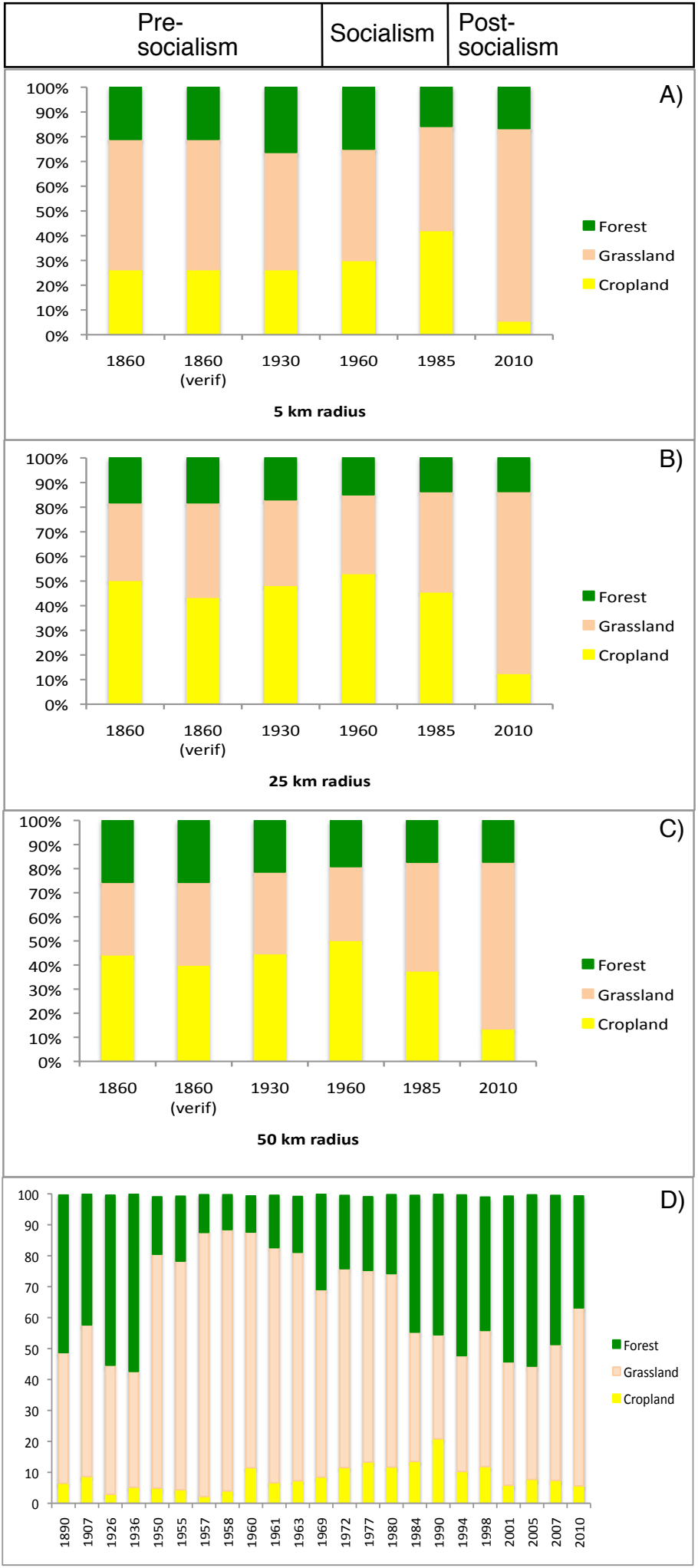

Pre-socialism
Socialism
Post-socialism
A)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1860
1860 (verif)
1930
1960
1985
2010
Forest
Grassland
Cropland
5 km radius
B)
25 km radius
C)
50 km radius
D)
100
90
80
70
60
50
40
30
20
10
0
1890
1907
1926
1936
1950
1955
1957
1958
1960
1961
1963
1969
1972
1977
1980
1984
1990
1994
1998
2001
2005
2007
2010

Figure 5

Figure 5

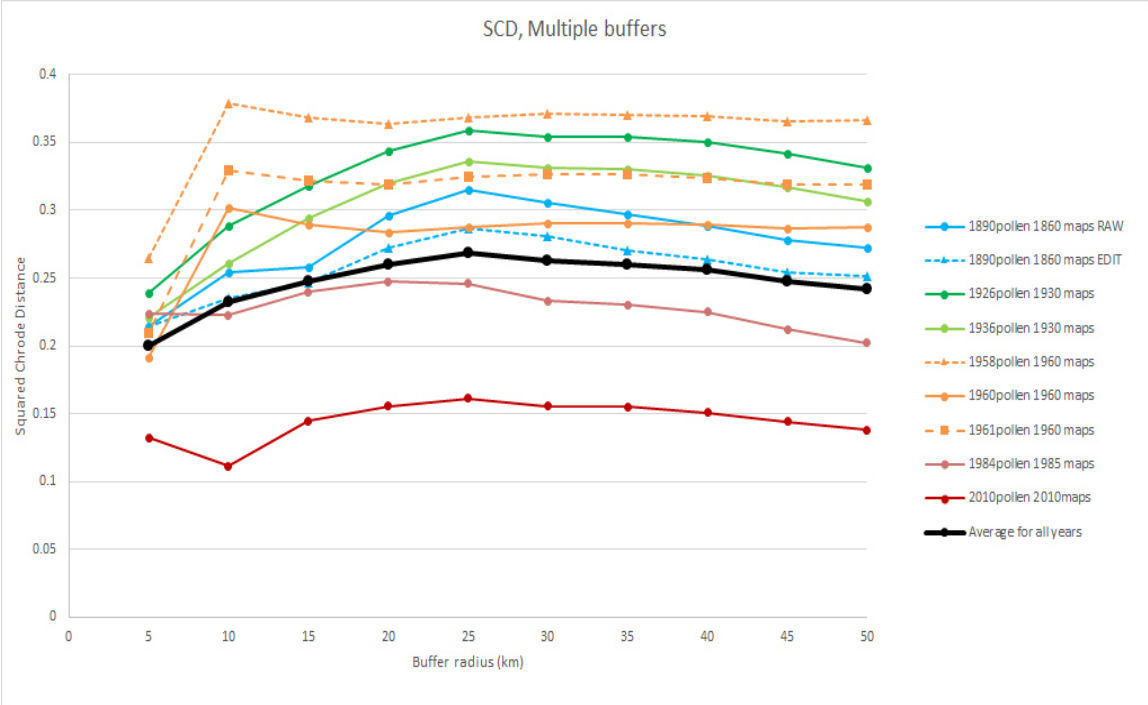
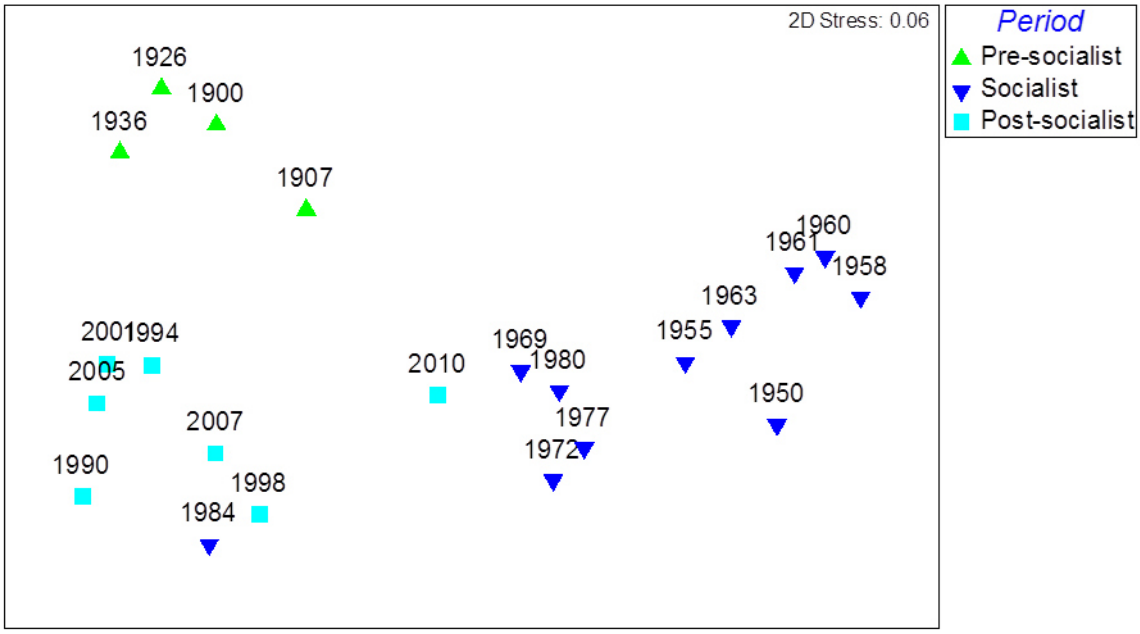
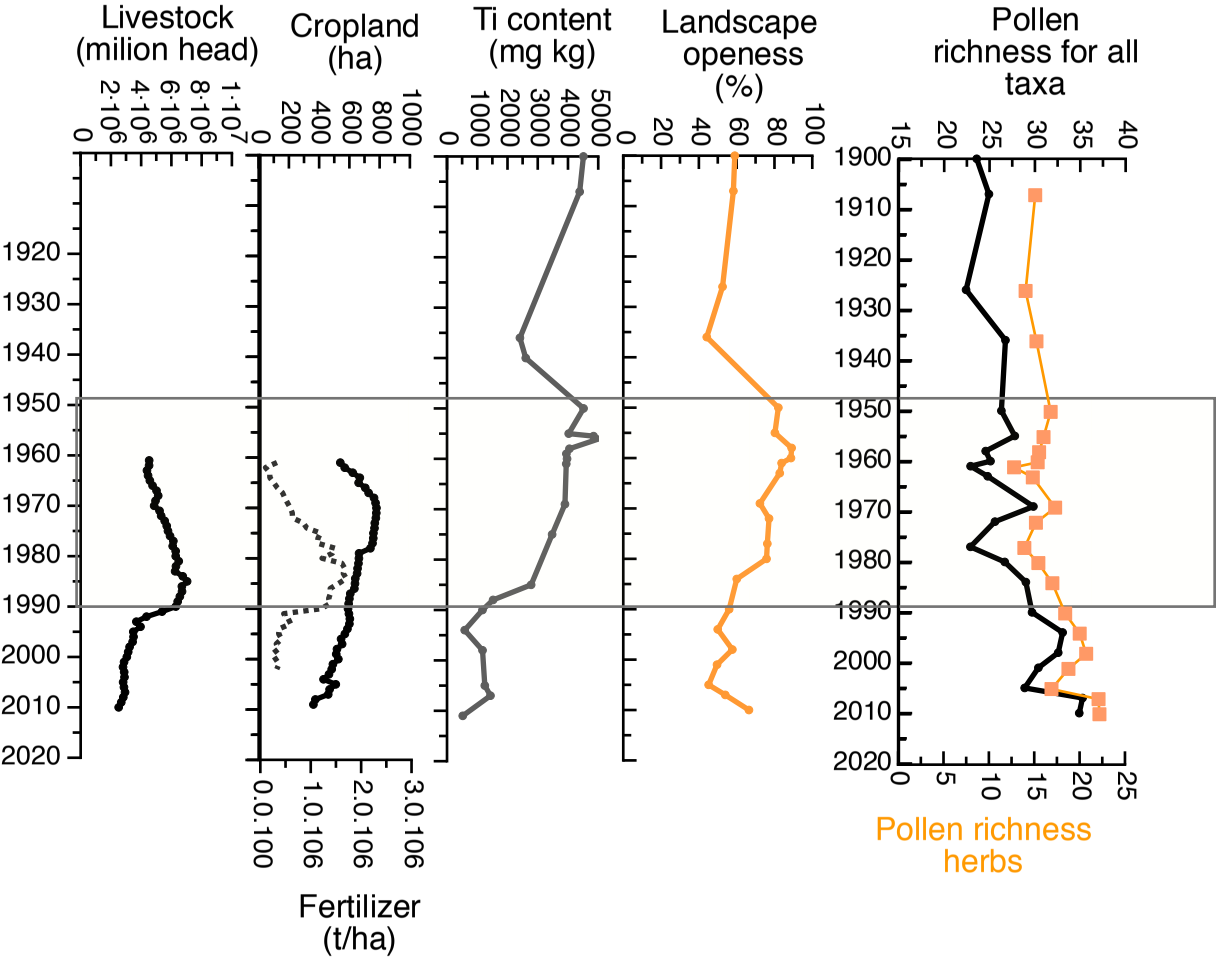
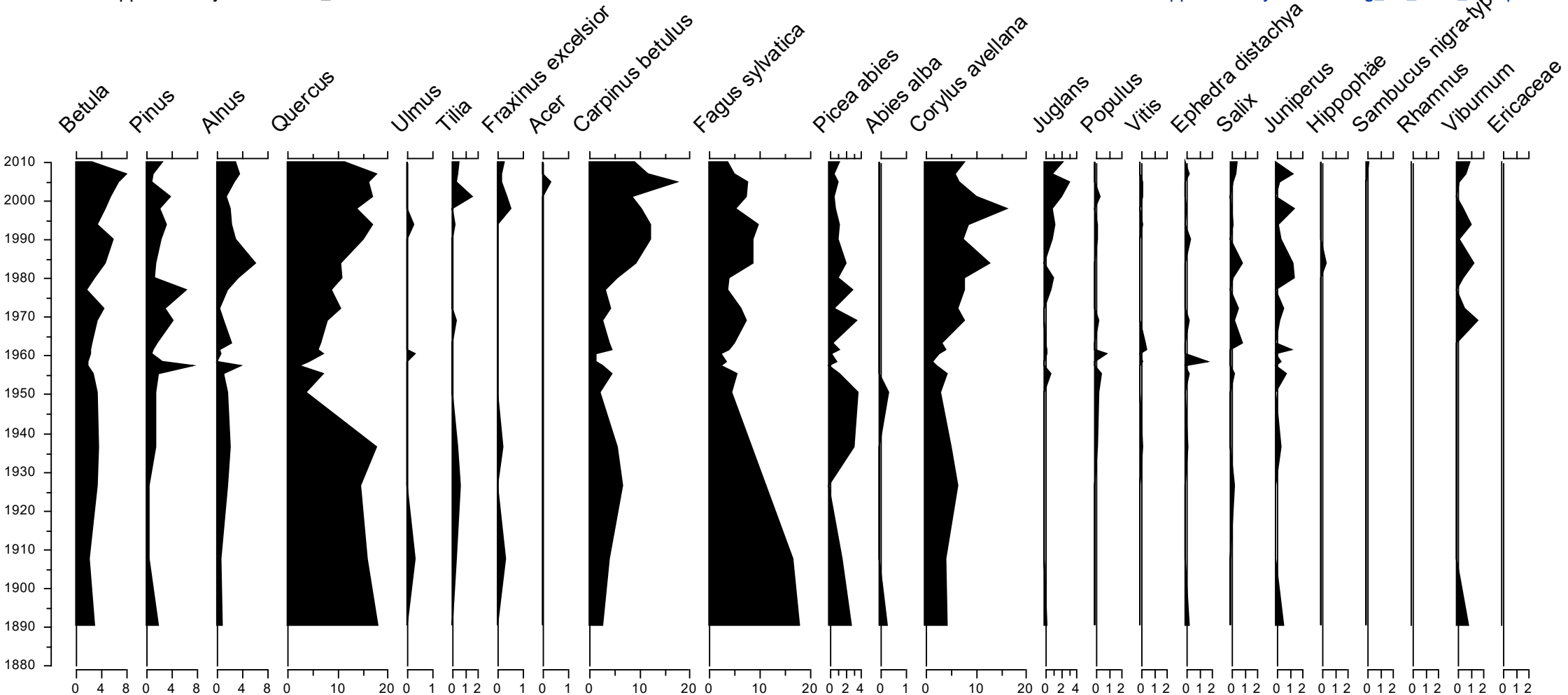


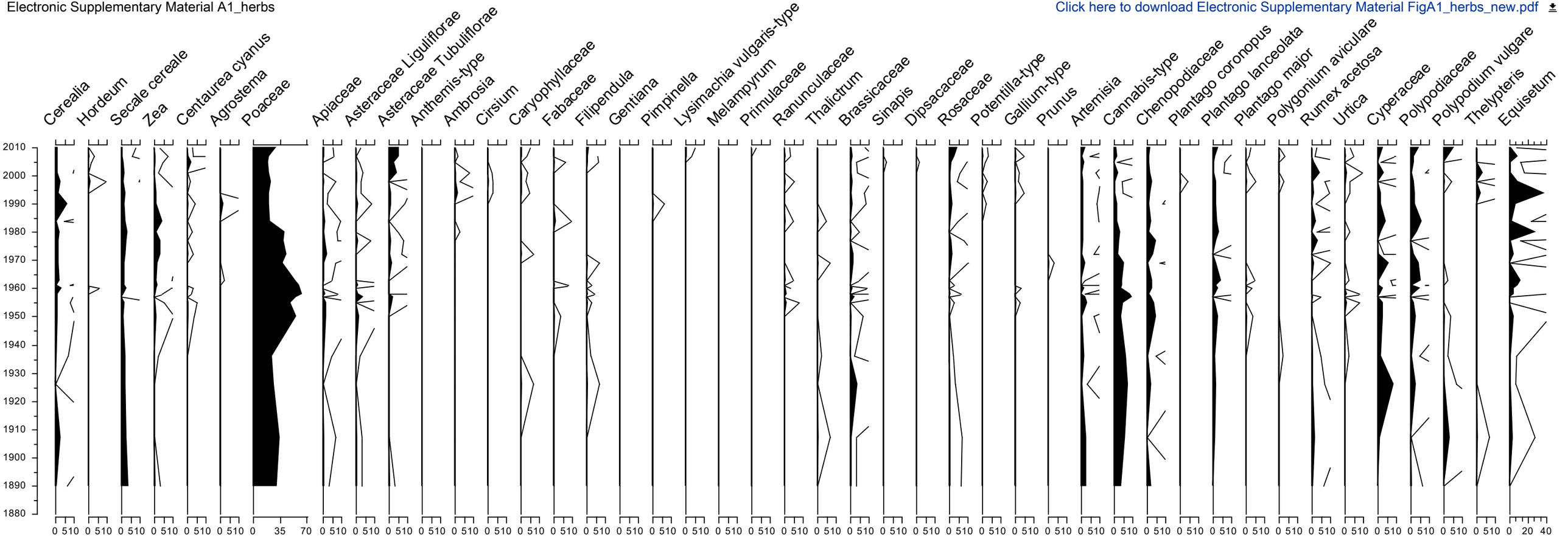
Figure 6


2D Stress: 0.06
Period
Pre-socialist
Socialist
Post-socialist
1926
1900
1936
1907
1960
1961
1958
1963
1955
1950
2001
1994
2005
2010
1969
1980
1977
1972
2007
1990
1998
1984


Livestock (milion head)
Cropland (ha)
Ti content (mg kg)
Landscape openess (%)
Pollen richness for all taxa
Pollen richness herbs
Fertilizer (t/ha)



Electronic Supplementary Material A1_herbs



SUPPORTING INFORMATION A2

Long-term land-cover/use change in a traditional farming landscape in Romania inferred from pollen data, historical maps, and satellite images

Angelica Feurdean[1], Catalina Munteanu[2], Tobias Kuemmerle[3, 4,] Anne B. Nielsen[5], Simon M. Hutchinson[6,] Eszter Ruprecht[7,] Catherine L. Parr[8, 9] Aurel Persoiu[10, 11,] Thomas Hickler [1,12]

Figure A 2: Extraction and harmonisation of pollen and map-based land-use/ cover classes

1. Extraction of land-cover classes from the pollen record

We used 28 pollen taxa (15 woody and 3 herb taxa for which estimates of pollen productivity (PPE) and fall speed (FSP) are available to derive land-cover classes (see Table 1). We used PPEs from the Czech Republic (Abraham and Kosakova, 2012) for *Alnus, Tilia, Quercus Plantago lanceolata* and *Urtica* because their study region is characterised by similar landscapes features and climatic conditions to ours. For other taxa, we used mean PPEs from Mazier et al (2012), based on estimates from mainly NW Europe. A full description of the application of the REVEALS model at this site is given in Feurdean et al. (2015). As pollen-based land-cover classes are compared with land-use/cover reconstructions derived from historical maps and satellite images, each pollen taxon was ascribed to one of the established classes in the harmonised maps: cropland, grassland and forest. The cropland category in the pollen-based land-cover class includes pollen of Cerealia and *Secale*. The grassland category includes pollen of grasses (Poaceae), and herbs / forbs occurring in meadows and pastures (Table 2). Many herb / forb pollen types such as *Artemisia*, *Plantago* species and *Rumex acetosa* are interpreted as growing in grasslands and ruderal environments. We have included them in the grassland group, as they are not strictly connected to cropland. We have included *Juniperus, Salix* and

Sambucus into grassland category on the basis that these shrubs / trees were more particularly related to wood pastures than forest.

Table 1. Fall speed (FSP) of pollen, relative pollen productivity estimates (PPE) and their standard error estimates (SE) for 28 taxa. (Data from Mazier et al. (2012) except those marked by * which are from Abraham and Kozakova (2012)).

Pollen taxa	Fall speed (m s^{-1})	PPE	SE
Abies	0.120	6.88	1.44
Alnus	0.021	2.56*	0.32*
Betula	0.024	3.09	0.27
Carpinus	0.042	3.55	0.43
Corylus	0.025	1.99	0.20
Fagus	0.057	2.35	0.11
Fraxinus	0.022	1.03	0.11
Juniperus	0.016	2.07	0.04
Picea	0.056	2.62	0.12
Pinus	0.031	6.38	0.45
Salix	0.022	1.22	0.11
Tilia	0.032	1.36*	0.26*
Ulmus	0.032	1.27	0.05
Quercus	0.035	1.76*	0.20*
Sambucus	0.013*	1.30*	0.12*
Apiaceae	0.042	0.26	0.01
Artemisia	0.025	2.77*	0.39*
Asteraceae Tubuliflorae	0.029	0.10	0.01
Asteraceae Liguliflorae	0.051	0.16	0.02
Cerealia	0.060	1.85	0.38
Chenopodiaceae	0.019*	4.28*	0.27*
Filipendula	0.006	2.81	0.43
Galium	0.019	2.61	0.23
Plantago lanceolata	0.029	3.7*	0.77*
Plantago major	0.024	1.27	0.18
Poaceae	0.035	1.00	0.00
Potentilla	0.018	1.19	0.13
Ranunculaceae	0.014	1.96	0.36
Rumex acetosa t.	0.018	2.14	0.28
Urtica	0.007*	10.52*	0.31*
Secale	0.060	3.02	0.05

Table 2. Harmonisation of the land-use/cover classes for pollen, and historical and satellite

image based maps.

Land-use/ cover classes	Map class assignment to the land-use/cover classes	Pollen assignment to the land-use/cover classes
Cropland	Cultivated land	Cerealia, *Secale*
Grassland	Meadow, pasture, wood pastures pasture with trees open land	Apiaceae, *Filipendula*, *Artemisia, Juniperus*, Poceae *Plantago lanceolata*, Ranuculaceae *Potentilla, Galium, Sambucus* *Rumex acetosa*, Asteraceae Tubuliflorae, Asteraceae Liguliflorae, *Salix, Sambucus*
Forest	Deciduous, coniferous mixed forest	*Quercus, Carpinus betulus, Corylus avellana* *Fagus sylvatica, Fraxinus, Tilia, Ulmus,* *Picea abies, Abies alba, Pinus,* *Betula, Alnus*
Non-pollen producing	Lake, Settlements, Deforestation/Clear cut	

2. Extraction of land-use/cover from historical maps and satellite images

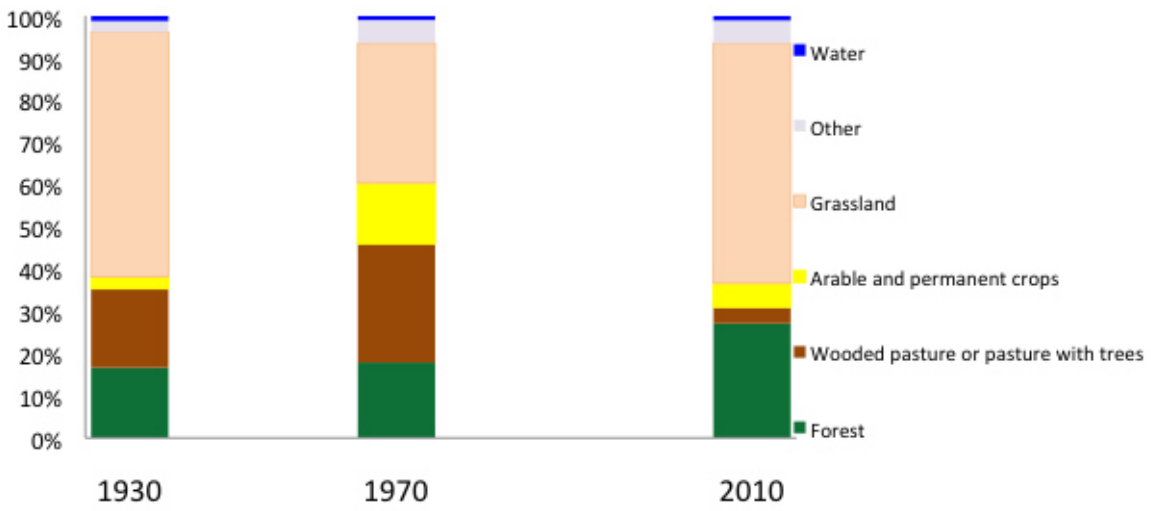
We extracted historical and recent land-use/cover on 50-km radius around the lake based on a combination of historical maps and satellite images covering five points in time (1860, 1930, 1960, 1985, 2010; Table 3). This is because the size of the area extracted from the land-use/cover maps has to be the same as the relevant source area of large sites used in the REVEALS model (Sugita 2007; Hellman et al. 2009). The land-cover/use reconstruction and homogenisation were based on the digitisation of four major land-cover/use classes that occurred in all maps (i.e., cropland, grassland, forest, other) for a regular grid of points, where points were spaced at 2 km. Due to the quality of the maps, for the year 1860 about 28% of the points could not be clearly assigned the class agriculture or grassland. For these points, we assumed that the land cover remained unchanged between 1860 and 1930, and assigned them the same class as in 1930 (Fig. 4 in the manuscript). In order to verify this assumption, we randomly assigned half grassland and half agriculture to these points and found only small differences in the two estimates (average 4.43%). For the years 1985 and 2010, the four land-use/cover classes were automatically extracted to the point grid from Landsat TM and ETM+ satellite composites for the Carpathian Ecoregion (Griffiths et al. 2013; 2014; Table 3, Fig 3 in the manuscript). In addition, the the National Topographic

Maps from the Cold War period (~1960-1970s) have been digitised as polygons to include the land cover class of wooded pastures and pasture with trees (Fig. 1).

Table 3

Approximate date of map	Map scale/ resolution	Map source/ description	Data source/ reference
1860	1:28.800	Second Austrian Military Survey	Timár, 2009; Timár et al. 2007, http://www.mapire.eu/
1930	1:20.000	Military Maps from Second World War (Planurile directoare de tragere)	eHarta: **Planurile Directoare** de **Tragere**. http://www.geo-spatial.org/
1960	1:50.000 and 1:25.000	Soviet and National Topographic Maps from the Cold War period	eHarta: **Hartile Sovietice reproiectate in Stereo70**. http://www.geo-spatial.org/
1985	30m	Landsat TM composite	Griffiths et al. 2013; Griffiths et al. 2014
2010	30m	Landsat TM/ ETM+ composite	Griffiths et al. 2013; Griffiths et al. 2014

Fig. 1 Changes in six land cover classes for the years 1930, 1960, 2010 for a 5-km radius buffer around Lake Stiucii. For these years, in addition to the four land cover classes used in the main analysis, and due to higher quality of map data, we obtain information on area of wooded pastures. Data sources for the years 1930, 1960 and 2010 are presented in the Table 3.



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eHarta: Planurile Directoare de Tragere. http://www.geo-spatial.org/

eHarta: Hartile Sovietice reproiectate in Stereo70. http://www.geo-spatial.org/

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Timár G (2009) System of the 1: 28 800 scale sheets of the Second Military Survey in Tyrol and Salzburg. Acta Geodaetica et Geophysica Hungarica 44: 95-104.

Timár G, Molnár G, Imecs Z, Păunescu C (2007) Datum and projection parameters for the Transylvanian sheets of the 2nd and 3rd military survey. Geographia Technica 84; 83-88.

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Fig. A3