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Post Hoc Assessment of Stand Structure Across European Wood-Pastures: Implications for Land Use Policy☆

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ABSTRACT

Europe's woodland and savanna rangelands, often part of silvopastoral systems known as *wood-pastures*, are deteriorating because of abandonment that leads to return to a forested state or lack of tree regeneration from overgrazing or tree and shrub removal. Despite numerous local studies, there has been no broader survey of the stand structure of European wood-pastures showing which systems are at risk of losing their semiopen character. This overview aims to 1) show some of the differences and similarities in wood-pastures from landscapes across Europe and 2) identify which of these wood-pastures are at risk of losing their semiopen character. We collated a dataset of 13 693 trees from 390 plots in wood-pastures from eight different European regions (western Estonia, eastern Greece, northern Germany, Hungary, northern Italy, southern Portugal, central Romania, and southern Sweden), including tree diameters at breast height, tree density, management type, and tree species composition. On the basis of their structural characteristics, we classified wood-pastures using principal component analysis (PCA) and cluster analysis. The PCA showed a gradient from dense wood-pastures with high levels of regeneration (e.g., in Estonia) to sparse wood-pastures with large trees but a lack of regeneration (e.g., in Romania). Along this gradient, we identified three main groups of wood-pastures: 1) sparse wood-pastures with mostly big trees; 2) dense wood-pastures composed of small trees, and 3) wood-pastures containing a wide range of tree ages. Our results show a large structural gradient in European wood-pastures, as well as regeneration problems varying in their severity, highlighting the importance of social-ecological context for wood-pasture conditions. To maintain the ecological and cultural integrity of European wood-pastures, we suggest 1) more comprehensively considering them in European policies such as the Common Agricultural Policy and EU Habitats Directive, while 2) taking into account their structural characteristics and social-ecological backgrounds.

Introduction

Woodland and savannah, rangelands with a semiopen tree canopy, represent the largest percentage of the world's rangelands (McKell et al., 1972; Platou and Tueller, 1988). In Europe they are typically part of silvopastoral systems known as *wood-pasture* (Bergmeier et al., 2010). The most well-known European wood-pastures are the Mediterranean oak woodlands of the Iberian Peninsula, generally referred to as *dehesas* or *montados*, but wood-pastures can be found in many other parts of Europe. Wood-pastures are permanent grassland combined with

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scattered trees or groups of trees or shrubs, often with large old trees functioning as keystone structures, and often forming ecotones between grasslands and forest (Bergmeier et al., 2010; Lindenmayer et al., 2014).

Human impact has shaped the structure of wood-pastures in Europe for thousands of years (Hartel and Plieninger, 2014; Jørgensen and Quelch, 2014; Hartel et al., 2015). Since their origin in the early Holocene (Bergmeier et al., 2010), wood-pastures have developed as social-ecological systems from forest-based livestock grazing to semiopen landscape elements, shaped by not only biogeographic and environmental conditions, such as climate, elevation, and soil, but also the needs of local people (Chételat et al., 2013; Huber et al., 2013; Bergmeier and Roellig, 2014; Hartel and Plieninger, 2014). The resulting mosaics of grassland with shrubs and trees of different ages, as well as variable light and shade conditions, provide important habitat for a wide range of plant, invertebrate, bird, and mammal species, many of which are threatened at local or landscape scales (Bergmeier and Roellig, 2014; Falk, 2014; Garbarino and Bergmeier, 2014; Hartel et al., 2014; Roellig et al., 2014). Moreover, wood-pastures can contribute to landscape connectivity (Fischer and Lindenmayer, 2002) and adaptation to climate change (Manning et al., 2006, 2009) as well as retain cultural values, including heritage, traditional knowledge, aesthetic, and recreational values (Sutcliffe et al., 2014; Varga and Molnár, 2014; Plieninger et al., 2015).

Despite their shared origin in forest-based livestock grazing, today wood-pastures across Europe are highly varied because of differences in past and present practices in grazing and tree management (Hartel et al., 2013; Bergmeier and Roellig, 2014; Plieninger et al., 2015). Therefore the structure of wood-pastures differs in tree species composition, density, distribution, and the age distribution of trees (approximated by the distribution of stem diameter classes) (Garbarino and Bergmeier, 2014; Hartel et al., 2015). Tree density can range from only a few trees per hectare (ha) to up to 500 per ha (Garbarino et al., 2011; Hartel et al., 2013). Abandoned wood-pastures with dense shrub regeneration can reach densities of woody vegetation that are higher by yet another order of magnitude (Varga et al., 2015; Roellig et al., 2016). The spatial arrangement of trees also differs significantly across Europe (Garbarino and Bergmeier, 2014). In the absence of tree management and under low grazing pressure, trees can form a nearly closed canopy. Wood-pastures with long-term traditional management, on the other hand, typically exhibit a relatively sparse distribution of trees, and where trees are planted (e.g., on the Iberian peninsula), their distribution can have close to a regular pattern (Pulido et al., 2001; Plieninger and Schaar, 2008). The time since wood-pasture establishment, together with the management and distribution of trees, also influences the distribution of stem diameter classes (Plieninger et al., 2003; Fischer et al., 2009). While natural and seminatural forest typically show a high proportion of young trees, the diameter distribution of trees in wood-pastures often follows a bell curve (Pulido et al., 2001; Plieninger et al., 2003; Fischer et al., 2009). Long-term intensive grazing and tree removal have led to a shift towards larger size classes, indicating a lack of regeneration (Bauer and Bergmeier, 2011; Plieninger et al., 2011). In abandoned wood-pastures, larger trees surviving from the former land use tend to become crowded by younger trees, resulting in an increase in the lower diameter classes (Plieninger et al., 2003; Rapp and Schmidt, 2006; Varga et al., 2015).

Despite their cultural and ecological importance, wood-pastures are facing multiple threats (Bergmeier and Roellig, 2014). A lack of regeneration due to overgrazing and the removal of wooded structures, as well as forest regrowth due to abandonment and subsequent shrub-encroachment, are two main threats to their persistence (Bergmeier and Roellig, 2014). A key challenge is that the management of wood-pastures is often not economically profitable anymore (Plieninger et al., 2015). Traditional management is typically labor intensive but economically less feasible than other grazing systems (Bergmeier et al., 2010; Roellig et al., 2016). Another major influence on wood-pastures are national and European Union (EU) land use policies. These policies often do not formally recognize wood-pastures, and even if they do, they are very insufficient or they treat wood-pastures as homogenous systems across Europe, ignoring the actual and historic variability of these habitats (Peeters, 2012; Beaufoy, 2014; Jakobsson and Lindborg, 2015). For example, wood-pastures with > 100 trees per ha are usually not eligible for the subsidies for agricultural land (single-area support payments [SAPs]) of the EU's Common Agricultural Policy (CAP) (Beaufoy et al., 2015). Furthermore, nature conservation policies such as the EU Habitats Directive recognize only four types of wood-pastures (e.g., *Fennoscandian* wooded pastures, *Juniperus communis* formations on heath or calcareous grasslands, *Arborescent matorral* with juniper, and *Dehesa* with evergreen oaks). Other wood-pasture types receive neither formal recognition nor protection at EU level (Bergmeier et al., 2010; Plieninger et al., 2015).

Despite a considerable number of local studies on the stand structure of wood-pastures (Plieninger, 2007; Plieninger et al., 2003; Pulido et al., 2001), there has been no comprehensive overview of the stand structure of wood-pastures in Europe showing which systems are most at risk of losing their semiopen character. To provide such an overview, in this study we aim to 1) show some of the differences and similarities in wood-pastures from different landscapes across Europe in terms of their tree species composition and stand structure, and on this basis 2) identify which of these wood-pastures are at risk of losing their semiopen character. To achieve these aims we compiled data on tree structures in wood-pastures from different landscapes across Europe.

Methods

Data Collection

To describe different wood-pasture systems across Europe we conducted a post hoc comparison largely drawing on existing datasets. To make sure data were comparable, existing data sets needed to have a minimum set of common descriptors including information on plot size, numbers of trees per plot (to calculate the tree density), diameters at breast height (DBH), and species (at least genus) for all surveyed trees within the plot. Management type (grazed or ungrazed) and geographical coordinates were also collected. Following these criteria, we collected a large dataset of 390 plots located in wood-pastures, broadly distributed throughout different parts of Europe (western Estonia, northern Germany, eastern Greece, northern Italy, southern Portugal, central Romania and southern Sweden, Hungary) (Fig. 1).

Data Limitations

Because our analysis is based on a post hoc comparison, the plots are not strictly representative of European wood-pastures and some regions known for their wood-pastures are missing (e.g., Spain, France, and England) because available data did not meet the above criteria. Notably for our data, sampling methods differed between plots and involved random to systematic sampling, in temporary or permanent plots. The plots always represented a subset of a wood-pasture, often placed subjectively in the center of a wood-pasture or in an area of representative tree cover (Table 1). To account for variable plot sizes, a standardized trees-per-ha density variable was developed for each wood-pasture. In addition, we calculated all structural variables (see later) per plot. Varying plot sizes were required to appropriately cover the different structural characteristics of a given wood-pasture. We caution that these inherent limitations to our post hoc comparison be kept in mind. Notwithstanding these limitations, our resulting dataset covered a wide sociogeographical range across Europe and, to the best of our knowledge, is the first of its kind that integrates quantitative data across multiple countries and datasets.

Tree Data

In each plot all trees that reached breast height were measured and identified. Because of the differences in sampling design, some of the

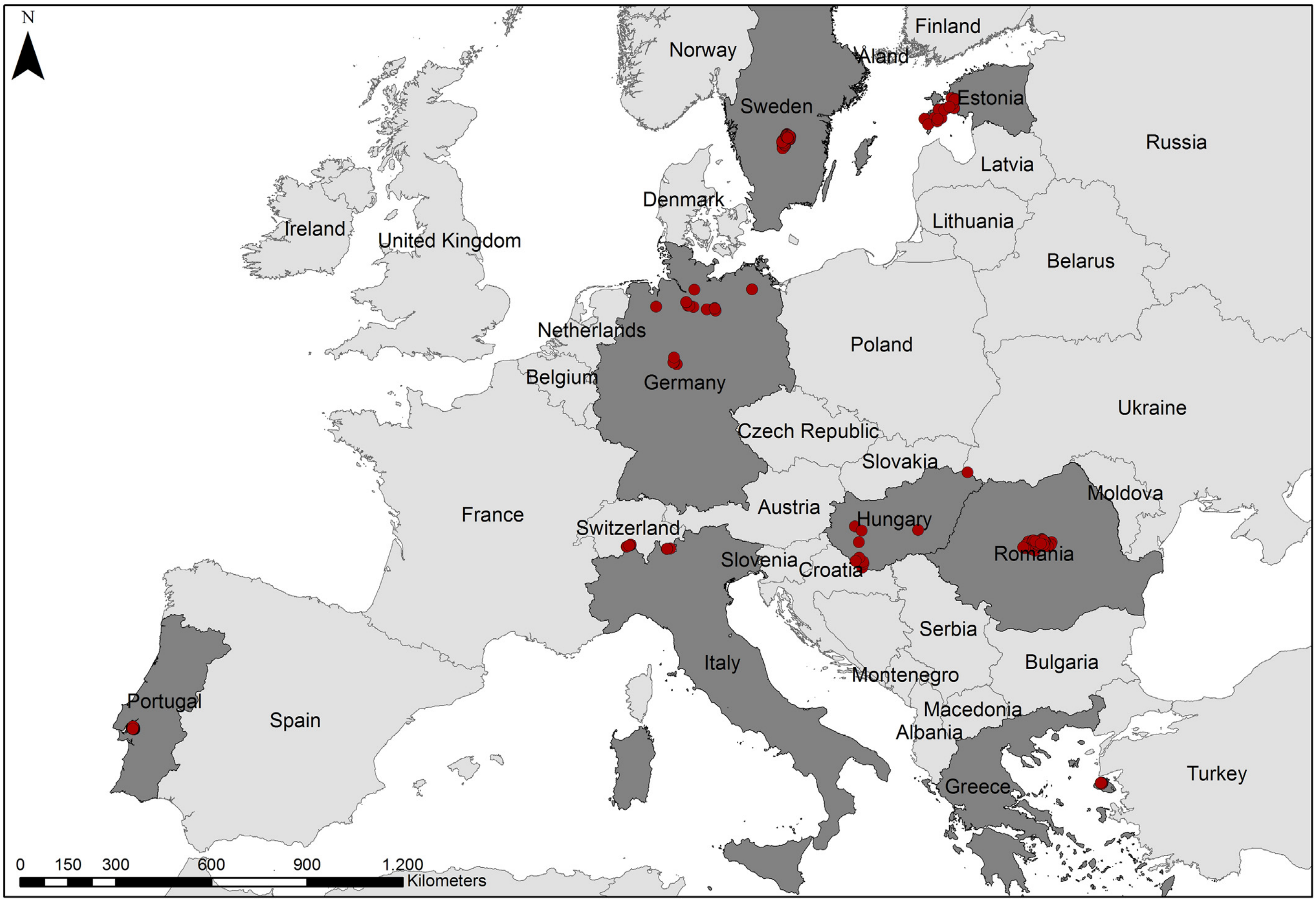

Figure 1. Study areas in Europe, showing the study regions for Estonia, Germany, Greece, Hungary, Italy, Portugal, Romania, and Sweden.

included datasets included trees, as well as tall shrubs species (e.g., such as hazel [*Corylus avellana*] and hawthorn [*Crataegus* spp.]). For data comparability, trees were defined for our study as woody plant species usually having one or few self-supporting stems, with a well-defined crown and being part of the canopy layer (> 5-m total height) when fully grown (Di Gregorio, 2005). Under this definition, tall shrub species were not considered and were excluded before analysis. Trees were usually identified to species level. In some plots, difficult-to-distinguish trees were only recorded at the genus level. For example, in plots from central Romania, sessile oak *(Quercus petraea)* and English oak *(Quercus robur)* were pooled as "oaks" (*Quercus* spp.) and in plots from western Estonia, birch (*Betula* spp.) species were pooled.

Table 1
Sampling design used to assess wood-pasture structure in eight European countries.

Country	Yr of data collection	Plots total	Plots grazed	Plots ungrazed	Plot size (ha)	Sampling design
Estonia	2013	30	20	10	0.0625	Pastures were chosen to cover old, restored, and abandoned pastures (10 in each category). Plots were subjectively placed in the center of each wood-pasture (see Roellig et al., 2016).
Germany	2013/ 2014	20	10	10	0.0625-0.5	Pastures were chosen to cover grazed and not grazed pastures (10 in each category). Plots were subjectively placed in the center of each wood-pasture (unpublished data).
Romania	2012	39	37	2	2	Pastures were chosen to cover average wood-pastures in the region. Plots were subjectively placed in the center of each wood-pasture (see Hartel et al., 2013).
Sweden	2013	64	64	0	0.8–1.39	Pastures were chosen to cover a large tree density gradient, from 0 to 214 trees/ha, of grazed wood-pastures. Plots were subjectively placed in a representative area of each pasture, in an area with homogeneous tree density (see Jakobsson and Lindborg, 2015).
Greece	2009	71	65	6	0.071	Pastures were chosen through a random-walk procedure, covering 5 clusters of contrasting site characteristics (distance to village, slope, aspect, and altitude). Plots were subjectively placed in the centre of each pasture (see Plieninger et al., 2011)
Hungary	2013-2014	10	10	0	0.1	Pastures were chosen to cover average grazed pastures. Plots were subjectively placed to include representative area of each pasture with an average tree density of the pasture within the plot (unpublished data).
Italy	2011	11	9	2	0.045-1	Temporary circular plots (Garbarino et al., 2013) and permanent quadrat plots (Garbarino et al., 2011) were chosen to cover grazed and abandoned subalpine wood-pastures.
Portugal	2007	148	148	0	0.2	Wood-pastures were chosen to cover a large cork oak woodland area with native pasture areas intercropped with grazing areas in a state-owned farm. Plots were placed using a systematic sampling design for cork oak forest inventory (see Costa et al., 2008, 2010).

Data Analysis

To assess composition of tree species we determined the 10 most abundant trees (species or in some cases genus) per wood-pasture in a given country. In order to characterize the structure of each survey plot, we calculated the mean, median, kurtosis, skewness, interquartile range, total range, standard deviation, and the 10% and 90% quantiles of the plot-level DBH distribution. On the basis of the number of trees per plot and plot size, we also calculated tree density per ha for comparison. All variables, except skewness, were not normally distributed and therefore were log-transformed before further analysis. In addition, all variables were scaled. With the resulting set of variables, we then performed a principal components analysis (PCA) to explore relationships between plots and countries. In the next step we performed a cluster analysis on the same variables, using the "Ward" method with the Euclidean distance as suggested by Dytham (2011), to classify wood-pastures across Europe. Ward's clustering was chosen because it usually produces clear group structures (no problems with chaining), and the resulting clusters were readily interpretable (Legendre and Legendre, 2012). All analyses were performed using the "stats" package in the software R (version 3.0.2, The R Foundation, Vienna, Austria) (R Core Team, 2013).

Results

In general the structure of our surveyed wood-pastures across Europe was highly variable, sometimes even within geographically similar regions. The tree density of wood-pastures in our plots ranged from 2 trees per ha (central Romania) to almost 5 000 trees per ha (western Estonia) across different regions in Europe, but also from 4 to 263 trees per ha within a region (southern Sweden). In plots in central Romania, followed by plots from Hungary, we found the highest DBH values, but also the highest range and standard deviation (Table 2). The lowest DBH values were found in plots in western Estonia, northern Germany, and southern Sweden. In northern Germany the DBH distribution in our plots was the most skewed and the narrowest. In our plots in Portugal, in contrast, DBH in wood-pastures was relatively normally distributed as judged by skewness and kurtosis values (see Table 2).

Species Occurrence

Overall, at least 55 tree species were recorded in our wood-pasture plots across Europe (for full species list see Appendix 1, available online at https://doi.org/10.1016/j.rama.2018.04.004). In our plots in Hungary, we found at least 19 species in all wood-pastures sampled; however, information on willow species (*Salix* spp.) was only collected at genus level. In plots from southern Sweden we found 19 species, and in our plots in northern Germany 18 species were recorded. At least 16 species were found in plots in western Estonia, where we had information on birch (*Betula* spp.) and willow only at the genus level. We identified at least 11 species in wood-pastures in plots in central Romania, with genus-level data for maple (*Acer* spp.), birch, ash (*Fraxinus* spp.), spruce (*Picea* spp.), willow, and lime (*Tilia* spp.). In Eastern Greece, 10 species were found in our plots, in northern Italy 4, and in Portugal only 1 (Fig. 2).

Some regions had high species richness in total, but a high percentage of individuals belonged to the three most abundant species. In the sampled wood-pastures in Hungary we found 19 species, but the three most abundant species together accounted for 63% of all trees (see Fig. 2). In plots from northern Germany (18 tree species), 73% of all trees were the three most abundant tree species, and in sampled plots of western Estonia 3 out of 16 tree species accounted for 50% of all trees. In sampling plots in eastern Greece and central Romania we found fewer tree species in total, and the three most abundant ones comprised up to 90% of all the trees. In surveyed plots from northern Italy the three most abundant tree species were almost 100% of the trees, while in our plots in Portugal 100% of the cover was of only one tree species.

Across all plots (except plots from Northern Italy), oak species (*Quercus* spp.) were among the three main species. Oak was most abundant in plots from Hungary, central Romania, eastern Greece, and southern Portugal. In plots from western Estonia and southern

Table 2

Minimum, maximum, and average values for the structural variables based on the DBH of plots in wood-pastures for each country. Minimum and maximum values for each variable are indicated in bold

		Mean	Median	Mode	Kurtosis	Skewness	IQR[1]	Range	SD[2]	Density	10%[3]	90%[4]
Estonia	Minimum	**3.75**	2.40	1.00	-1.93	-0.18	0.70	**1.30**	**0.53**	80.00	1.06	**5.94**
	Maximum	26.80	25.50	50.00	27.36	4.85	35.30	82.89	17.13	**4944.00**	15.98	49.66
	Average	14.51	12.54	10.90	4.01	1.42	11.12	42.97	9.64	945.60	5.25	25.59
Sweden	Minimum	7.17	**1.00**	1.00	-2.17	-0.89	9.00	27.00	8.80	4.00	1.00	21.00
	Maximum	46.36	50.00	57.00	8.09	2.43	41.00	125.00	26.08	263.00	26.80	67.70
	Average	22.61	21.12	15.02	0.76	0.65	18.71	64.44	14.72	83.55	5.96	40.56
Germany	Minimum	5.02	1.20	**0.00**	-1.39	-0.87	1.35	22.60	7.06	86.00	0.30	8.34
	Maximum	60.04	63.35	60.00	**55.23**	**7.18**	42.00	125.30	31.44	3504.00	45.80	88.32
	Average	25.37	19.81	14.75	4.96	1.65	21.74	82.03	20.02	876.86	7.56	49.82
Hungary	Minimum	17.59	8.00	5.00	-1.83	-0.53	8.44	21.34	9.41	40.00	5.00	54.00
	Maximum	108.37	116.00	143.00	7.42	2.85	**119.00**	175.80	58.89	3980.00	84.78	155.60
	Average	62.12	58.26	53.90	0.37	0.54	45.12	126.02	35.11	687.00	27.17	108.04
Greece	Minimum	15.02	13.69	10.00	**-2.75**	-0.71	**0.48**	2.88	2.04	28.29	9.99	18.27
	Maximum	52.15	48.70	68.00	10.65	3.35	29.76	82.97	32.68	778.04	42.27	76.27
	Average	24.29	22.78	22.47	-0.28	0.58	11.04	30.62	9.63	251.60	14.92	34.68
Romania	Minimum	28.17	15.60	8.00	-1.94	-1.67	11.38	35.33	11.64	**2.00**	8.28	64.74
	Maximum	**124.24**	**146.10**	**162.00**	3.98	1.82	100.75	**197.35**	**59.38**	16.00	**99.95**	**203.50**
	Average	77.29	76.28	62.44	-0.74	0.11	33.71	85.07	26.24	8.09	48.09	106.21
Italy	Minimum	14.13	7.50	10.00	-2.25	-1.10	3.50	25.00	11.09	88.00	4.70	26.20
	Maximum	47.87	56.00	64.00	4.76	2.23	38.88	85.50	24.63	332.00	35.40	75.50
	Average	34.02	32.02	38.64	-0.37	0.44	22.58	56.55	18.10	190.09	16.82	53.25
Portugal	Minimum	15.98	12.41	0.00	-2.21	**-1.91**	0.96	10.82	3.20	25.00	**0.00**	22.54
	Maximum	61.50	64.30	83.00	8.06	2.78	33.42	86.58	27.02	265.00	55.51	70.83
	Average	31.72	30.87	30.09	-0.23	0.29	13.37	40.18	11.72	76.39	19.61	44.47

1 Interquartile range.
2 Standard deviation.
3 10% Quantil.
4 90% Quantil

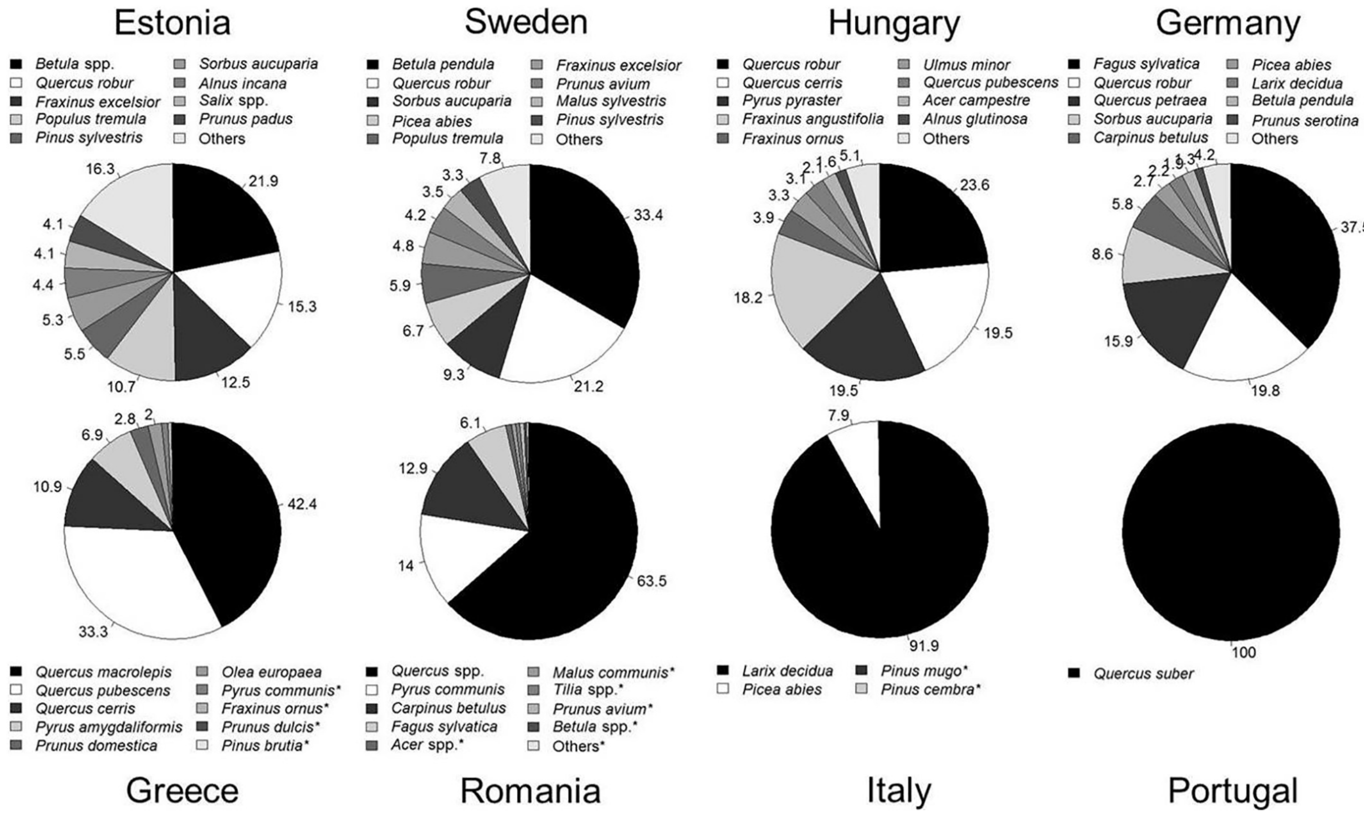

Figure 2. Average proportion of tree species in wood-pastures per country as percentages. If > 10 species were present, only the 9 most common are presented. The rest is grouped under "others." Species with a percentage under 1% are marked with an asterisk (*).

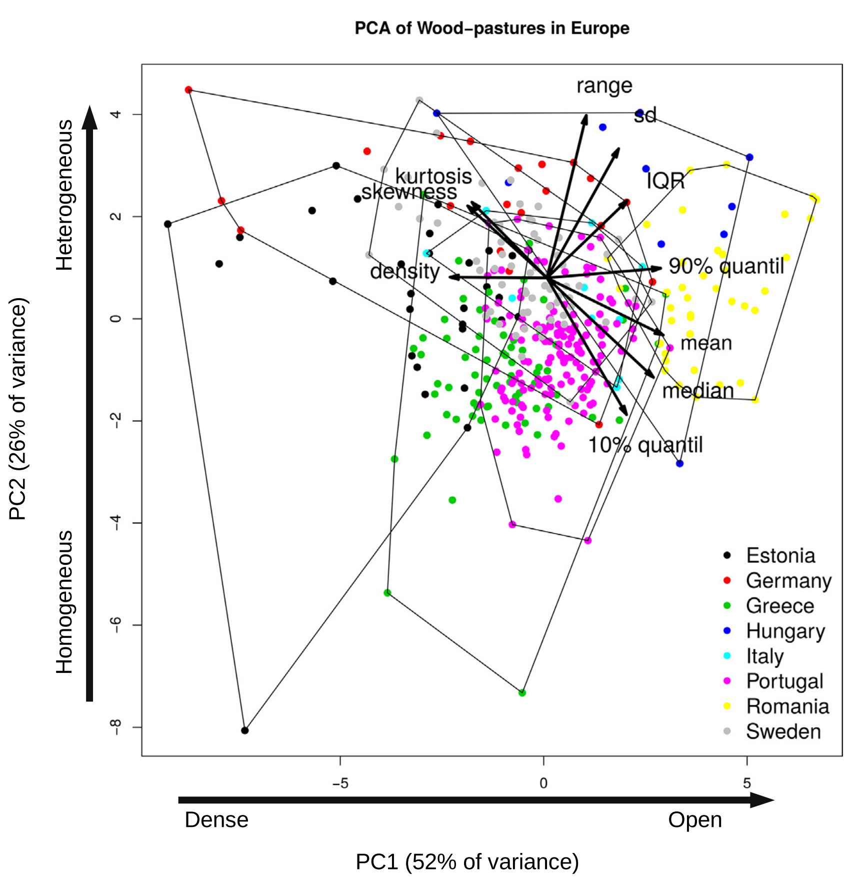

Figure 3. First two axes of the principal component analysis (PCA) of the 10 structural variables describing the stand structure of wood-pastures in eight countries across Europe.

Sweden, birch species (*Betula* spp.) were most common, while in plots in northern Germany beech *(Fagus sylvatica)* was most abundant (see Fig. 2).

Stand Structure of Wood-pastures

Principal components analysis separated our surveyed wood-pastures on the basis of tree density per ha, tree diameters, and the range of diameters within a plot (Fig. 3). The first PCA axis of structural variables explained 52% of the variance and represented a gradient from dense stands with low DBH values (left-hand side of ordination; plots from western Estonia and northern Germany) to sparse wood-pastures with a dominance of large trees (right side of ordination; plots from Hungary and central Romania). The second axis explained 26% of the variance and described wood-pastures with a high variation in stand structure (upper part of ordination), due to a high range of DBH and a high mean DBH, such as plots from Hungary, to homogenous wood-pastures with a rather low DBH, such as plots from southern Portugal or eastern Greece (lower part of ordination). There was a substantial overlap across regions shown by the PCA—only plots from western Estonia and central Romania did not overlap (Fig. 3).

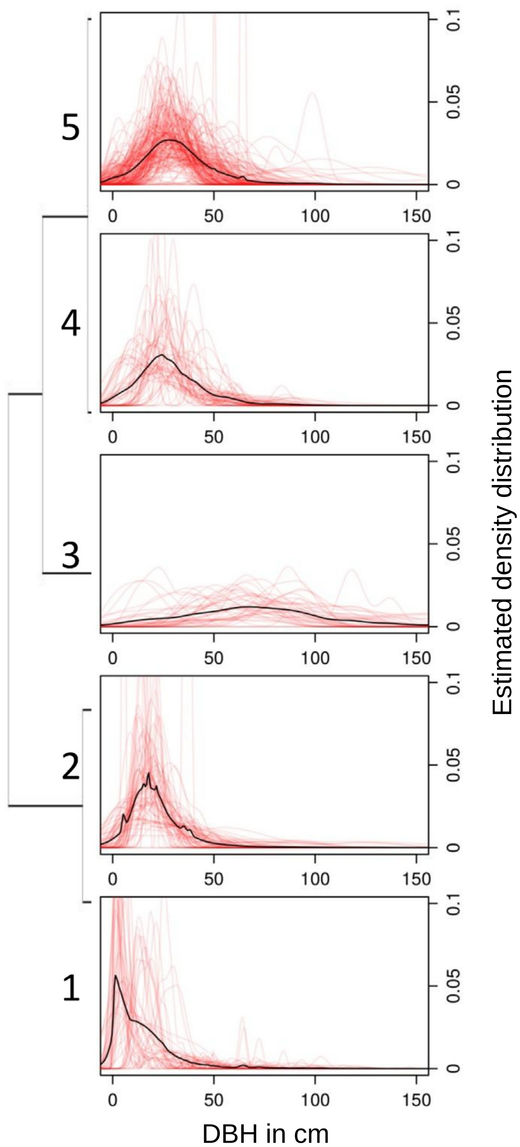

Figure 4. Distribution of the diameters at breast height (DBH) structure of wood-pastures for the different clusters (1 − 5). Each red line denotes the estimated probability density distribution of the DBH (in cm; x-axes) in a single plot. The black lines indicate the average density distribution for plots in a given cluster.

On the basis of a visual inspection of the dendrogram (Appendix 2, available at https://doi.org/10.1016/j.rama.2018.04.004), we identified five clusters of wood-pastures. These clusters occurred in two large branches, one including two and the other including three clusters. The first branch contained clusters 1 and 2 (Fig. 4). Wood-pastures in the first branch were characterized by a high tree density and low DBH values. Furthermore, they showed a very right-skewed DBH distribution. In the first cluster, wood-pastures were denser and had lower DBH values than in the second cluster, while the range and standard deviation of the DBH was the lowest of all clusters in cluster 2 (Table 3). In both clusters, plots from all regions but central Romania were represented.

The second branch was formed by clusters 3, 4, and 5. These were wood-pastures with lower stem densities and higher values for the mean, median, and mode of the DBH. Clusters 4 and 5 were relatively similar. Both contained plots from homogenous wood-pastures with a low interquartile range and standard deviation, especially in cluster 5. DBH followed an approximately normal distribution in both clusters (Fig. 4). Cluster 4 included plots from northern Germany, Hungary, southern Sweden, and southern Portugal, while in cluster 5 plots from all regions were represented except plots from western Estonia. In contrast to clusters 4 and 5, in cluster 3 we found wood-pastures with a very low tree density and trees with a high DBH but also a wide range and standard deviation in DBH. This cluster contains almost only plots from central Romania, apart from a small number of exceptions from southern Sweden.

Most of the geographical regions were present in two to four different clusters, except plots from southern Sweden, which were present in all clusters, while plots from central Romania were almost entirely restricted to a cluster three (Fig. 5). Wood-pastures from northern Germany occurred mainly in clusters 1 and 2, while eastern Greece, Hungary, and northern Italy were spread among clusters 1, 2, and 5. Plots from southern Portugal were mostly represented in clusters 4 and 5.

There was no clear pattern regarding grazed versus ungrazed plots. The ungrazed plots of western Estonia were split between cluster 1 ($n = 6$) and cluster 2 ($n = 4$). Ungrazed plots from northern Germany were found in cluster one (5), cluster two (4), and cluster five (1). The ungrazed plots from Eastern Greece were split in half (5) between clusters 2 and 5. Both ungrazed plots from northern Italy were split in cluster 1 and cluster 5. The only ungrazed plot from central Romania was found in cluster 3.

Discussion

Our results demonstrate a large structural gradient in wood-pastures from different landscapes across Europe, sometimes even within regions. We identified five different clusters along this gradient, showing three major groups of structural differences. The first group (clusters 1 and 2) contained dense wood-pastures composed of small trees. The second group (cluster 3) was formed by sparse wood-pastures with relatively big trees, while a third group (clusters 4 and 5) had intermediate characteristics. In the following, we discuss these findings in relation to current knowledge on regeneration patterns, biogeographical and social-ecological differences, and current policy environment. We conclude by outlining key implications for the future.

Patterns of Tree Regeneration and Density

The distribution of current tree diameters in the three different groups of wood-pastures provides a clear indication of the status of

Table 3
Minimum, maximum, and average values for the structural variables based on the DBH of plots in wood-pastures used for the principal component analysis in all 5 clusters

		Mean	Median	Mode	Kurtosis	Skewness	IQR[1]	Range	SD[2]	Density	10%[3]	90%[4]
Cluster 1	Minimum	3.75	1.00	1.00	−0.17	0.86	1.35	26.74	4.72	38.00	0.57	6.22
	Maximum	33.48	29.60	64.00	55.23	7.18	27.00	144.00	26.78	4944.00	23.11	55.00
	Average	14.74	9.89	9.19	7.61	2.43	9.88	65.14	13.40	989.93	5.92	28.20
Cluster 2	Minimum	11.78	9.75	0.00	−1.59	−0.47	3.82	14.01	3.00	288.00	0.30	18.27
	Maximum	48.57	27.37	50.00	2.25	1.53	87.00	156.00	51.24	778.04	18.59	127.00
	Average	21.11	18.12	14.72	−0.13	0.67	17.56	45.29	12.46	479.67	8.49	38.67
Cluster 3	Minimum	15.33	15.50	1.00	−2.17	−0.69	10.50	27.00	11.27	2.00	3.00	27.50
	Maximum	124.24	146.10	162.00	2.33	1.82	100.75	197.35	59.38	16.00	99.95	203.50
	Average	73.03	72.57	59.80	−0.93	0.13	31.77	80.32	25.20	7.44	44.90	100.58
Cluster 4	Minimum	15.44	10.50	1.00	−1.13	0.45	2.39	20.37	6.60	20.00	1.00	26.30
	Maximum	50.57	46.79	83.00	4.89	1.74	36.95	107.80	28.12	164.00	38.87	83.92
	Average	28.73	25.69	24.78	0.93	1.09	14.18	56.94	13.86	80.95	15.72	44.53
Cluster 5	Minimum	14.25	11.00	0.00	−2.75	−1.91	0.96	10.82	3.20	15.50	0.00	22.54
	Maximum	108.37	116.00	143.00	5.58	2.03	119.00	175.80	58.89	440.00	84.78	155.60
	Average	32.77	32.63	30.30	−0.84	0.00	17.04	43.02	13.11	89.72	17.97	47.30

[1] Interquartertile range.
[2] Standard deviation.
[3] 10% Quantil.
[4] 90% Quantil.

tree regeneration in different regions across Europe (Plieninger et al., 2003; Garbarino and Bergmeier, 2014; Varga et al., 2015). While wood-pastures in the first and second cluster, mostly containing plots from western Estonia and northern Germany, show a lot of regeneration but very few old trees, in cluster 3 of mostly central Romanian plots we found the largest trees but a near complete lack of regeneration. With the exception of clusters 1 and 2, in all the wood pastures examined, regeneration is suppressed when compared with natural forest systems (Plieninger et al., 2003; Hartel et al., 2013).

To date, little is known about the regeneration rate of trees needed to secure the persistence of a given wood-pasture. However, drawing on the conceptual model of Plieninger et al. (2003) of changes in diameter distribution following the transformation from forest to *dehesa* in Spain, the DBH distribution in plots from central Romania shows a clear trajectory for wood-pastures from that region toward becoming treeless pasture. In contrast, the wood-pastures in cluster 1 (mostly plots from western Estonia and northern Germany) show clear indications of abandonment, despite most of the sites being actively managed. Although wood-pastures in clusters 4 and 5 showed a normal (or bell-shaped) distribution typically associated with stand structure in wood-pastures (Plieninger et al., 2003; Garbarino and Bergmeier, 2014), it is not clear if regeneration in these wood-pastures is sufficient. A model by Kirby (2015) based on oak regeneration in wood-pastures in England emphasizes that the number of younger trees needs to be disproportionally large to sustain a population with only a few large old trees in the future—a condition that is rarely met in current wood-pastures. This finding, in turn, is consistent with Gibbons et al. (2008), who modeled the regeneration status of scattered tree systems around the world. For most regions, the persistence of trees is questionable, especially in the case of central Romanian wood-pastures, which had very low tree densities. In combination, our findings suggest that wood-pastures in different regions of Europe face different structural problems. Regions such as central Romania are at risk of losing their semiopen character from a lack of tree regeneration, whereas regions such as western Estonia are at risk of losing this character due to too much regeneration. Nevertheless, as wood-pastures are social-ecological systems, it is important to consider their social-ecological histories and conditions when talking about sustainable regeneration rates, and further research is needed.

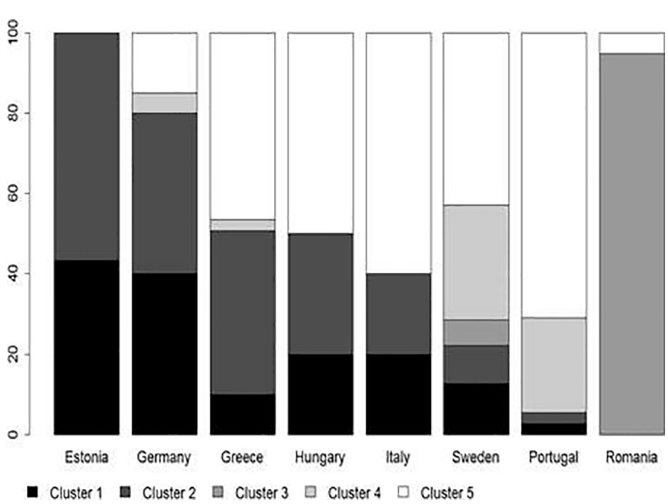

Figure 5. Distribution of the five clusters over the different countries.

Biogeographical Differences and Social-Ecological Backgrounds

Generally speaking, species composition in wood-pastures was broadly similar to expected species composition in the surrounding forest in a given region, apart from a higher occurrence of fruit trees in some regions (Drössler, 2010; Bölöni et al., 2011; Garbarino et al., 2013; Hartel et al., 2013; Roellig et al., 2016). Only in plots from central Portugal was there was only one species present. In most regions, oak species were among the most abundant species, except in northern Italy, where oaks do not grow due to the high altitude (Ellenberg and Leuschner, 2010).

The structure of wood-pastures, especially tree diameter distribution, is influenced by species composition. Some tree species such as birch do not grow to a large DBH (Ellenberg and Leuschner, 2010), and thus wood-pastures with a high percentage of birch evidently have more trees in the lower DBH classes—this may be the case for some wood-pastures in southern Sweden and western Estonia. Still, plots from southern Sweden were found in all clusters. In contrast, in northern Germany, for example, wood-pastures were dominated by trees that can reach large DBH values such as oak, beech, and hornbeam, especially when not grown under a closed canopy (Pretzsch et al., 2015). Despite this potential for large DBH values in northern German wood-pastures, most plots actually were found in clusters with a high number of trees in the lower DBH classes, suggesting that management effects, rather than species composition, kept the DBH values low. This difference is clearly apparent when comparing plots in Romania and Hungary, which are geographically relatively close, located in similar hilly areas, and had similar species composition, but very different structures.

When it comes to management, one key part of wood-pasture management is the current grazing regime (Van Uytvanck and Verheyen, 2014). In the sample from Estonia, one third of the wood-pastures were ungrazed, while in Germany half of the sampled wood-pastures were ungrazed. We expected to find more ungrazed sites in the first cluster than in all other clusters, but there was no clear pattern in our results, suggesting that current grazing management is partly responsible for the persistence of a semi-open character, but not the only influence on the structure of wood-pastures. Importantly, our variable describing the status of grazing management related only to the present but did not contain information on how long a given site had been grazed or ungrazed—this, in turn, may explain why we did not observe systematic differences between grazed and ungrazed sites.

Consistent with this, local history and past management appeared to have an important effect and can partly explain differences in the structure of wood-pastures across Europe. In Estonia, forest grazing was common hundreds of years ago, but during the past century, due to regime shifts and intensification of agriculture, wood-pasture management has almost disappeared (Kukk and Sammul, 2006; Lotman and Lotman, 2011). This partly explains the high tree density and large number of trees in the lower DBH classes. The high tree densities in northern Germany can be explained by a law that banned forest grazing (including wood-pastures) in the 19th century almost everywhere in Germany until today (Luick, 2008). In central Romania, in contrast, the same prohibition (of grazing in the forest) led to an entirely different structure. Already opened up grazed forests were turned from forests into open pastures, and today's sparse wood-pastures with old and large trees developed as a result of ongoing, long-term grazing management (Sutcliffe et al., 2014). In Hungary the same law also separated grazing and forest management, but a decrease in grazing activities in the mid-20th century led to increased tree regeneration (Varga et al., 2015). Also in northern Italian subalpine wood-pastures, selection of larch trees historically maintained a low tree density, but in the second half of the 20th century, abandonment caused grazing to decline and there was a subsequent increase in regenerating trees (Garbarino et al., 2011). Wood-pastures in southern Sweden in contrast are located in a hilly landscape where small-scale farming and livestock rearing survived over a long period, leaving wood-pastures with a diverse structure due to differences in topography and management (Jakobsson and Lindborg, 2014). Similarly, history influenced wood-pasture structure in Portugal. Here, active tree management from the beginning of the 18th century, including planting and replanting, fundamentally shaped the stand structure of current wood-pastures (Joffre et al., 1999; Costa et al., 2014). The structure of Greek wood-pastures is similar to the distribution of natural Mediterranean oak forests, suggesting that the traditional land-use system has supported continuous regeneration. However, the almost complete absence of seedlings in the plots indicates that regeneration has been interrupted more recently, probably as a consequence of the major intensification in livestock husbandry that has taken place over the past 20 to 30 yr in the area (Plieninger et al., 2011).

European and National Policies and Challenges for Wood-Pasture Management.

The loss of the semiopen character of wood-pastures is associated with a loss of biodiversity at both the local and landscape level (Bergmeier et al., 2010). The positive effects of trees, especially large old trees, have been reported for numerous groups of organisms (Söderström et al., 2001; Manning et al., 2006). So far, recent studies have found no specific tree density threshold that maximizes biodiversity benefits in wood-pastures. For example, Aavik et al. (2008), as well as Jakobsson and Lindborg (2015), found no significant difference in the diversity of ground vegetation along a tree density gradient. Similarly, Jakobsson and Lindborg (2017) found no negative impacts of increased tree density on bird diversity in Swedish wood-pastures, although Hartel et al. (2014) found a higher absolute species richness of passerine birds in wood-pastures compared with closed forests and open pastures in central Romania. In combination, existing work suggests that the semiopen character of wood-pastures in general is more important than any specific tree density threshold (see also Sammul et al., 2008). Instead of defining tree density limits, wood-pastures thus should be acknowledged as complex systems that are important for biodiversity largely because of their structural heterogeneity. The benefits of such a pluralistic understanding of wood-pastures should be reflected by adequate flexibility in relevant European nature conservation and agricultural policies.

Finally, the current and historical social-ecological context affecting wood-pasture management needs to be taken into account when designing policies for wood-pastures (Plieninger et al., 2015). Estonian wood-pastures are much denser due to their history and environmental conditions, and their management cannot be directly compared with systems that are environmentally and historically different, such as wood-pastures in central Romania or Portugal. Nevertheless, where SAPs from the CAP of the EU do not cover the additional workload or financial cost to maintain the semiopen character of wood-pastures, such as replanting or cutting trees, national policies need to be established to motivate farmers to carry out the additional management (see also Roellig et al. 2015).

Implications

As in many silvopastoral systems around the world, semiopen rangelands depend on maintaining a balance of trees and grassland that can be put at risk by agricultural intensification or abandonment, and changes in fire, climate, and herbivory. The risk of losing the semiopen character of many our surveyed wood-pastures poses a key challenge for conservation of these systems. So far, management actions and policies are focusing on maintaining wood-pastures as open as possible, but this uniform focus does not adequately account for differences in the threats to their persistence across Europe. As demonstrated by our results, wood-pastures in some locations (e.g., central Romania; cluster 3 in Fig. 4) are at risk of being too open, whereas wood-pastures in other locations are at risk of getting too dense (e.g., Germany, Estonia; clusters 1 and 2 in Fig. 4). These differences, as well as the importance of the social-ecological background driving them, need to be taken into account more fully in policies targeting wood-pasture management. We emphasize that the nature of the data presented in this paper is somewhat preliminary because we conducted a post hoc assessment of existing studies, rather than designing new pan-European research from the outset. A newly designed study could elicit both social and ecological variables in multiple settings in more detail than we were able to and would be valuable in the future. Notwithstanding these limitations and local variation in wood-pasture status and history, some general recommendations are likely to be useful throughout the EU. Specifically, we recommend that to maintain wood-pastures: 1) all wood-pastures should be eligible for the SAPs of the European Common Agricultural Policy, independently of the number of trees per ha; 2) nature conservation policies at the EU level need to include all wood-pastures across Europe as special habitat, while acknowledging regional differences; and 3) regions with too much or too little tree regeneration should be supported by national policies for specific management actions.

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