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published in
Landscape and Urban Planning
2016

DOI (link to publisher)
10.1016/j.landurbplan.2016.02.005

document version
Publisher's PDF, also known as Version of record

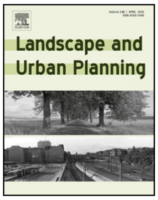
citation for published version (APA)
van der Zanden, E. H., Levers, C., Verburg, P. H., & Kuemmerle, T. (2016). Representing composition, spatial structure and management intensity of European agricultural landscapes: A new typology. *Landscape and Urban Planning*, *150*, 36-49. https://doi.org/10.1016/j.landurbplan.2016.02.005

Landscape and Urban Planning 150 (2016) 36–49

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan



Representing composition, spatial structure and management intensity of European agricultural landscapes: A new typology

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HIGHLIGHTS

- We present a spatially-explicit typology of European agricultural landscapes.
- Datasets representing land cover, landscape structure and land management are used.
- An expert-based top-down typology is compared with a data-driven bottom-up approach.
- Inclusion of land management differentiates our results from existing typologies.
- We find clear overlaps in general landscape patterns with existing typologies.

ARTICLE INFO

Article history:
Received 18 November 2014
Received in revised form 26 January 2016
Accepted 4 February 2016

Keywords:
Agricultural landscapes
Landscape typology
Land use intensity
Self-organizing maps
Europe
Land management

ABSTRACT

Comprehensive maps that characterize the variation in agricultural landscapes across Europe are lacking. In this paper we present a new Europe-wide, spatially-explicit typology and inventory of the diversity in composition, spatial structure and management intensity of European agricultural landscapes. Agricultural landscape types were characterized at a 1 km^2 resolution based on Europe-wide datasets that represent land cover, landscape structure and land management intensity. Two alternative approaches for typology development were used: an expert-based top-down approach, and a bottom-up approach based on automated clustering using Self Organizing Maps (SOMs). Comparison with available national and European landscape typologies showed that our typology deviates from existing biophysical and anthropocentric typologies relevant to agricultural landscapes as result of the inclusion of land management aspects. Concordance occurred between specific European typology classes, while the comparison with national landscape typologies showed a correspondence in agricultural landscape patterns. Our agricultural landscape typology can provide a basis for landscape assessment at a European-scale to help to identify agricultural landscape types prone to change and landscapes that may require policy response.

1. Introduction

Land use has transformed more than 80% of the global land surface, by conversion of natural ecosystems into agriculture or cities or by using natural ecosystems at varying intensity (Ellis, Klein Goldewijk, Siebert, Lightman, & Ramankutty, 2010). While much research has focused on how land conversions create agricultural and other human-dominated landscapes (Ramankutty et al., 2006; Verburg, van Asselen, van der Zanden, & Stehfest, 2013), much less attention has been paid to characterizing the spatial variation in agricultural landscapes that has developed in relation to the variation in management intensity within these landscapes, even though management intensity is a main driver of rural landscape change in many world regions (Sayer et al., 2013).

Three important dimensions of present-day agricultural landscapes are land cover, land management and landscape structure (Verburg et al., 2013). Land cover types and their arrangement determine the overall agricultural type. Land management refers to the “ways in which humans treat vegetation, soil, and water” for a specific purpose (Lambin, Geist, & Rindfuss, 2006); in other words, the land use practices that people carry out within broad

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http://dx.doi.org/10.1016/j.landurbplan.2016.02.005

land cover types. Examples of such practices include use of fertilizers or pesticides, irrigation schemes and tillage (e.g., Erb et al., 2013; Follett, 2001). Land management can impact landscape functioning and ecosystem services supply substantially (Tscharntke, Klein, Kruess, Steffan-Dewenter, & Thies, 2005; Zhang, Ricketts, Kremen, Carney, & Swinton, 2007). While such effects have been extensively studied at the local scale (e.g., Shriar 2000; Herzog et al., 2006), the spatial patterns of land management at regional to global scales, and thus their impacts on ecosystem functioning, services and biodiversity, are often ignored (Kuemmerle et al., 2013; Verburg et al., 2013). Landscape structure is scale-dependent and refers to the spatial heterogeneity of the landscape (Turner, 1989), for example the arrangement of land uses or cropland fields, or the prevalence of linear landscape elements (e.g., hedges, ditches, terraces, Paracchini et al., 2012; Kumaraswamy & Kunte, 2013). On a regional scale, landscape structure is closely linked to ecosystem services provisioning, especially for a number of regulating services (e.g. erosion prevention, pollination) and cultural services (e.g. landscape aesthetics and tourism, Pinto-Correia & Breman, 2008; Power, 2010; Syrbe & Walz, 2012; van Zanten et al., 2013), as well as the biodiversity-friendliness of agricultural landscapes (Burel & Baudry, 1995; Dramstad et al., 2001).

Land cover, land management, and landscape structure are also central features differentiating landscapes with exceptional cultural heritage and values (Plieninger, Höchtl, & Spek, 2006). Cultural landscapes – a term adopted in the 1990s by international bodies as a conservation category (Jones, 2003) – often have relatively high structural complexity, traditional, low-intensity landscape practices and historical elements, altogether contributing to the often exceptional value of these landscapes (Antrop, 2005; Fischer, Hartel, & Kuemmerle, 2012; Plieninger & Bieling, 2012). Many cultural landscapes, however, have recently undergone stark transformations as new land-use paradigms based on more intensive agricultural production are adopted (Vos & Meekes, 1999).

Europe is particularly rich in landscapes that are recognized for their natural and cultural heritage (Vos & Meekes, 1999; Plieninger, Höchtl, & Spek, 2006). Many of these cultural landscapes have been shaped by traditional land uses and contain high conservation values that are dependent on continuation of low-intensity agricultural practices (Dieterich & van der Straaten, 2004; Fischer et al., 2012). Historical socioeconomic and institutional events shaped landscape structure and are visible in the landscape today. An example is the high level of fragmentation of ownership and field sizes in post-socialist countries, which is a result of collectivization of land during the socialist time and the re-privatization processes since 1989 (Hartvigsen, 2014; Kuemmerle et al., 2008). Conserving European cultural landscapes, as well as their cultural and natural heritage has received increased attention in European policy making recently, with the introduction of the High Nature Value (HNV) farmland concept as the clearest example (EEA, 2010; Kleijn, Rundlöf, Scheper, Smith, & Tscharntke, 2011; Paracchini et al., 2008; Robinson & Sutherland, 2002; Walz & Syrbe, 2013). Furthermore, specific EU policies, such as the Common Agricultural Policy (CAP), increasingly promote a landscape-based approach (Paracchini & Capitani, 2011), although there is also critique on the dominant environmental focus of landscape management in these policies (Agnoletti, 2014).

To better understand the large spatial heterogeneity of agricultural landscapes across Europe, and to monitor changes in landscape functions and values, it is necessary to reduce the complexity in agricultural landscapes to manageable units that could be an interesting target for policy-making at the European scale. Several initiatives have sought to identify and classify landscapes in Europe since the 1990s (Paleo, 2010), including the Pan-European Biological and Landscape Diversity Strategy (PEBLDS, Council of Europe 1996) and the European Landscape Convention (ELC, Council of Europe 2000). The ELC encouraged member states to identify and assess the national landscapes and their features, but with a focus on member state autonomy and a clear subsidiarity principle (Council of Europe, 2000). Thus, the national landscape maps differ substantially in mapping approaches (see Supplementary material A), data sources, and the underlying landscape-concept (i.e., interpretation of the role of humans in the landscape; see Angelstam et al., 2013 for an overview; Cassatella & Voghera, 2011; Groom, 2005). Substantial progress in developing a Pan-European Landscape map, an important action theme of the PEBLDS (Council of Europe, 1996), was made. Meeus (1995) developed a qualitative classification of traditional European landscapes. Building on this, Mücher et al. (2010) developed a Landscape Map (LANMAP) aimed to give an overall classification of landscape types in Europe, based on quantitative spatial analysis and a consistent classification framework. However, previous research efforts have not incorporated key dimensions that are important for differentiating agricultural landscapes, such as land management and landscape structure.

Our main objective is to focus on this research gap, by developing a typology of the diversity in composition, spatial structure and management intensity of European agricultural landscapes. By focusing on these selected dimensions, we aim to provide a generic basis (i.e., independent from specific locations or geographic contexts) for assessment and comparison of agricultural areas in Europe. Such an approach is highly complementary to existing classifications and typologies which mainly capture biophysical dimensions of landscapes in great detail. A second objective is to compare methods for typology development. As traditional approaches in typology development either take a top-down or a bottom-up approach, we compared an expert-based top-down, and a bottom-up approach based on automated clustering.

Europe is an interesting case for such analysis, as landscape characterization and assessment is a key aspect in European landscape research (Plieninger, Dijks, Oteros-Rozas, & Bieling, 2013). But the typology development also provides a methodological example for the delineation of agricultural typologies for other world regions, moving beyond the standard approach of characterizing differences in landscape and land use by their dominant land cover only (e.g., Busch, 2006; Verburg et al., 2013). The representation of critical aspects of agricultural landscapes is currently lacking on a regional scale, while progress has been made with global scale typologies (see Verburg, van Asselen, van der Zanden, & Stehfest, 2013). Improved representation of agricultural landscapes within subglobal assessments can furthermore clarify landscapes' influence on environmental change (Verburg, van Asselen, van der Zanden, & Stehfest, 2013).

2. Materials and methods

Traditional approaches to develop landscape typologies using geospatial data have applied either a top-down or bottom-up approach. In a top-down approach, the typology is commonly delineated based on a decision tree defined by expert rules and supervised threshold selection (Maxwell & Buddemeier, 2002). A bottom-up approach, in contrast, determines landscape types based on groups of locations that have similar characteristics, usually with the help of statistical clustering methods. We used both of these approaches, specifically a top-down expert-based classification and a bottom-up approach based on automated clustering using self-organizing maps (SOMs) (see Fig. 1), that used the same input data for the land cover, land management and landscape structure dimensions of agricultural landscapes. We then carried out a map comparison to assess the influence of method selection on the resulting maps.

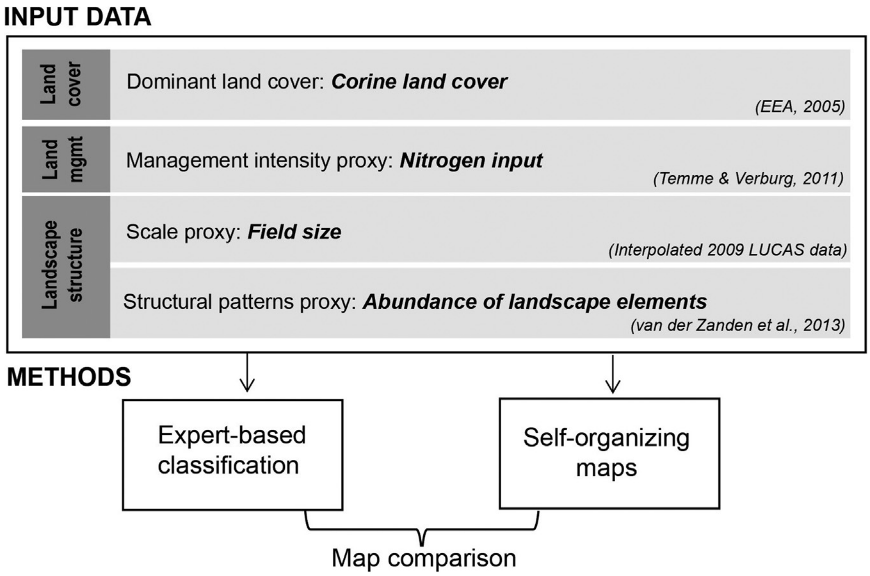


Fig. 1. Methodology of agricultural landscape typology development.

Table 1
Input data for the classification of the diversity in composition, spatial structure and management intensity of European agricultural landscapes.

Agricultural landscape dimension	Dataset	Unit	Resolution	Time period	Source	Validation
Dominant land use	CORINE Land use/cover	Area (250 m)	1 km^2	2006	CLC 2006 land cover (www.eea.europa.eu/data-and-maps/)	
Land management	Fertilizer application rates	N application class (kg N/ha)	1 km^2	2003–2006	Temme & Verburg (2011), Overmars et al. (2014)	The intensity classes are tested by reviewing the data assignment to irrigated vs. non-irrigated areas (CORINE 2000).
Landscape structure	Field size	Size class in ha	1 km^2	2009	Kuemmerle et al. (2013)	In Supplementary Material B.
Landscape structure	Linear landscape elements	Number of intersections with elements	1 km^2	2009	van der Zanden et al. (2013)	Independent validation of green lines based on aerial photographs (van der Zanden et al., 2013)

2.1. Datasets used

To represent the land cover, land management and landscape structure dimensions of agricultural landscapes, we used a range of independent datasets which are publicly available for the territory of the European Union (Table 1). Regarding information on land cover, we used the CORINE land cover (CLC) map (EEA, 2005) to select agricultural areas using non-irrigated arable land (CLC 2.1.1), permanent crops (CLC 2.2), pasture (CLC 2.3) and heterogeneous agricultural areas (CLC 2.4). We aggregated this information to 1 km^2 raster cells using a majority rule.

Regarding information on land management, we used nitrogen input as a proxy for the use of capital-intensive inputs to agriculture. Nitrogen input is often used as an indicator for agricultural intensification due to its strong effects on the biodiversity of agricultural landscapes, although a combination of different indicators may better capture patterns of intensity (Erb et al., 2013; Herzog et al., 2006). We created the nitrogen input map following Temme and Verburg (2011) and Overmars et al. (2014). This approach was chosen because the resulting pixel-based maps were more suitable for our purpose than nitrogen input levels reported in statistics for national or sub-national administrative units. The creation of nitrogen input maps began with nitrogen input levels (kg/ha) at sub-administrative level (NUTS 2) per crop type per administrative unit, available from the Common Agricultural Policy Regionalized Impact modelling System (CAPRI; Britz, 2005; Leip et al., 2008). These nitrogen input levels were downscaled to the pixel level using point-based crop observations in the same administrative units assuming that the cropping pattern can serve as a proxy for the variation in nitrogen application within an administrative unit. We used point-based observations from the 2003 and 2006 land use/cover area frame statistical surveys (LUCAS) database (~150.000 sample points, Delincé 2001; Gallego & Delincé 2010). The LUCAS project, which currently has five sampling years (2001, 2003, 2006, 2009 and 2012), collects field observations and includes information on land cover/use and additional visual information, e.g., on slope, field size, water management and grazing (Eurostat, 2009). In recent survey years, the number of sample points was extended and the sampling scheme was adjusted (Gallego & Delincé, 2010). The possible influence of different sampling schemes on the nitrogen input was evaluated by Temme & Verburg (2011) which showed that the higher spatial autocorrelation in the 2003 LUCAS dataset does not strongly affect the results of the method. In our approach, we reclassified the CAPRI based nitrogen application rates assigned to each LUCAS point into three classes: low intensity (<50 kg N/ha); medium intensity

(50–150 kg N/ha) and high intensity (>150 kg N/ha), based on the variation of nitrogen application rates throughout Europe (see Leip et al., 2008) and the relevance of these levels for biodiversity in agricultural areas (Kleijn et al., 2009). With respect to agro-biodiversity, a threshold of <50 kg N/ha is indicative of low fertilizer inputs (Atkinson et al., 2005; Tallowin, Smith, Goodyear, & Vickery, 2005). While thresholds for very intensive arable land vary, Billeter et al. (2008) reported a negative relationship between vascular plant species and intensively fertilized land (>150 kg N/ha). After the reclassification of the nitrogen input levels the point observations were extrapolated to all cropland pixels using country-specific multinomial regression models and a set of environmental and socio-economic location factors. Grassland was modeled using a different approach, where we estimated nitrogen input based on local cattle stocking densities using livestock maps from Neumann et al. (2009) and assuming a uniform quantity of 100 kg N/ha per cow per year (van Grinsven et al., 2015; van der Hoek, 1998), based on total N of dairy cattle minus the N in animal products (e.g., milk). Following the approach of Temme & Verburg (2011), nitrogen input was reclassified into two classes; extensive (<50 kg N/ha) and intensive (>50 kg N/ha) grasslands.

As indicators for landscape structure, we used field size and the density of green linear landscape elements. Field size captures the spatial configuration of fields as well as important components of land management history, as current field size is often influenced by field patterns of the past (e.g., Sklenicka et al., 2009). Also, in other studies field size is used as a variable to characterize the agricultural landscape structure (Geiger et al., 2010). We based the field size information on the 2009 LUCAS database which provides field size information at the sampling point based on observers estimating the size of the agricultural parcel belonging to one out of the following classes: 1) less than 0.5 ha, 2) greater than or equal to 0.5 ha and less than 1 ha, 3) greater than or equal to 1 ha and less than 10 ha, 4) greater than 10 ha (Eurostat, 2009). We interpolated the field size class information to a 1 km^2 raster with European coverage using an Ordinary Kriging method (K-means variogram model with 50 observation points in the search radius), which gave the best results in a comparison of different kriging methods. Comparable field size classes and method are used for mapping field size on a global scale by Fritz et al. (2015). We validated the field size information using 150 randomly generated 10 km by 10 km sampling squares in agricultural and mosaic landscapes. In these sampling squares, the field size was analyzed for 5 random points according to the LUCAS sampling procedures using high-resolution images from Google Earth. For further details on the validation see Supplementary material B.

Linear landscape elements provide important interconnections in heterogeneous landscapes and are explicitly acknowledged as important cultural features, and linked to recreational, aesthetical, and heritage values (Burel & Baudry, 1995). Green linear landscape elements also provide important ecological functions, such as ecological corridors, pollution control, pollination, and erosion and wind control (see overview in van der Zanden, Verburg, & Mücher, 2013). Other landscape elements such as agricultural ditches, terraces or grass margins are also potentially important (Herzon & Helenius, 2008; Oslon & Wäckers, 2007), but not included here due to data limitations. We used a map of linear landscape elements described in detail in van der Zanden et al. (2013). As a basis for this map, the transect information on linear elements from the 2009 LUCAS database was used. On each 250 m transect, surveyor's report crossings of linear landscape features (features wider than 1 m and at least 20 m long, except for walls and fences). This information was collected for 19 classes of linear landscape elements, of which a combination of avenue trees, conifer and bush/trees hedges (managed and non-managed), grove/woodland margins, heath/scrub and dry stone walls were selected. van der Zanden et al. (2013) interpolated the point count information per transect to the 1 km^2 pixel level using Zero-Inflated Negative Binomial (ZINB; Lambert, 1992) regression models, with different biophysical and socio-economic location factor data as independent variables.

Several case studies highlight linkages between agricultural intensity and landscape structure, although such broad generalizations can be misleading (Roschewitz, Thies, & Tscharntke, 2005). For example, Rodríguez and Wiegand (2009) investigated machine-efficiency originating field enlargement in Southern Spain, as agricultural intensification and scale-enlargement often leads to an increased field size. Thenail (2002) and Thenail and Baudry (2004) analyzed the influence of a gradient of decreasing hedgerow density and increasing field size, showing that a decrease in hedgerow density was related to increased production and technical means in dairy farms. Land-use allocation in farms was also dependent on hedgerow density, thereby influencing the landscape structure.

2.2. Expert-based typology

Landscape typologies are often based on a combination of expert-based rules and numerical analysis. A notable example of this approach is Meeus (1995), who developed the first approach towards a European landscape map by qualitatively combining information from national typologies, maps and scientific expertise. In several national typologies this method was also used, ranging from pure expert-based interpretation (e.g., Hungary; Márton, 1989) to the combination of thematic maps to form a composite map (e.g., Lithuania; Kavaliauskas & Veteikis, 2006). In general, expert-based landscape typologies can be described as top-down, hierarchical delineations in which the subdivision of an area is based on a synoptic view and usually executed by expert rules and supervised threshold selection. Such classifications are typically based on a limited number of variables to keep the interpretation of classification trees manageable (Maxwell & Buddemeier, 2002; Van Eetvelde & Antrop, 2009).

For the division of the land cover categories, we relied on the CORINE land cover classes: arable land, grassland, permanent crops and mosaic land cover. We reclassified the linear landscape elements map (van der Zanden et al., 2013) into two classes: presence and non-presence, to distinguish open and more enclosed landscapes. We chose the threshold for this division based on the correspondence with presence of known areas of enclosed landscapes within European typologies (bocage and semi-bocage) and documentation of the characteristics of these landscapes (e.g., Zimmermann, 2006 and the digitized version of the Meeus landscape map in Stanners & Bourdeau 1995). We aggregated the field size classes into three classes: small-scale (<1 ha), medium-scale (1–10 ha) and large-scale (>10 ha), based on presence of these classes in the study area. For the nitrogen input, we used the classes of the original dataset.

To delineate the landscape classes we developed an expert-based decision tree in order to follow a systematic classification of landscape types (Fig. 2). To prevent delineation of too many classes, we combined classes that overlapped in character into meaningful aggregates based on secondary information such as country reports, national typologies and informal consultation with landscape experts. Furthermore, if classes were negligible in area for the European Union (<1%) they were merged into higher level classes. For example, enclosedness is an important element of several grassland and mosaic landscapes, but had little value for distinguishing different arable landscape types (see Supplementary material D for all possible class combinations and related areas).

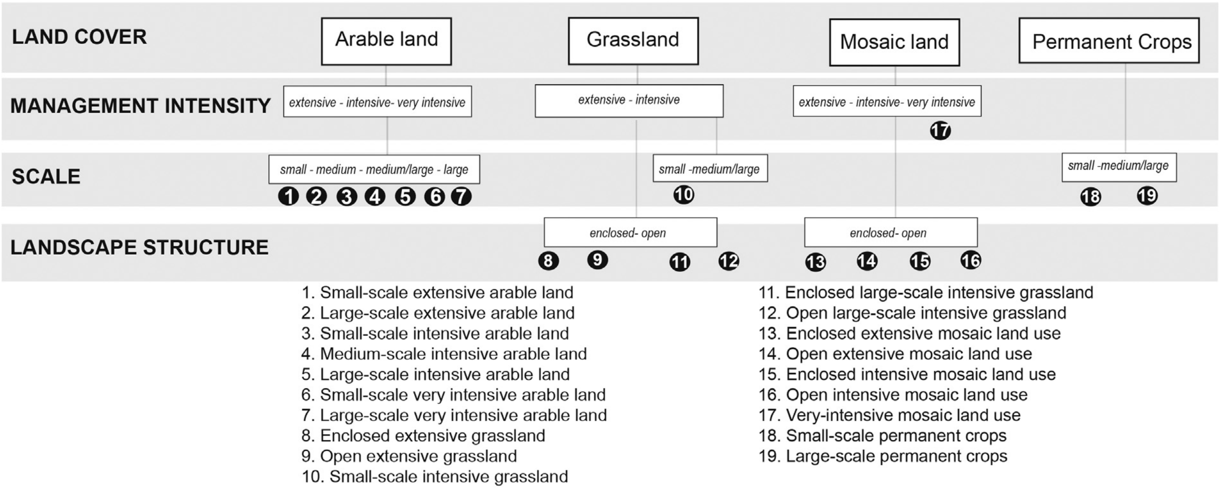


Fig. 2. Simplified version of the agricultural landscape classification decision tree. A detailed version of the expert-based decision tree is available in Supplementary material C.

2.3. Self-organizing maps

Automated clustering as a classification tool has been used in many landscape stratifications to visualize high-dimensional data in fewer, often two, dimensions. A method that includes both dimensionality reduction and clustering is the self-organizing map (SOM) algorithm (Kohonen, 2001). SOMs are based on an unsupervised competitive learning algorithm and are part of so-called Artificial Neural Networks (ANNs) techniques. The aim of SOMs is to reproduce the geographic topology of the input data, i.e., try to keep the same neighbors, while grouping the data and reducing their complexity. SOMs can therefore be thought of as a spatially-constrained form of k-means clustering (Ripley, 1996). SOM-based algorithms have been widely applied in various fields, including geographic information science (Agarwal & Skupin, 2008; Kohonen, 2001).

The general structure of an ANN consists of a set of input nodes and a set of output nodes, which are also described as neurons or processing/computational units. When using a k-mean clustering analogy, every computational unit in a SOM corresponds to a cluster and the number of clusters is determined by the size of the SOM grid (Wehrens & Buydens, 2007). In the standard procedure, the SOM algorithm is repeated for a number of successive iterations until the output nodes represent the input patterns that are closer to these nodes (vector quantization). During this iteration and optimization process, a non-linear relationship between the input data space and the SOM grid is established. Consequently, every sample in the dataset is mapped to the nodes, which "centroid" characteristics are represented by a codebook vector (vector projection). The SOM grid is usually arranged in a rectangular or hexagonal fashion, and presents the most similar units close to each other. Both the SOM grid type and the size of the SOM grid need to be determined before the algorithm is applied (Agarwal & Skupin, 2008). For a complete overview of the SOM methodology, see Kohonen (2001).

We conducted the SOM analysis in R, using the package 'kohonen' (Wehrens & Buydens, 2007). First, we normalized the variables by scaling them to zero mean and unit variance. For linear elements information, we used the reclassified map (presence/non-presence). An appropriate size of the output SOM grid depends on the input data and, in this case, on the meaningful and efficient representation of landscape categories. If the SOM grid is too small, many samples (pixels) will be mapped together, while empty clusters start to occur when the SOM grid is too large. We determined the size of the SOM grid by focusing on a natural breakpoint in the distance of the samples to the codebook vector of the SOM and the Davies–Bouldin clustering validity index. The Davies–Bouldin index represents the ratio of the sum of within-cluster scatter to between-cluster separation and, therefore, the objective is to minimize the index during a clustering procedure (Davies & Bouldin, 1979).

2.4. Comparison with other landscape classifications

To assess the relationship between our typology and widely used European datasets, we compared our expert-based and SOM typology with selected classifications that capture different dimensions of the agricultural landscape using MapCurves, a goodness-of-fit test for the spatial concordance of categorical maps (Hargrove, Hoffman, & Hessburg, 2006). This test indicates the degree of spatial overlap, or positive spatial correlation between maps with the same spatial extent. The goodness-of-fit (γ) equation we used was:

$$\gamma = \sum \left[\left(\frac{C}{B+C} \right) \left(\frac{C}{A+C} \right) \right]$$

The first term here indicates the proportion of category sharedness between two maps, determined by the intersection of a category between two maps (C) and the total area of a category on the reference map (B). The second term weights by fractional share of the category area; (A) is the total category area on the compared map. The score ranges between 0 and 100, with 100 being a perfect correspondence (Hargrove et al., 2006).

3. Results

3.1. Expert-based typology

Although the agricultural landscape types of the expert-based typology are generic across Europe, the spatial patterns of occurrence of the different agricultural landscape types showed clear regional differences (see Fig. 3, with a detailed legend in Fig. 4). Intensive arable land was present throughout Europe, but there was a distinct pattern of very intensive arable lands in Western Europe, with large-scale areas in France, Southeastern UK, Germany and the Po Valley (Northern Italy). The scale and intensity of arable land in the Mediterranean and Eastern European countries was more limited. Small-scale arable practice was limited to local areas, but also occurs throughout Europe. Dominant grassland landscapes were present in the countries in the Atlantic region and smaller areas

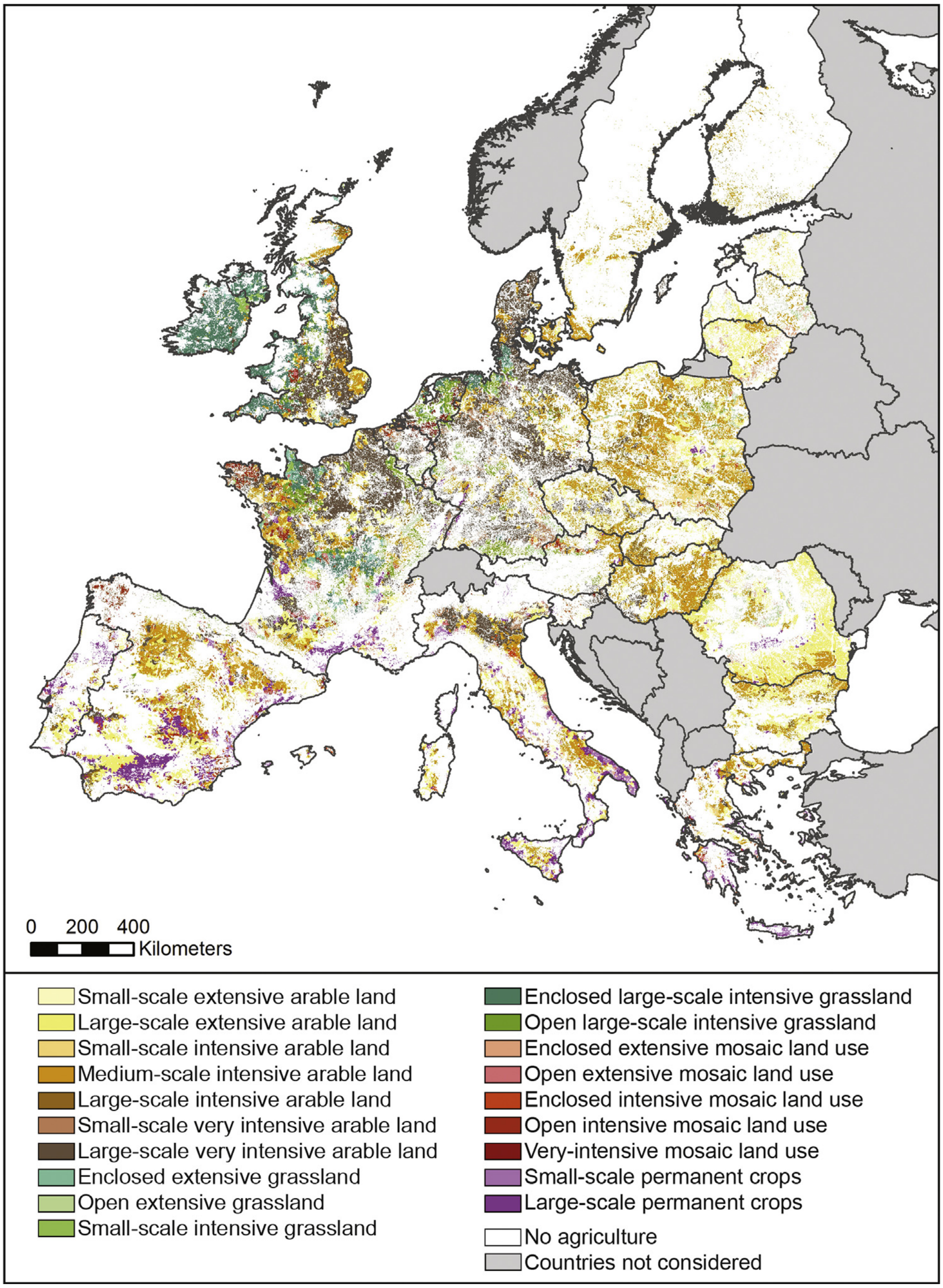


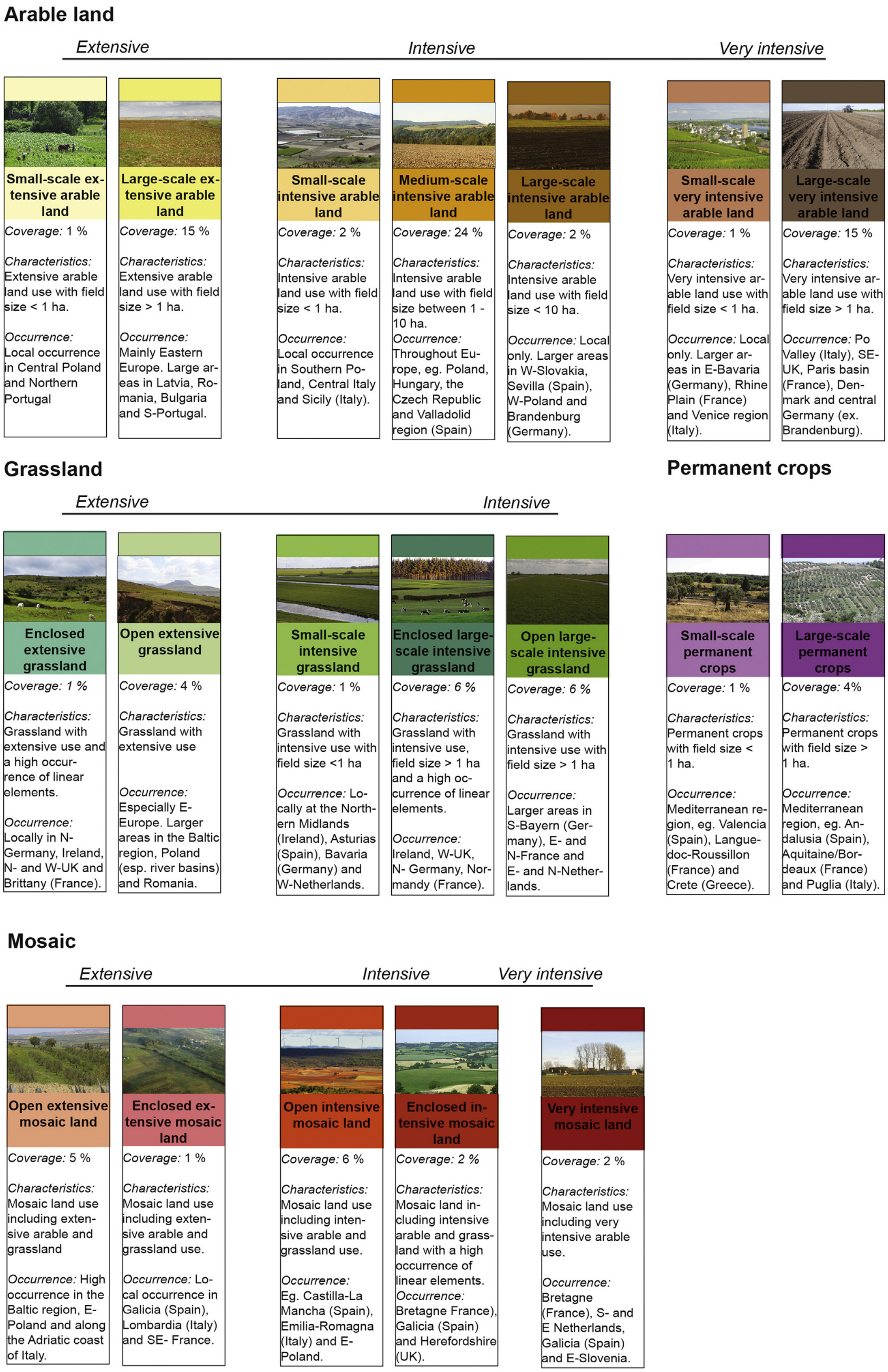
Fig. 3. Agricultural landscapes types as delineated by the expert-based typology. For visibility purposes, only areas >10 km^2 are displayed.

in Austria and Poland. For grassland, there was no clear regional divide between the more extensive and intensive areas. Enclosed grasslands occurred in large continuous areas; geographically limited to the Western UK and Ireland, Northern Germany, Northern Netherlands and North-West and Central France. The enclosed mosaic landscapes were generally linked to the enclosed grassland areas, with the exception of Galicia (North-West Spain) which was characterized by a mixture of extensive and intensive enclosed mosaic lands. The open mosaic landscapes occurred in different areas that were sometimes characterized by viniculture.

3.2. SOM results

The number of SOM clusters was determined by analyzing the natural breakpoints in a number of performance indicators upon an increase in number of clusters. Fig. 5 shows the mean and standard deviation of the distance of values to the codebook vector and the Davies–Bouldin Index value. The clustering indices showed a natural breaking point at 12 clusters. A further comparison of the resulting classifications of the 3 × 4 and 4 × 5 SOM grids confirmed that 12 clusters capture the main variation between the landscapes well.

A SOM plot gives information on the specific relationship between the input data and the SOMs (Fig. 6). The spatial location of the cluster in the segment plot indicates the similarity with the other clusters while the segments indicate the contribution of the different variables in determining the cluster. The segment plot indicates two general groups of agricultural landscapes: 1) arable landscapes that mainly vary in land management (top-right) and



Small-scale extensive arable land
Coverage: 1 %
Characteristics: Extensive arable land use with field size < 1 ha.
Occurrence: Local occurrence in Central Poland and Northern Portugal

Large-scale extensive arable land
Coverage: 15 %
Characteristics: Extensive arable land use with field size > 1 ha.
Occurrence: Mainly Eastern Europe. Large areas in Latvia, Romania, Bulgaria and S-Portugal.

Small-scale intensive arable land
Coverage: 2 %
Characteristics: Intensive arable land use with field size < 1 ha.
Occurrence: Local occurrence in Southern Poland, Central Italy and Sicily (Italy).

Medium-scale intensive arable land
Coverage: 24 %
Characteristics: Intensive arable land use with field size between 1 - 10 ha.
Occurrence: Throughout Europe, eg. Poland, Hungary, the Czech Republic and Valladolid region (Spain)

Large-scale intensive arable land
Coverage: 2 %
Characteristics: Intensive arable land use with field size < 10 ha.
Occurrence: Local only. Larger areas in W-Slovakia, Sevilla (Spain), W-Poland and Brandenburg (Germany).

Small-scale very intensive arable land
Coverage: 1 %
Characteristics: Very intensive arable land use with field size < 1 ha.
Occurrence: Local only. Larger areas in E-Bavaria (Germany), Rhine Plain (France) and Venice region (Italy).

Large-scale very intensive arable land
Coverage: 15 %
Characteristics: Very intensive arable land use with field size > 1 ha.
Occurrence: Po Valley (Italy), SE-UK, Paris basin (France), Denmark and central Germany (ex. Brandenburg).

Enclosed extensive grassland
Coverage: 1 %
Characteristics: Grassland with extensive use and a high occurrence of linear elements.
Occurrence: Locally in N-Germany, Ireland, N- and W-UK and Brittany (France).

Open extensive grassland
Coverage: 4 %
Characteristics: Grassland with extensive use
Occurrence: Especially E-Europe. Larger areas in the Baltic region, Poland (esp. river basins) and Romania.

Small-scale intensive grassland
Coverage: 1 %
Characteristics: Grassland with intensive use with field size <1 ha
Occurrence: Locally at the Northern Midlands (Ireland), Asturias (Spain), Bavaria (Germany) and W-Netherlands.

Enclosed large-scale intensive grassland
Coverage: 6 %
Characteristics: Grassland with intensive use, field size > 1 ha and a high occurrence of linear elements.
Occurrence: Ireland, W-UK, N- Germany, Normandy (France).

Open large-scale intensive grassland
Coverage: 6 %
Characteristics: Grassland with intensive use with field size > 1 ha
Occurrence: Larger areas in S-Bayern (Germany), E- and N-France and E- and N-Netherlands.

Small-scale permanent crops
Coverage: 1 %
Characteristics: Permanent crops with field size < 1 ha.
Occurrence: Mediterranean region, eg. Valencia (Spain), Languedoc-Roussillon (France) and Crete (Greece).

Large-scale permanent crops
Coverage: 4%
Characteristics: Permanent crops with field size > 1 ha.
Occurrence: Mediterranean region, eg. Andalusia (Spain), Aquitaine/Bordeaux (France) and Puglia (Italy).

Open extensive mosaic land
Coverage: 5 %
Characteristics: Mosaic land use including extensive arable and grassland
Occurrence: High occurrence in the Baltic region, E-Poland and along the Adriatic coast of Italy.

Enclosed extensive mosaic land
Coverage: 1 %
Characteristics: Mosaic land use including extensive arable and grassland use.
Occurrence: Local occurrence in Galicia (Spain), Lombardia (Italy) and SE- France.

Open intensive mosaic land
Coverage: 6 %
Characteristics: Mosaic land use including intensive arable and grassland use.
Occurrence: Eg. Castilla-La Mancha (Spain), Emilia-Romagna (Italy) and E-Poland.

Enclosed intensive mosaic land
Coverage: 2 %
Characteristics: Mosaic land including intensive arable and grassland with a high occurrence of linear elements.
Occurrence: Bretagne France), Galicia (Spain) and Herefordshire (UK).

Very intensive mosaic land
Coverage: 2 %
Characteristics: Mosaic land use including very intensive arable use.
Occurrence: Bretagne (France), S- and E Netherlands, Galicia (Spain) and E-Slovenia.

Fig. 4. Detailed legend for the agricultural landscapes as delineated by the expert-based typology.

2) mosaic and grassland landscapes defined by landscape structure (bottom-row).

The agricultural landscapes as delineated by the SOM typology are shown in Fig. 7. An interpretation describing the different clusters and the average values of the non-standardized values of the

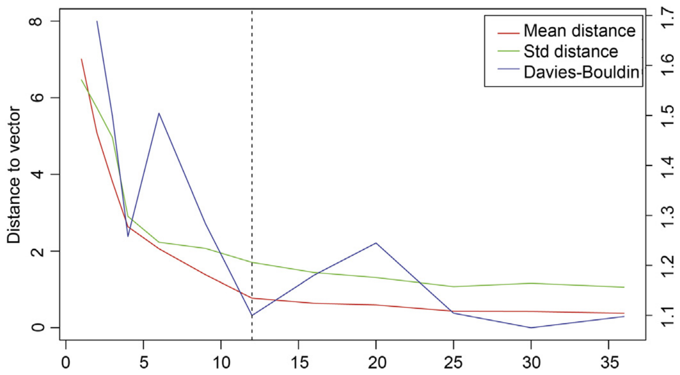


Fig. 5. Mean and standard deviation of the distance of values to the codebook vector and the Davies–Bouldin Index value for an increasing number of clusters.

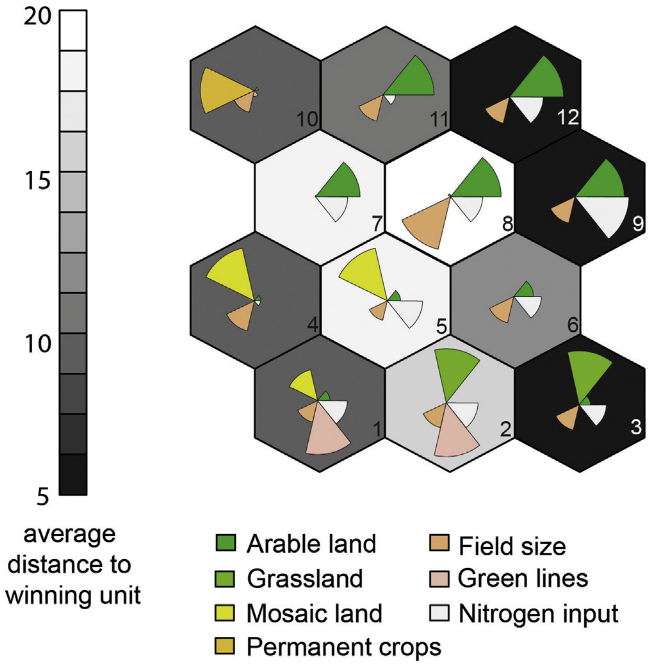


Fig. 6. Segment plot of 3 × 4 SOM clusters with their cluster number and the distance of each cluster to the winning unit.

different input datasets are available in Supplementary material E and F. Fig. 8 shows the map of the distance of each raster cell to the codebook vector, which can be regarded as a quality assessment of the classification procedure. Regions with a large distance to the winning SOM unit are Southern Spain, Northern Ireland and Brittany (North-West France). This indicates that in these regions, the assigned SOMs are not optimal to capture the variability in occurring agricultural landscapes.

3.3. Comparison between mapping approaches

Spatial comparison between the two different approaches used to construct the typology shows that there is, in general, a large overlap between classes. Such overlap between both methodologies is not surprising as both the expert-based and SOM method aim at classification of the diversity of the composition, spatial structure and management intensity of agricultural landscapes. An exact overlap exists between three SOM classes (cluster 8, 9 and 11) and expert-based classes (large-scale extensive arable land, medium-scale intensive arable land and large-scale very intensive arable land respectively), while cluster 10 is a combination of the small-scale and large-scale permanent crops classes. A cross-tabulation between the mapping approaches is available in Table 2.

In general, the differences are caused by the aggregation of the more specific expert-based categories in single classes in the SOM classification. For example, cluster 3 in the SOM ("enclosed grassland") includes both small-scale and enclosed grassland classes of varying intensity and scale. SOM cluster 12 ("large-scale arable land") includes large-scale arable classes from all intensities of the expert based typology. Some classes that are, from an expert perspective, important to distinguish are not sufficiently differentiated in the spatial data to appear as separate classes in the SOM typology.

3.4. Comparison with other typologies and national landscape classifications

To assess the relationship between our typology and widely used European datasets, we selected maps that capture different aspects of the agricultural landscape, including climate and biophysical dimensions. We included the climate-focused Environmental Stratification of Europe (EnS) and the LANMAP classification, which has four separate levels (Mücher et al., 2010). We also used the European Environment Agency (EEA) landscape types map, which is based on a neighborhood analysis of land cover types (EEA, 2006), the analogue Meeus landscape map as digitized in Stanners and Bourdeau (1995) and the Anthromes map (Ellis &

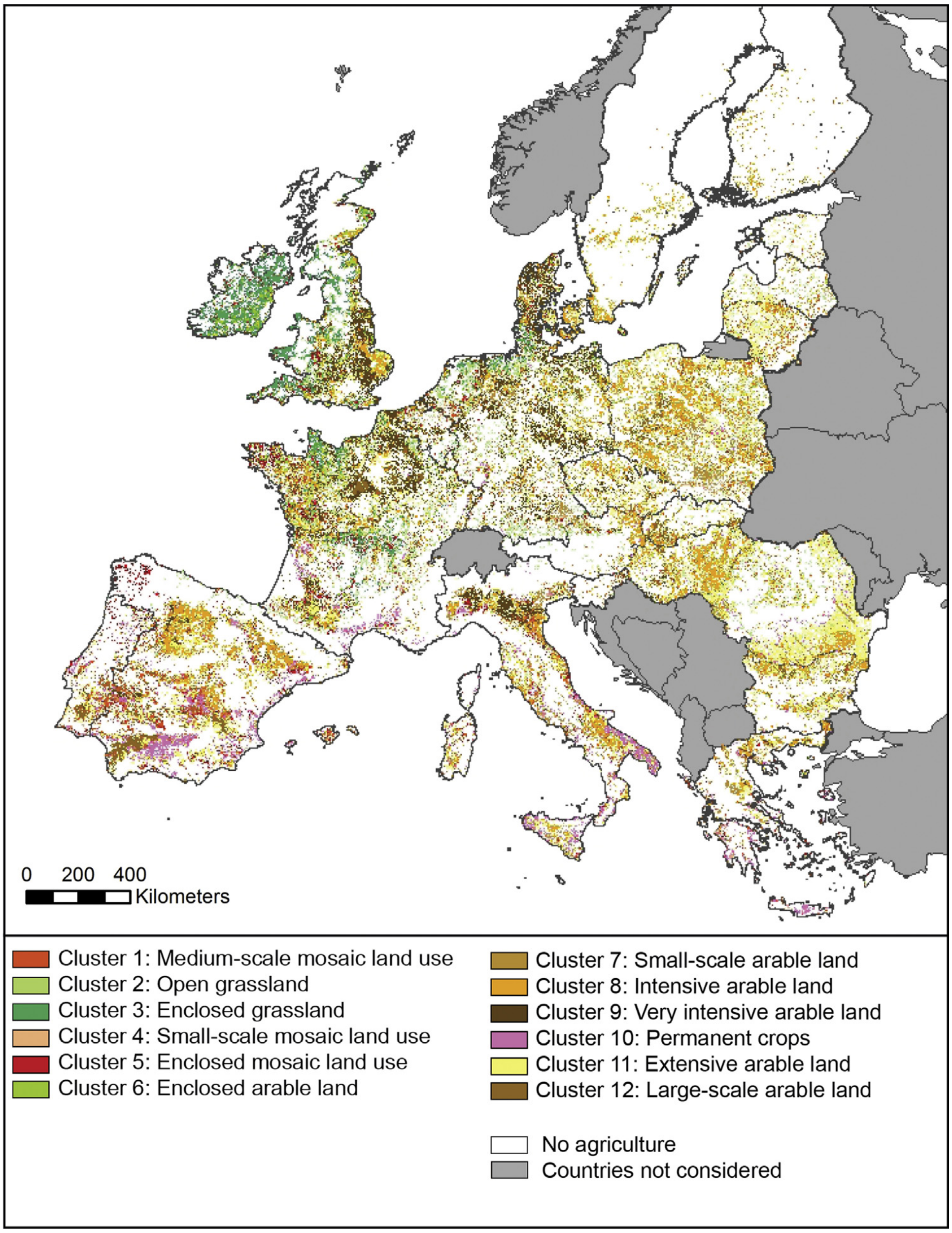


Fig. 7. Agricultural landscapes as delineated by the SOM based typology. A detailed legend is available in Supplementary material E.

Ramankutty, 2008), which is based on global data on population, land use and land cover.

The highest agreement exists between the SOM and the expert-based map (75.5%) developed in this study. These maps are not independent, due to the similar input data and similar aims. The results in Table 3 clearly show that our typologies capture very different dimensions of the agricultural landscape as compared to the other datasets, as the concordance with the other included datasets is low to very low (Hargrove et al., 2006). More specifically, the expert-based typology shows the highest concordance with the climate dimension of LANMAP (level 1), followed by the EEA land cover based map and the EnS climatic zones. These agreements were likely the result of the partial overlap of the “broad pattern intensive agriculture” of the EEA land cover based map with the medium intensive arable and very intensive arable land classes and by the overlap between the continental climate zone with very intensive arable areas. The SOM map also has a high agreement with the LANMAP level 1 and EEA dominant landscapes, followed by the Meeus map. This mainly is based on the enclosed grassland cluster, which has a high agreement with both “rural mosaic and pasture landscapes” (EEA) and “Atlantic Bocage” as delineated in the Meeus map.

Another European map useful for a comparison is the Types of Agriculture Map of Europe (Kostrowicki, 1984). While the map is outdated, the classification used compares well with our present work, as it accounts for the scale and intensity dimensions by using land use statistics, input-related statistics, production attributes and structural attributes (permanent crops, permanent grassland, and livestock). It was not possible to quantitatively compare this map as no digital version is available. A visual comparison with our typologies showed clear differences for the regions that faced widespread scale enlargement and intensification in the past 30 years, such as in Southern Denmark and the agricultural region around Paris (France). But we also found remarkable similarities, for example, between French regions with small-scale intensive

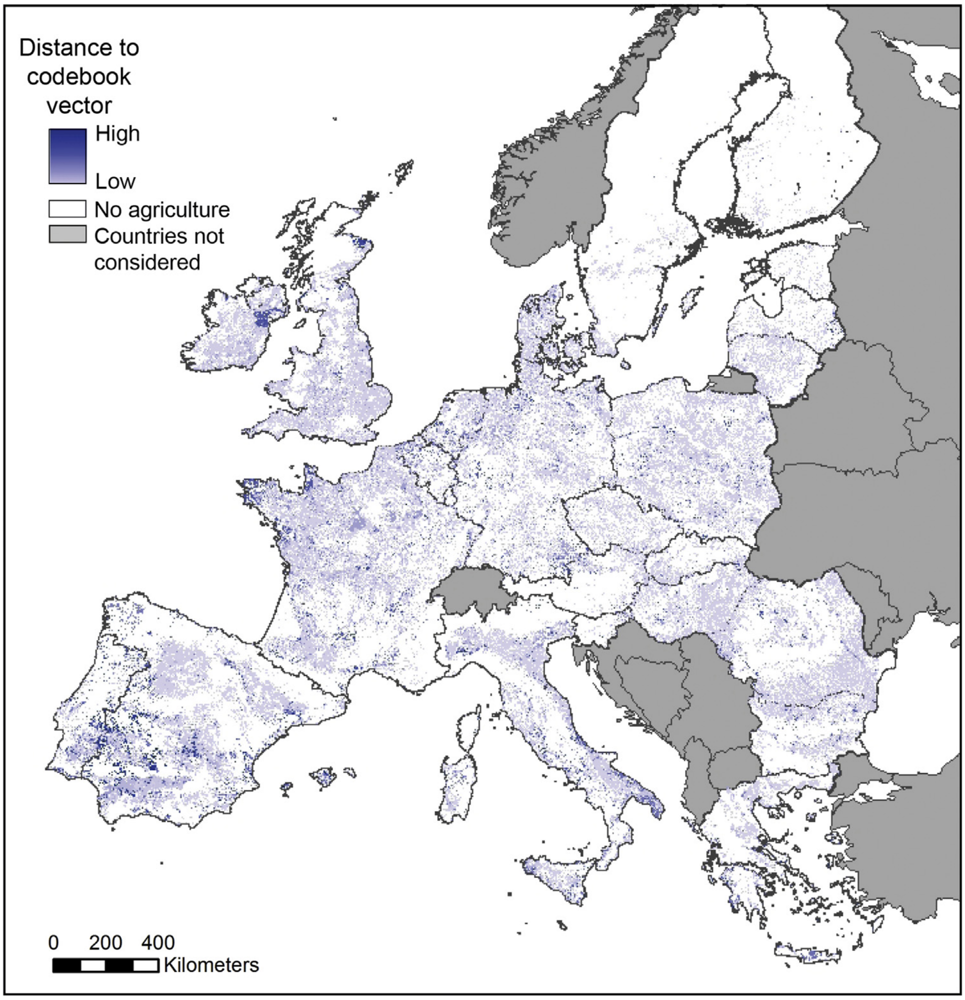


Fig. 8. Distances of raster cells to the codebook vector of the 3 × 4 SOM clusters. Low values indicate a good quality of mapping.

Table 2
Cross-tabulation between the expert-based and the SOM-based typology (in km^2).

Expert-based classes	SOM-based classes											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	0	0	0	941	17565	0	0	0	0	0
2	0	0	0	0	0	4521	0	0	0	0	172620	17587
3	0	0	0	0	0	1567	26836	0	0	0	0	0
4	0	0	0	0	0	13608	0	289765	0	0	0	0
5	0	0	0	0	0	820	0	0	0	0	0	24662
6	0	0	0	0	0	1431	15909	0	0	0	0	0
7	0	0	0	0	0	7980	0	0	171804	0	0	13669
8	0	0	13107	0	0	0	0	0	0	0	0	0
9	0	50640	0	0	0	0	0	0	0	0	0	0
10	0	9596	5155	0	0	0	0	0	0	0	0	0
11	0	0	71591	0	0	0	0	0	0	0	0	0
12	0	76235	0	0	0	0	0	0	0	0	0	0
13	50032	0	0	10180	0	0	0	0	0	0	0	0
14	0	0	0	0	14798	0	0	0	0	0	0	0
15	57888	0	0	13087	0	0	0	0	0	0	0	0
16	0	0	0	0	26407	0	0	0	0	0	0	0
17	16998	0	0	3578	6210	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	16589	0	0
19	0	0	0	0	0	0	0	0	0	53403	0	0

grassland (e.g., Normandy and S-Auvergne region) and small-scale mixed agriculture (e.g., Brittany).

A qualitative comparison of national landscape classifications shows that the classifications based on land cover display a similar general pattern with our European typologies, for instance in Austria (Schmitzberger, Szerencsits, & Wrbka, 2001) and the Czech Republic (Hrnciarová, 2009). A closer look at the German typology gives information on land cover and landscape structure dimensions (Gharadjedaghi et al., 2004). Major areas with hedgerows overlap with "enclosed grassland" areas, for instance along the

Table 3
Goodness-of-fit scores using MapCurves (Hargrove et al., 2006).

	SOM	Meeus[a]	Anthromes[b]	EnS[c]	EEA[d]	LANMAP l1[e]	LANMAP l2[e]	LANMAP l3[e]	LANMAP l4[e]
Expert-based	75.5	8.1	5.1	10.2	16.5	17.9	6.3	6.5	6.9
SOM		12.9	8.6	10.5	16.6	17.1	10.3	10.6	11.2
Meeus			4.9	17.7	13.9	30.7	11.7	11.0	13.2
Anthromes				11.3	11.9	16.0	5.2	4.7	5.4
EnS					12.4	26.0	15.1	15.5	17.8
EEA 10						14.5	12.4	12.5	13.0
LANMAP level 1							99.9	99.9	99.9
LANMAP level 2								100.0	100.0
LANMAP level 3									100.0

[a] Meeus (1995) as digitized in Stanners and Bourdeau (1995).
[b] Ellis & Ramankutty (2008).
[c] Metzger et al. (2005).
[d] EEA (2006).
[e] Mücher et al. (2010) with four levels: climate (1), altitude (2), parent material (3) and land cover (4).

western coastline of the North Sea, the Rhine border region with the Netherlands and around Göttingen (Central Germany). Our typology, however, underrepresents the hedgerow complexes of Baden-Württemberg (South-West Germany; Kantelhardt, Osinski, & Heissenhuber, 2003). While the "structural cultural landscapes" in Bavaria (Southern Germany) clearly overlap with both open and enclosed mosaic landscape classes, this is also not well reflected westwards (Bundesamt für Naturschutz, 2011; Gharadjedaghi et al., 2004).

4. Discussion

The shortcomings of landscape information on EU level (Vervloet & Spek, 2003; Wascher, 2004) hamper the comparison of agricultural landscapes across wider geographic scales. While agricultural typologies exist on the national and global scale (Václavík, Lautenbach, Kuemmerle, & Seppelt, 2013 ; van Asselen & Verburg, 2012), there is a need for a better description and representation of the variation in agricultural landscapes at the regional scale. Regional and EU-level policies on conservation and agriculture need to be adapted to the variation in local and regional context (Turner II, Lambin, & Reenberg, 2007; Verburg et al., 2013). Landscape typologies can provide insight and a reduction of the complexity of the variation in agricultural landscapes and thus help to inform and assess the regional needs and consequences.

4.1. *Evaluation of methods*

The evaluation of the quality and robustness of landscape typologies is challenging. To identify the most important components of the landscape represented in the typology, the selection process of the dimensions included should be clear and the scientific theory behind the conceptual framework should be communicated. Since most environmental datasets are continuous, the boundaries between the classes should be reproducible and without personal bias (Hazeu et al., 2011). This is, however, not easy to achieve given the continuous nature of environmental information (Metzger, Bunce, Jongman, & Mücher, 2005).

We used two different techniques to develop a landscape typology and in spite of the stark methodological differences (top-down vs. bottom-up) the outcomes show a high degree of agreement. The expert-based approach has the advantage that the construction of the typology is transparent and that the emerging classes are clearly interpretable. However, as in all expert-based typologies, personal judgment cannot be completely excluded (Jongman et al., 2006). The use of the SOM avoids some of these subjective decisions, since this method does not need a supervised classification set-up and instead searches for major structures and clusters without an a priori hypothesis (Agarwal and Skupin, 2008). Moreover, automated clustering methods can discover unknown patterns in the data, which an expert-based approach rules out. However, while SOM classes display the statistical optimal solution given the current information (and input data), transferring this typology to another dataset, e.g., representing future conditions, is challenging. Therefore, we recommend users to use the expert-based typology for future work.

Our typology compared favorably with many national-scale typologies and an outdated land management-based typology (Kostrowicki, 1984), indicating a correspondence of identified types with commonly denoted differences between agricultural landscapes. The typology was robust between the two approaches used, and adds useful dimensions of land management and landscape structure to existing typologies. At the same time, several points of uncertainty need to be discussed. The choice of included dimensions within the developed typology was constrained by data availability and quality on landscape properties and could be expanded by including information on historical or cultural landscape dimensions, especially in applications related to cultural heritage. While our typology takes some of these aspects into account by including landscape structure and field size, important information on e.g., historical features such as agricultural buildings and roads and aesthetic landscape features (e.g., Bastian, Walz, & Decker, 2013; Carvalho-Ribeiro et al., 2013) were missing, since this data is often limited to regions or specific for local sites (Van Eetvelde & Antrop, 2009). Furthermore, information on the social perception of agricultural landscapes could provide information on values and meaning embedded in the landscape. For example, Paracchini and Capitani (2011) presented the development towards an rural-agrarian landscape indicator in Europe, including a composite indicator of societal awareness of landscapes at sub-national administrative level (using protected products, rural tourism and protected areas), while van Zanten et al. (2014) made a systematic review of landscape preference studies in Europe. Another limitation of the current approach is the focus on agricultural areas as designated by the CLC data and the use of a majority rule in the aggregation of the land cover data to the 1 km^2 resolution. This may have caused certain heterogeneous mixed farming-forestry or semi-natural areas that are extensively grazed to be underrepresented in our map. Finally, since the developed typology focuses on generic agricultural landscape types across Europe, unique regional characters are generalized and this can therefore lead to an underestimation of the regional identity (Mücher et al., 2010).

A main factor affecting the quality of the typology is the quality and quantity of the input data. Sources of uncertainty are both related to the processing of the source data as well as to the reliability of ground-based inventories, such as LUCAS (Eurostat, 2013; Kuemmerle et al., 2013; Verburg, Neumann, & Nol, 2011). The European land cover data used has generally high accuracy, although identification of specific land cover classes can be problematic (Büttner & Maucha, 2006). Uncertainties in the other datasets are higher. Our own assessment of the uncertainty of the field size data and linear landscape element data (Supplementary material B and van der Zanden et al. (2013)) suggests reliability of these dimensions. Unfortunately, no full uncertainty analysis was conducted for the nitrogen input data due to a lack of validation data at the pixel level. Partial validation based on differences of nitrogen input in irrigated and non-irrigated land use showed, however, promising results (see Temme and Verburg (2011)). A further limitation of the nitrogen dataset is that the intensity measure is not continuous. Other European scale nitrogen datasets have been developed using comparable methods (e.g., Leip et al., 2011 for N flux budgets), but these are not publicly available. Alternative continuous mapping approaches, such as Teillard et al. (2012) are limited to certain countries and in spatial resolution. In general, the different datasets used are not based on data from the same reference year, which could cause some mismatches in regions with rapid change. Since most of the source data is updated every few years, a useful extension of our study would be the identification of typical change patterns in agricultural landscapes.

4.2. Applications

Our agricultural landscape typology and map can be used in a wide range of applications. First and foremost, our results may become a tool for communication between scientists, policy makers and others interested in agricultural landscapes. A harmonized approach such as ours can help identify and characterize policy areas of attention, for instance on the linkages between cultural landscapes, landscape structure and biodiversity conservation. This new typology can also serve as a starting point for further analysis, as a first phase of more detailed regional characterization, or as a tool to compare case studies across different agricultural landscapes in Europe. An example is the application of the map to determine the distribution of landscape preference case studies across different agricultural landscape types by van Zanten et al. (2014). Our results can also serve as a basis for sampling, or the (pre-) selection of study sites (Hazeu et al., 2011; Mücher et al., 2010).

Our typology can also be a useful tool for the assessment of multiple ecosystem services across agricultural landscapes, since spatial diversity and landscape structure influence service provision. An interesting application of our typology would thus be to use the agricultural landscapes we identified as units to summarize ecosystem bundles (Bennett, Peterson, & Gordon, 2009). Land management and structure are also considered important elements for modeling or comparing individual ecosystem services, such as pollination (Schulp, Lautenbach, & Verburg, 2014) and landscape aesthetics (Gobster, Nassauer, Daniel, & Fry, 2007) and can therefore serve as a basis for mapping these services. Especially since the vast majority of ecosystem services studies use lookup tables and benefit transfer-based mapping based on land cover, ignoring the role of important landscape features and configurations. Also for the mapping of more 'intangible' cultural ecosystem services, Plieninger et al. (2013) acknowledge the need for information on landscape properties beyond land cover, for instance for preselection of sites for the assessment of cultural landscape services or to combine with more fine-grained landscape or stakeholder information (Norton, Inwood, Crowe, & Baker, 2012). The typology of agricultural landscapes in Europe presented here explicitly acknowledges the variation within agricultural areas important to the functioning and values of these landscapes and moves beyond the standard approach of characterizing differences in landscape and land use by the dominant land cover only (e.g., Busch, 2006; Verburg et al., 2013).

5. Conclusion

The influence of land management intensity and landscape structure on the spatial variation of agricultural landscapes has received little attention in Europe, while these factors are important for assessing landscape functions and values. To improve the understanding of agricultural landscapes across Europe and to identify landscapes that may require policy response, it is necessary to reduce the complexity in agricultural landscapes to manageable units. During the past 20 years, different initiatives have been developed to identify and classify landscapes in Europe, but important management dimensions, including land management intensity and landscape structure, have not been included in these initiatives. To fill this gap, we have developed a Europe-wide spatially-explicit typology and inventory of agricultural landscapes, using Europe-wide datasets representing land cover, land management intensity and landscape structure on a 1 km^2 resolution. We have compared two alternative mapping approaches: an expert-based top-down, and a bottom-up approach based on automated clustering using self-organizing maps (SOMs).

Despite the clear difference in typology delineation methodology (top-down vs. bottom-up) the outcomes do not differ greatly. Comparison with national-scale typologies, a dated land management typology and other Europe-wide datasets revealed that the developed typology was robust and added useful dimensions to existing typologies. Improvement is possible, for instance by including information on historical and cultural dimensions, which was currently limited by data availability and quality. The quality and quantity of the input data remains influential, e.g., by including non-continuous input data sets. Overall, the typology aimed to provide a generic basis (i.e., independent from specific location or geographic context) for agricultural landscape assessment, complementary to current biophysically focused classifications and typologies. Therefore, it can be seen as a first step towards a comprehensive regional framework for comparison of agricultural landscapes across Europe.

Acknowledgements

The data are available upon request to the corresponding author.

This work was supported by the VOLANTE, HERCULES and CLAIM projects, all funded by the European Commission (FP7 Programme), and the Einstein Foundation Berlin, Germany. The authors would also like to thank the participants of the MSc course Land System Science' at the Geography Department of Humboldt University Berlin in 2013 for their assistance. Emiel van Loon is thanked for the MapCurves script.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landurbplan.2016.02.005.

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