Assessing the spatial distribution of grassland age in a marginal European landscape

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A B S T R A C T

Grassland age is increasingly recognised to be an indicator for present-day biodiversity, e.g. plant species richness, and is also important for other landscape functions. We developed a methodological approach to systematically assess the spatial distribution of grassland age in marginal European landscapes. This approach – applied to the Lahn-Dill Highlands (1270 km2), a marginal landscape in Hesse, Germany – comprises three steps: (1) in a two-stage stratification process, we pre-stratified the study area according to recent land-cover patterns and their changes between 1955 and 1995 (stratification I) and classified grassland types by combining data on soil moisture, base-richness, and elevation (stratification II), From 50 grassland types, we randomly selected 1000 representative grassland patches. (2) We determined the age of these patches by means of aerial photograph interpretation of a chronosequence dating back to 1953 and classified each patch with respect to the age classes young (< 18 years), mid-aged (18–47 years), and old (>47 years). (3) Based on this information, we calculated grassland type-specific probabilities for grassland patches to belong to the respective age classes. These probabilities were projected to districts by direct extrapolation. An exemplary validation of extrapolation results for two test areas was performed. The results revealed that 49% of the investigated patches were old grassland. The remaining patches were mid-aged (36%) or young grassland (15%). The extrapolation results indicated accordingly a predominance of old grassland at the district scale. Occurrences of mid-aged grassland were concentrated in districts with a pronounced land-cover change, whereas young grassland is apparently evenly distributed across the study area. Validation results suggest that our approach is suitable for a realistic estimation of grassland age in marginal European landscapes. The method may be applied in landscape models of various disciplines that rely on large-scale information on grassland age.

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1. Introduction

Since the end of World War II, many marginal European landscapes have experienced severe land-use changes. Several socio-economic factors like unfavourable agricultural structures, changing labour markets, relative prices for agricultural products, agricultural policies, migration, and infrastructure developments were identified as important driving forces of land-use change in these landscapes (Baldock et al., 1996; MacDonald et al., 2000; Strijker, 2005). However, most marginal agricultural landscapes are characterised by abiotic constraints, such as less favoured topographic, edaphic, and climatic conditions for cultivation, which are the main obstacle for modern agricultural development (cf. Frede and Bach, 1999; MacDonald et al., 2000).

In many marginal landscapes, large portions of arable land have been consecutively abandoned in favour of grassland (Baldock et al., 1996; MacDonald et al., 2000). As a consequence of this successive land-use change, the current landscape pattern consists of a large number of grassland patches that differ in age, i.e. in the duration of grassland management after cessation of arable farming. The increase in grassland, its driving forces, and the potentially large impacts on ecological functions and processes are thus important topics in integrative landscape research (cf. Turner et al., 2001; Wu and Hobbs, 2002).

Recent studies focussed on the influence of grassland age on soil properties like soil carbon and nitrogen content or pH (e.g. Breuer et al., 2006; McLauchlan et al., 2006). Further, grassland age may also have an impact on faunal species richness (e.g. Balmer and Erhardt, 2000; Dauber and Wolters, 2005; Purtauf et al., 2004) or the genetic structure of arthropod (Holzhauer et al., 2006) and plant populations (Prentice et al., 2006). In particular, plant species richness and species composition depend on grassland age (e.g. Austrheim and Olsson, 1999; Bruun et al., 2001; Cousins and...
structure of the Lahn-Dill Highlands is dominated by small farm adjoining Rhine-Main area as well as the introduction of the EC Additional non-agricultural jobs within the region and in the pattern of the Lahn-Dill Highlands has changed considerably. employment alternatives. Since the 1950s, the agricultural land-use and steel industry had an outstanding relevance as non-agricultural lands, and fallow lands (mean field size of about 0.4 ha; cf. Waldhardt and Otte, 2003 ). From Austrheim and Olsson (1999) and age is an important indicator for plant species diversity (e.g. Luoto et al., 2002; Norderhaug et al., 2000; Waldhardt et al., 2003).

Despite the obvious importance of grassland age for various ecological functions and processes, there have been, to our knowledge, no attempts to reproduce and assess grassland age at larger spatial scales. A reason might be that quantifying grassland age in a large-scale context is considered to require area-wide, spatially explicit, high-resolution data on land-cover 1 change for at least several decades. Several studies indicate that aerial photographs are a powerful tool to detect land-cover changes in the landscape (e.g. de Blieck et al., 2001; Ihse, 1995; Pan et al., 1999; Ruuska and Helenius, 1996). An area-wide interpretation of aerial photographs is yet time-consuming and costly and thus not feasible for large regions.

Given this background, our objective was to develop a methodological approach to systematically assess the spatial distribution of grassland age in a marginal European landscape. Our approach is based on a representative selection of a large number of grassland patches from regionally differentiated grassland types, applicable at several spatial scales (i.e. from patches to districts and landscapes of several hundred square kilometres), and covers the last five decades.

2. Materials and methods

2.1. Study area

The Lahn-Dill Highlands cover a total area of about 1270 km² in the western part of the state of Hesse, Germany (Fig. 1) and are a typical marginal agricultural landscape characterised by unfavourable conditions for cultivation (Frede and Bach, 1999). The low-mountainous landscape features altitudes between 150 and 670 m above sea level (a.s.l.) and slopes of up to about 20°. The small-scale mosaic of soil types comprises a relatively high amount of poor soils such as acidic shallow ranker soils and regosols. The climatic conditions are rough and rather damp (mean annual temperature: 6–8 °C, mean annual precipitation: 650–1100 mm). The agrarian structure of the Lahn-Dill Highlands is dominated by small farm sizes (mean farm size 14 ha; Waldhardt and Otte, 2003) and a heterogeneous, small-parcelled mosaic of arable fields, grasslands, and fallow lands (mean field size of about 0.4 ha; cf. Simmering et al., 2006; Waldhardt et al., 2004). The entire study area is included in the less favoured area support scheme since 1976 (EC Regulation No 75/268).

Agriculture in the Lahn-Dill Highlands always was a matter of small-scale farming providing only a sideline income, while mining and steel industry had an outstanding relevance as non-agricultural employment alternatives. Since the 1950s, the agricultural land-use pattern of the Lahn-Dill Highlands has changed considerably. Additional non-agricultural jobs within the region and in the adjoining Rhine-Main area as well as the introduction of the Common Agricultural Policy (CAP) led to a substantial abandonment of business by many part-time farmers and a general decrease in farming activities throughout the region. In large parts of the study area, extensive grassland use has replaced the former predominant crop production (Hietel et al., 2004, 2005; Kohl, 1978; Schulze-von Hanxleden, 1972). Today, about 51% of the agricultural land (about 405 km²; according to land-cover data by Nöhles (2000)) are grasslands managed at low intensity ranging from grazing without fertiliser application to mowing three times a year for fodder production (Wellstein et al., 2007). Owing to the predominance of extensive farming systems, the Lahn-Dill Highlands feature a high biological diversity and thus are one of the most species-rich, low-mountainous landscapes in Germany (Nowak, 1988). This is specifically true for the plant species diversity of grasslands (Nowak, 1992; Simmering et al., 2006; Wellstein et al., 2007).

2.2. Methodological approach

Our GIS-based methodology permits to systematically assess the spatial distribution of grassland age in a marginal agricultural landscape and involves three major steps: (1) a two-stage stratified random selection of grassland patches; (2) a multitemporal aerial photograph interpretation of the selected patches; and (3) the spatial extrapolation of grassland age (Fig. 2). Supplementary to our approach, we performed a validation procedure using reference data for two test areas (Fuhr-Bossdorf et al., 1999). All spatial data were processed with the ESRI Inc. software package ArcGIS 9.0 and the Spatial Analyst extension.

2.2.1. Two-stage stratified random selection of grassland patches

The two-stage stratification process performed in our analysis (Fig. 2) is based on the assumption that the probability of a grassland patch to have a certain age is affected by socioeconomic variables and physical attributes (cf. Section 1) at different spatial scales. On an intermediate spatial scale (stratification I), the administrative unit ‘Gemarkung’ (district), which traditionally represents the smallest political and socioeconomic entity in Germany, we often find homogeneous socioeconomic characteristics depending on, for example, local traditions, the predominance of independent or ‘follow-the-leader’ mentalities, and the pace of spread of innovation. These strongly affect the probability of a patch to be recently managed as either arable field, grassland, or fallow (Hietel et al., 2005, 2007). In order to systematically consider the close connections between the socioeconomic environment and land–use, we pre-stratified the entire study area according to recent land–cover patterns and their changes between 1955 and 1995. The data sets were derived from agricultural statistics from 1955 (Hessisches Statistisches Landesamt, 1956) for 187 districts of the study area (five more districts were identified as outliers in previous analysis (cf. Reger et al., 2007) and not considered) and a 1995 satellite image interpretation (Landsat-TM, 25 m raster; Nöhles, 2000). At the scale of the districts, we calculated: (1) the percentage of grassland in 1995; and (2) the percentage of fallow land in 1995 with respect to the total area of agricultural land.

We considered the percentage of grassland and fallow land since cessation of arable farming favoured these land–cover types in the study area within the investigated time period. To obtain an integrated estimate for land–cover changes, we further assessed (3) the arable land to grassland ratios for 1955 and 1995 and calculated the difference between the two ratios for each district. By means of a k-means cluster analysis based on the three input variables, we identified and localised six types of land-cover patterns and dynamics (TLPDs; Reger et al., 2007) that represent patterns of present-day agricultural land-cover and past land-cover dynamics between 1955 and 1995 at the district scale (Fig. 3). A description of the TLPDs is given in Table 1. For more details see Reger et al. (2007).

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1 Following the definitions of Turner and Meyer (1994), we use the term land-cover to refer to the physical state of the land, whereas land-use denotes the human employment of the land.
Fig. 1. Map of the study area showing (A) its location in Hesse, Germany and (B) its topographical situation. Test area A: Erda; test area B: Steinbrücken and Eibelshausen.

Fig. 2. Schematic workflow of the methodological approach to assess the spatial distribution of grassland age in a marginal landscape.

1. Two-stage stratified random selection of grassland patches
   - Stratification I: by types of land-cover patterns and dynamics
   - Stratification II: by grassland types
   - Random selection of grassland patches

2. Multitemporal aerial photograph interpretation
   - Age determination of grassland patches by a chronosequence from
     - 2001
     - ...
     - 1953

3. Spatial extrapolation
   - Calculation of grassland type-specific age probabilities
     - \( p_h^{(a)} = \ldots \)
   - Direct extrapolation of age to districts
     - \( P(a) = \ldots \)
Grassland and fallow land are calculated as the median proportions of agricultural land in the districts.

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<td></td>
<td></td>
<td>Median [%]</td>
<td>25–75% percentile</td>
<td>Median [%]</td>
</tr>
<tr>
<td>I</td>
<td>46</td>
<td>259</td>
<td>24.9</td>
<td>20.4–30.9</td>
<td>5.5</td>
</tr>
<tr>
<td>II</td>
<td>50</td>
<td>338</td>
<td>46.8</td>
<td>40.0–51.6</td>
<td>12.2</td>
</tr>
<tr>
<td>III</td>
<td>29</td>
<td>210</td>
<td>43.7</td>
<td>38.8–49.8</td>
<td>35.7</td>
</tr>
<tr>
<td>IV</td>
<td>40</td>
<td>289</td>
<td>61.8</td>
<td>58.4–66.1</td>
<td>20.7</td>
</tr>
<tr>
<td>V</td>
<td>11</td>
<td>65</td>
<td>72.4</td>
<td>64.4–74.1</td>
<td>22.3</td>
</tr>
<tr>
<td>VI</td>
<td>11</td>
<td>78</td>
<td>85.4</td>
<td>76.8–88.3</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Grassland and fallow land are calculated as the median proportions of agricultural land in the districts. n = number of districts. *Values below zero indicate a decrease of arable land in favour of grassland.

On a small spatial scale (stratification II), i.e. at the scale of patches, physical attributes like soil moisture, base-richness, and elevation are the most relevant variables that influence land-use decisions by farmers (e.g. Bürgi and Turner, 2002; Hietel et al., 2004; Pan et al., 1999). Particularly in marginal landscapes, which are often characterised by a heterogeneous topography and a broad range of different soils, these physical attributes are important variables for grassland age as they strongly affect the potential for agricultural land-use (Hietel et al., 2004). For the second stratification, we classified grassland types within the identified TLPDs. The localisation of recent grassland was obtained from the satellite-derived land-cover map from 1995 (Landsat-TM, 25 m raster; Nöhles, 2000). Users’ accuracy for grassland was 86.7% (Nöhles, 2000). We classified and combined soil moisture, base-richness, and elevation obtained from digital soil maps and DEM to derive physical attributes (Table 2) according to their suitability and constraints for different types of agricultural land-use.

The intersection of physical attributes with TLPDs led to a total of 118 grassland types. Grassland types of alluvial plains (soil moisture: wet, n = 13 grassland types; cf. Table 2) were excluded from further analysis, since they were continuously managed as grasslands over the last half century and not subject to land-cover change (Hietel et al., 2004). Additionally, grassland types (n = 55), covering less than 5% of the grassland area within each TLPD, were omitted from the analysis. Thus, the final grid data set consisted of 50 grassland types, which were included in the stratified random selection of grassland patches.

Subsequently, grassland types were assigned to polygons derived from digital cadastral maps from 2004 (scale 1:5000). The shape and size of the cadastral polygons represent land parcels, which are the smallest spatial unit of uniform land-cover development since 1945 (Herzog et al., 2001; Hietel et al., 2004). Using GIS, we randomly selected an equal sample size of 20 polygons per grassland type to ensure balanced representation of each grassland type. Hence, a total of 1000 scattered grassland patches with a mean size of about 0.3 ha were sampled for the survey of land-cover change.

2.2.2. Multitemporal aerial photograph interpretation
In order to assess the duration of grassland use for the sampled patches, we reconstructed the land-cover history of each patch by visual multitemporal aerial photograph interpretation (Fig. 2). For the entire study area, a chronosequence of black and white aerial photographs since 1953 was available (mainly at a scale of 1:12,000 covering an area of about 4 km², 1:24,000 for 1953). Recent grassland use was differentiated from former land-cover types (i.e. arable land or fallow land with woody plant succession) according to tonal contrast and texture. However, with respect to the entire study area the aerial surveys cover different time intervals. Therefore, we had to consider periods of several years in our investigation. We started with photographs from the period 1998–2001, since these were the most recent photographs available and continued with photos from the periods 1989–1994, 1979–1983, 1967–1973, 1959–1962, and 1953. The time span between the photographs was approximately 10 years. Moving back in time until the land-cover changed, the interpretation of the time series permitted to assign each sampled grassland patch to either the age class young (<18 years), mid-aged (18–47 years), or old (>47 years), which are expected to be ecological relevant stages for grasslands (cf. Austrheim and Olsson, 1999; Waldhardt and Otte, 2003). The resulting age classes of the grassland patches were tested for significant differences between the TLPDs, soil moisture, base-richness, and elevation classes by performing G-tests. The G-test is equivalent to the more commonly used chi-square test, but is computationally simpler and G appears to follow the chi-square distribution a bit more closely (Sokal and Rohlf, 2004).

2.2.3. Spatial extrapolation
The identified age of the grassland patches was used to perform a spatial extrapolation (Fig. 2). Our approach is based on the
assumption that grassland patches of the same grassland type – patches with comparable physical attributes located in areas with similar land-cover patterns and dynamics – have the same probability to belong to a certain age class since we expect that farmers’ decisions are driven by similar physical attributes and socioeconomic conditions. Based on the three age classes and the 50 grassland types, we calculated grassland type-specific age probabilities \( p_{h}^{(a)} \), defined as:

\[
P_{h}^{(a)} = \frac{n_{h}^{(a)}}{n_{h}}
\]

where \( n_{h}^{(a)} \) is the number of investigated patches found to belong to age class \( a \) of grassland type \( h \), and \( n_{h} \) is the number of investigated patches of grassland type \( h \), in our case \( n_{h} = 20 \).

In order to determine the areal proportions of grassland age classes at the scale of districts we used direct extrapolation. For each district, we first weighted the area \( A_{h} \) covered by grassland type \( h \) by the probability \( p_{h}^{(a)} \) (Eq. (1)) and summed over all grassland types \( h = 1, 2, ..., 50 \). Dividing this sum by the total grassland area of the corresponding district, we obtained the proportions of the age classes young, mid-aged, and old in the district. The areal percentage \( P(a) \) of age class \( a \) for each district is thus calculated by the formula

\[
P(a) = \frac{\sum A_{h}^{(a)} \cdot p_{h}^{(a)}}{\sum A_{h}} \cdot 100\% \tag{2}
\]

### 2.2.4. Validation procedure based on reference data

In order to judge if our results permit a realistic estimation of the grassland age for single districts, we performed an exemplary validation using reference data. The estimated proportions of grassland belonging to the respective age classes were validated for two test areas with contrasting land-cover dynamics (Fig. 1B). Test area A, the district Erda (11.6 km²), represents TLPD I (Table 1) with little land-cover dynamics, whereas test area B, the neighbouring districts Steinbrücken and Eibelshausen (9.3 km²), belongs to TLPD V (Table 1), which is characterised by a strong land-cover change in favour of grassland. Results of an interpretation of black and white aerial photographs from the years 1953, 1961, 1972, 1979, and 1989 and field data from 1996 covering the entire surface of agricultural land (Fuhr-Bossdorf et al., 1999) provided independent information on the age of the entire grassland in the two areas. We grouped the data from this study into the age classes young (<18 years), mid-aged (18–47 years), and old (>47 years), calculated their areal proportions, and compared these with the estimated proportions from the study. To test for significant differences between the extrapolation results and the reference data, a G-test was performed.

### 3. Results

#### 3.1. Age structure in TLPDs and physical attributes of the investigated patches

In total, 49% of the 1000 investigated grassland patches were old or permanent grassland stands. The remaining patches were young (15%) and mid-aged grasslands (36%), almost all of which were formerly used as arable land. Pronounced differences of the grassland age structure, i.e. the proportions of grassland patches belonging to the age classes, were observed between the six TLPDs and confirmed by statistical analysis (G-test, \( G_{adj} = 40.09, df = 10, p < 0.001 \); Fig. 4A). For TLPD I, which is characterised by a low proportion of grassland and an almost unchanged ratio of arable land to grassland from 1955 to 1995, our analysis indicated that 61% of the investigated grassland patches were old. Also in TLPD II–IV, old grassland patches predominated with a comparatively high proportion (53–57%). The grassland age structure of TLPD V differed significantly from TLPDs I–III and was characterised by a proportion of old grassland patches well below the average. With a severe decrease of arable land in favour of grassland since 1955 in TLPD V, only 30% of the investigated patches in TLPD V were old. Mid-aged grassland patches showed a relatively high proportion of about 56%. The highest proportion of young grassland of all types was found with 22% in TLPD II and VI.

Statistical analysis of the frequency of age classes among classes of physical attributes revealed that grassland age structure is independent from base-richness and elevation, but not from soil moisture (G-test, \( G_{adj} = 13.26, df = 4, p < 0.05 \)). Moist grassland stands were predominantly permanent grassland (60%), since moist sites are less suitable for arable farming (Fig. 4B). Some of the moist grassland types comprised almost exclusively old grassland patches. In contrast, dry sites featured only 38% old grassland. Hence, more than 60% of dry grassland were subject to land-cover changes in the respective time period. Base-poor grassland patches also tended to be predominantly mid-aged (Fig. 4C). However, moderate and base-rich sites accounted for 48% and 53% of old grassland patches. The proportions of young, mid-aged, and old grassland patches per elevation class were nearly identical (Fig. 4D).

#### 3.2. Extrapolation of grassland age at the district scale

Based on the age of the investigated grassland patches, we calculated a total of 150 grassland type-specific age probabilities for grassland patches (Appendix 1). Considering all 187 districts, these probabilities were extrapolated to the districts (Eq. (2)). The extrapolation results were mapped separately for the grassland age classes old, mid-aged, and young (Fig. 5). Very high proportions of old grassland stands (>75%) were calculated for 31 districts mainly located in the eastern part of the Lahn-Dill Highlands (Fig. 5A). In large parts, mostly in the centre of the study area (n = 90 districts), old grassland stands were less dominant (50–75%). Except for one single district, all remaining districts (n = 65 districts) in the north-western and south-western part had an estimated proportion of old grassland stands of only 25–50%. High proportions of mid-aged grassland (>50%) were calculated for only nine districts in the western and southern part of the study area, while low proportions

### Table 2

<table>
<thead>
<tr>
<th>Variable</th>
<th>Class Description</th>
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<tbody>
<tr>
<td>Soil moisture</td>
<td>1 dry AWCV &lt;50 mm or AWVC 50–90 mm and &gt;5° slope</td>
</tr>
<tr>
<td></td>
<td>2 mesic AWCV &lt;90 mm or AWVC 50–90 mm and ≤5° slope</td>
</tr>
<tr>
<td></td>
<td>3 moist Low to mean gleyic/stagnic soil properties</td>
</tr>
<tr>
<td></td>
<td>4 wet High gleyic/stagnic soil properties</td>
</tr>
<tr>
<td>Base-richness</td>
<td>1 base-poor Soil types with acidic substrate (e.g. sandstone to claystone, quartzite, schist)</td>
</tr>
<tr>
<td></td>
<td>2 moderate Soil types with neutral substrate (e.g. siliciclastic sedimentary rocks, metamorphic rocks)</td>
</tr>
<tr>
<td></td>
<td>3 base-rich Soil types with alkaline substrate (e.g. basaltic extrusive rocks)</td>
</tr>
<tr>
<td></td>
<td>4 calcareous Soil types with calcareous substrate (e.g. limestone, dolomite)</td>
</tr>
<tr>
<td></td>
<td>1 colline &lt;400 m a.s.l.</td>
</tr>
<tr>
<td></td>
<td>2 submontane &gt;400 m a.s.l.</td>
</tr>
</tbody>
</table>

*a* Information derived from official digital soil map of Hesse (scale 1:50,000), HLUG (Hessisches Landesamt für Umwelt und Geologie).

*b* Information derived from digital elevation model (40 m raster), HVBG (Hessische Verwaltung für Bodenmanagement und Geoinformation).

*c* Available Water Capacity in the root zone.
(<12.5%) were estimated for 15 districts in the eastern part (Fig. 5B).
Most districts, however, featured 12.5–50% mid-aged grassland. For
districts in the western and north–western parts of the Lahn-Dill
Highlands we estimated 25–50% mid-aged grassland compared to
12.5–25% in districts in the east and south–east. Most notable for all
districts, however, was the relatively low proportion of young
grassland, which varied between 2% and 31% ( Fig. 5 C). Eighty-five
districts had even less than 12.5% young grassland. These districts
were found in the east and the west of the study area. Only districts
in the southern part of the Lahn-Dill Highlands had an estimated
proportion of 25–50% young grassland.

3.3. Validation of extrapolation results

The validation results indicated that the estimated proportions
of grassland belonging to the respective age classes were well in
accordance with the reference data (Fuhr-Bossdorf et al., 1999) of
test area A, Erda ( Fig. 6A). The largest difference with 13% was found
for young grassland stands under dry soil conditions (grassland
type 121), while the other results differed less than 9%. In
comparison to the district Erda, the validation results of test area B,
Steinbru¨ cken and Eibelshausen, revealed a lower conformity of the
estimated proportions with the reference data ( Fig. 6 B). The
differences varied between 2% and 21%. The calculated proportions
obtained from spatial extrapolation tended to underestimate old
grassland stands (3–13%), while the proportion of mid-aged
grassland stands were overestimated (8–21%). However, statistical
analysis of the grassland age classes revealed a significant differ-
cence between the extrapolation results and the reference data only
for grassland type 121 (G-test, Gadj = 9.89, df = 2, p < 0.01).

4. Discussion

4.1. Methodological approach

In this paper we proposed a methodological approach for the
assessment of the spatial distribution of grassland age in marginal
European landscapes. The results showed that our approach is
suitable for a realistic estimation of grassland age in a marginal
landscape. We combined data sets and techniques of geographical
information systems (GIS), remote sensing, and spatial extrapola-
tion that are well established in landscape research. In the
following, we discuss the steps of our methodological approach in
detail.

4.1.1. Stratified random sampling

Stratified random sampling is considered to maximise the effi-
ciency of landscape ecological assessment while focusing on
maximum variation and representativeness of sampling (Goedickermeier et al., 1997; Knollová et al., 2005). Stratification enables the organisation of environmental variability of large areas into strata that are relatively homogeneous according to the characteristics of interest (Jongman et al., 2006). Thus, modern surveys of ecologically relevant data in large areas increasingly use environmentally stratified sampling designs (e.g. Bunce et al., 1996; Cooper and Loftus, 1998; Grabherr et al., 2003; Smart et al., 2003; Stohlgren et al., 1997).

The feasibility of our stratified random survey primarily depends on appropriate stratification data, their quality, and error propagation. Problems encountered at any of these levels can result in lower prediction success. The selection of data used for stratification in our study was primarily limited by availability. We used land-cover statistics, a DEM, and soil data for the two-stage stratification process to derive variables shown to be relevant for land-cover change in previous research (Hietel et al., 2004; Reger et al., 2007). Stratification permitted to systematically outline the spatial heterogeneity within the study area, regarding TLPDs at the district scale and physical attributes at the patch scale. A subsequently performed G-test confirmed that the grassland age of the investigated patches significantly differed according to the TLPDs and soil moisture, not, however, according to the physical attributes base-richness and elevation.

Generally, the assessment of accuracy and errors in spatial data like land-cover data (e.g. Bach et al., 2006; Foody, 2002; Wickham et al., 2004) or DEM (e.g. Bolstad and Stowe, 1994; Holmes et al., 2000; Wechsler and Kroll, 2006) has received considerable attention in recent research. Unfortunately, it has not yet become a standard to state positional and thematic accuracy of a data set (Bach et al., 2006). Hence, we do not know the accuracy of the DEM and soil data used. Visual screening for extreme values, however, gave us confidence of sufficient data quality. Errors in spatial data may be further propagated by GIS based operations like the conversion of different formats (i.e. vector to raster) or the intersection of different thematic layers (Heuvelink, 1998). Error propagation may thus influence the quality of the stratification outcome. However, general, integrated practical tools for statistical error propagation in GIS are still missing (Burrough and McDonnell, 2000).

4.1.2. Multitemporal aerial photograph interpretation

Aerial photographs provide only arbitrary snapshots in time. Our interpretation is dependent on six snapshots from the period 1953 to 2001, since further aerial photographs were not available. Therefore, temporary alterations of cropland and grassland use between two snapshots cannot be detected by using exclusively aerial photographs. This uncertainty could be diminished by a more integrative approach that also considers time-dependent patch characteristics like soil pH (Breuer et al., 2006; Waldhardt and Otte, 2003) or local farmers' knowledge on past management (Calvo-Iglesias et al., 2006; Robertson and McGee, 2003). Nevertheless, several studies show that multitemporal aerial photograph interpretation is an effective way to receive valid information on past land-cover changes in

Fig. 5. Extrapolation results mapped for the grassland age classes (A) old (>47 years), (B) mid-aged (18–47 years), and (C) young (<18 years) in 187 districts.
agricultural landscapes, even when land-cover history is assessed by using aerial photographs of longer time intervals (e.g. Alard et al., 2005; Chen et al., 2001; Olsson et al., 2000; Poudevigne et al., 1997). Additional data sets for the analysis of land-cover change within larger regions, e.g. satellite images, historical maps, or statistics, are usually limited by a lack of appropriate time periods, infrequent observations, or a coarse resolution.

It seems to be of greater importance to consider visual misinterpretations as a source of under- or overestimated grassland age. Considering our sample size of 20 patches per grassland type, a misinterpretation of one patch has an effect of 5%. However, due to the variation in tonal contrast and its specific texture, grasslands can be readily identified in black and white aerial photographs at a scale of about 1:12,000 (Albertz, 1991; Schneider, 1974), so that potential misinterpretations may be minimal in terms of both, the sampled grassland patches and the reference data (Fuhr-Bossdorf et al., 1999).

4.1.3. Spatial extrapolation

Our multitemporal interpretation of aerial photographs facilitated the calculation of grassland type-specific age probabilities, which we then generalised via direct extrapolation to the district scale. Direct extrapolation is a prominent technique in landscape ecology in cases when measurements were made at relatively fine scale (Miller et al., 2004; Turner et al., 2001). The challenges of direct extrapolation lie in a correct definition of the spatial and temporal heterogeneity of the fine-scale information (i.e. grassland age) and both an accurate integration and aggregation of this heterogeneity to the broader scale (King, 1991). By aggregating the investigated grassland age into three classes, we considered successional stages of grasslands (cf. Austrheim and Olsson, 1999; Waldhardt and Otte, 2003), which may be expected to be of ecological relevance after abandonment of arable land. However, aiming for other target values such as soil properties, it may be necessary to adapt the classification of the basic stratification units as well as the age classes we used in our methodological approach.

4.1.4. Validity

The validation of our extrapolation results focussed on two test areas with contrasting land-cover dynamics since area-wide reference data for further test areas were not available. Nevertheless, our results indicate the validity of our approach. The comparison of the estimated proportional area of grassland age classes with the reference data of the two test areas (Fuhr-Bossdorf et al., 1999) showed a satisfying conformity for the test area Erda, which underwent rather moderate land-cover changes in the past. However, over- and underestimation up to 21% were detected for the test area Steinbrücken and Eibelshausen, being significant only for one grassland type. These uncertainties may be viewed as an effect of the extensive land-cover changes within these districts and the rather low number of investigated patches. A better assessment within such areas might be attainable by increasing the number of patches. However, a larger sample size and thus a higher certainty would also increase the amount of work and costs and may thus be only practicable for single grassland types.

4.2. Grassland age structure

The grassland age structure of the entire study area reflects a high spatial heterogeneity, which can be ascribed to successive land-cover changes reported in the Lahn-Dill Highlands (Hietel et al., 2004, 2005; Kohl, 1978; Schulze-von Hanxleden, 2003). The majority (49%) of investigated grassland patches were old (>47 years). But one could expect that in a landscape with such unfavourable conditions for arable farming (see Section 2.1), the proportion of permanent and old grasslands should be even higher. However, after World War II the lack of food led to relatively high proportions of arable land within the entire study area, so that even poor soils on steep slopes were cultivated (Schulze-von Hanxleden, 1972). Only sites with conditions completely unsuitable for arable farming (e.g. wet soil conditions) were used as permanent grasslands.

The high amount of mid-aged grassland patches (36%) may be closely related to major land-cover changes, which took place since the early 1960s. Since that time, Germany and other European countries strove to increase production and efficiency in agriculture (cf. Meeus et al., 1990). Economic prosperity and increasing mechanisation, intensification and specialisation of agriculture led to intensive cropland farming on more fertile sites whereas cultivation on less favourable sites ceased. Former fields were either turned into grassland or were completely abandoned (e.g. Bender et al., 2005; Fjellstad and Dramstad, 1999; Krausmann et al., 2003; Mottet et al., 2006). Thus, particularly districts with poorest conditions for cultivation showed an increase of grassland (Hietel et al., 2005).
et al., 2004). Consequently, we found higher proportions of mid-aged grassland in these districts.

In the 1980s, Common Agricultural Policy (CAP) was fundamentally reoriented with the aim to reduce overproduction and environmental pressures caused by intensive production. With the implementation of the MacSharry reforms of the CAP in 1992, market price support was partially replaced by a system of direct payments to farmers. Accompanying these reforms, regional agri-environmental schemes were established that financially supported the extensification of grassland (de Putter, 1995; Primdahl et al., 2003). In their study, Hietel et al. (2007) identified that the agri-environmental schemes offered by the state of Hesse favoured the conversion to grassland use. These changing economic conditions for agricultural land-use led to a further phase of abandonment in areas with inferior conditions for cropland farming, representing today’s young grassland patches. These young patches are almost uniformly distributed across the entire study area, which indicates that economic developments in the last two decades affected the grassland age structure in all districts of the marginal landscape.

5. Conclusions

In this study we proposed a three-step methodological approach to systematically assess the spatial distribution of grassland age in a marginal European landscape. Based on the combination of an a-priori two-stage landscape stratification with conventional aerial photograph interpretation of selected patches, and the subsequent spatial extrapolation of the determined grassland age, our approach sidesteps the shortcomings caused by the lack of feasible data on spatially explicit land-cover change. Results proved that our approach provides a realistic estimation of grassland age at the scale of districts and over a time period of five decades. We found that the derived probabilities of grassland age classes are specific for grassland types in areas with a homogenous pattern of land-cover change. Furthermore, the results confirmed a predominance of old grassland patches and a high amount of mid-aged grasslands that can be ascribed to major land-cover changes in this time period.

Due to comparatively simple data sets and techniques, our approach may be applied to other marginal agricultural landscapes under study – given the existence of feasible data. Further, our approach is suited for application in landscape models of various disciplines, which rely on large-scale information on grassland age. For instance, grassland age can be used as indicator for the prediction of vascular plant species richness in mosaic landscapes (Waldhardt et al., 2004). Moreover, the approach may be easily adapted to other land-cover types such as fallow land whose phytodiversity is also dependent on age (Simmering et al., 2001).

Acknowledgements

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Appendix 1

Grassland type-specific age probabilities ($p_{\text{age}}$; Eq. (1)) for young (<18 years), mid-aged (18–47 years), and old (>47 years) grassland patches within the six TLPDs (cf. Table 1). Coding of the grassland types (e.g. 111) refers to Table 2 in the order soil moisture, base-richness, and elevation.

<table>
<thead>
<tr>
<th>Grassland type</th>
<th>Age class</th>
<th>TLPD 1</th>
<th>TLPD 2</th>
<th>TLPD 3</th>
<th>TLPD 4</th>
<th>TLPD 5</th>
<th>TLPD 6</th>
</tr>
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<tr>
<td>111</td>
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<td>0.15</td>
<td>0.35</td>
<td>0.55</td>
<td>0.55</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Mid-aged</td>
<td>0.40</td>
<td>0.35</td>
<td>0.15</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Old</td>
<td>0.35</td>
<td>0.30</td>
<td>0.55</td>
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<td>0.45</td>
<td>0.45</td>
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<tr>
<td>121</td>
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<td>0.25</td>
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</tr>
<tr>
<td></td>
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<td>0.20</td>
<td>0.10</td>
<td>0.10</td>
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</tr>
<tr>
<td></td>
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<tr>
<td>122</td>
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<tr>
<td>131</td>
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<tr>
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<td>0.45</td>
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</table>

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