

Geographic determinants of spatial patterns of *Quercus robur* forest stands in Latvia: biophysical conditions and past management

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Most of the forest area dominated by pedunculate oak (*Quercus robur* L.) in Latvia was lost to arable land several centuries ago and the remnant patches of *Q. robur* stands are small and spatially scattered. We hypothesized that a large part of the present *Q. robur* stands in the Eastern Baltic area of the hemiboreal forest zone developed around the past manor houses in the period of social and political turmoil and subsequent agricultural land abandonment. Our aim was to determine the relationship of *Q. robur* stand occurrence with soil properties, climatic conditions and proximity to past manor houses. Our study area was the entire territory of Latvia (64,589 km²), divided into 16 landscape regions. We used the State Forest Inventory database to filter out all stands dominated by *Q. robur* (n=3746). Spatial aggregation of the stands was tested by multi-distance spatial clustering analysis (Ripley's K method). Mean stand area and Euclidean nearest-neighbour distance for stands were calculated for landscape regions. Binary logistic regression with the calculation of autocovariates showed that winter temperature, soil texture, carbonate concentration and distance to closest manor house were the independent factors significantly ($p < 0.01$) related to the probability of occurrence of *Q. robur* stands. The results showed that *Q. robur* is spatially clustered, i.e., significantly different from a random distribution ($p < 0.05$). Higher densities of stands occurred in landscape regions with milder maritime climatic conditions. The largest proportional area of stands established between 1885 and 1914 in the period when peasants gained title to lands and manor lords lost control over their land holdings. In addition, in the landscape regions of Rietumkursā, Austrumkursā and Rietumzemgale, the abundance of *Q. robur* stands coincided with high densities of past manor houses. Thus, establishment of the *Q. robur* stands likely responded to suitable conditions (open canopy) made available for tree colonization during the land reform occurred 100 years ago. Our results suggest that priority for conservation should be given to spatial aggregations of stands with high connectivity and on richer soils in more maritime conditions.

Keywords: Forest Management, Geographic Distribution, Land Use History, Soil, Manor, Spatial Pattern, *Quercus robur*

Introduction

The impact of man on transformation of the landscape has been profound and understanding of these changes is required for the development of optimized management systems (Costanza et al. 2007). Clearing of forest for the exploitation of wood resources together with the conversion of

land use to agriculture in the Holocene has been estimated to have reached 60-100% in most parts of Europe by 1800 AD (Kaplan et al. 2009). Presently, in the European Union, 40% of woodlands are located in agricultural landscape matrix and 15% of woodlands are strongly fragmented (Estreguil et al. 2013). In Western Europe, the

existing temperate woodland is mostly represented by secondary forests that regenerated on abandoned agricultural land, and virtually all stands have been managed (Hermy & Verheyen 2007). In the boreal forest zone of Northern Europe the forest area is less fragmented and woodlands cover 53.2% of the land area (Forest Europe 2015).

The hemiboreal zone represents the transition between temperate nemoral forests and northern boreal forest, where nemoral species like pedunculate oak *Quercus robur* L. are close to their northern range limit (Hytteborn et al. 2005). *Q. robur* is an ecologically plastic species, which behaves as a pioneer species in certain conditions (Eaton et al. 2016). *Q. robur* exhibits preference for a maritime climate (Krampis 2011, Matisons et al. 2013). Spring, summer and winter temperature, and summer drought are climatic factors known to limit for *Q. robur* survival and growth in the hemiboreal zone (Drobyshev et al. 2008, Matisons et al.

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2012, Eaton et al. 2016). Since 1900, there has been a shift in the main limiting factors in the Eastern Baltic region from winter temperature to summer temperature (Matisons et al. 2012). *Q. robur* is mostly found on fertile and moist soils (Neophytou et al. 2010), although it can also regenerate and develop successfully on poorer soils if light conditions are suitable (Ikauniece et al. 2013, Brumelis et al. 2017). In Europe *Q. robur* rarely forms pure stands and occurs mostly in admixture with other noble broadleaved trees like *Carpinus betulus*, *Fraxinus excelsior*, *Tilia cordata* and *Acer platanoides* (Eaton et al. 2016). *Q. robur* also occurs as individual trees in open landscapes and in small patches surrounded by cultivated lands.

Q. robur forests reached maximum extent during the Middle Holocene (Holocene climatic optimum) about 8000-4000 yrs BP (Stivris et al. 2014) when the climate was more maritime with warmer temperatures and more precipitation (Giesecke 2005). Its range later shrank due to cooling of the climate. In addition to climatic changes, anthropogenic pressure caused wide-scale land-use changes and, consequently, the decrease of *Q. robur* in north-eastern Europe, due to clearing for valuable timber and the expansion of cultivated lands. The most fertile lands were preferred for farming, grazing and timber production. The ship building industry in Latvia during the 17th and 18th centuries created a high demand for *Q. robur* timber, thus contributing to the loss of previously abundant *Q. robur* forests (Zunde 1999) and fragmentation of surviving stands. At the beginning of the 20th century, the total forest area in Latvia had fallen to 23.9% (Vasilevskis 2007), but subsequently increased to 52% in 2016. Due to past management decisions, spruce was planted extensively on forested land (Terauds et al.

2011), although soil conditions permitted the growth of *Q. robur* woodland (Ikauniece et al. 2013). The present area of *Q. robur* as the dominant species is 0.3% of the total forest area (State Forest Service 2017). In regions of intensively managed agricultural landscape, only about 0.4% of the forest area on rich soils has been continuously forested for at least 250 years (Fescenko et al. 2014).

In Europe much of the past forested area was open woodland with veteran trees, a landscape that was rapidly lost due to intensive agriculture and forest management (Miklin & Cizek 2014). In the hemiboreal zone, traditional open woodland parks were centered around manor houses, with cropland in the surrounding area (Lohmus et al. 2014). The feudal manorial system of land ownership existed for centuries across Europe. Manors functioned as agricultural enterprises, in which lands were owned by a titled landowner and were cultivated by peasants (serfs). These areas can be considered as patches of historical agricultural matrix. Aside from administrative and production functions, manors and their surrounding landscapes had significant aesthetic function, reflecting the owner's wealth, status and prevailing architectural styles. The first manorial estates in rural landscapes in Latvia emerged during the 16th century (Nikodemus et al. 2018) and nearly all land belonged to German-Baltic nobility. In parts of Latvia, peasants were given title to land already around 1850. About one-fifth of the manor houses were burned during an uprising in 1905 (Svabe 1958). However, the manorial estate system was fully dismantled only with the land reform of 1920 when approximately one half of the cultivated land of former manors was given to landless peasants (Nikodemus et al. 2018). In Russia, the manorial system was dismantled around the

same time (Nafziger 2012). Even if manor houses were completely destroyed, parks and gardens remained in a part of these areas. Bearing also in mind the need for open areas for establishment of *Q. robur*, we hypothesized that a large part of the present *Q. robur* stands in the Eastern Baltic area of the hemiboreal forest zone developed around the past manor houses in the period of social and political turmoil and subsequent agricultural land abandonment.

Small and spatially scattered patches of *Q. robur* stands present a challenge for effective management and conservation activities, particularly as climatic conditions in the future are predicted to promote expansion of the distribution of broad-leaved tree species (Hanewinkel et al. 2013). Our goal was to test the effect of soil properties, climatic conditions and location of past manor houses as spatial determinants for *Q. robur* stand occurrence in Latvia. Our main objectives were: (1) to determine the age group distribution of *Q. robur* stands; (2) to describe the spatial configuration of *Q. robur* stands in landscape regions of Latvia; and (3) to determine the main factors explaining *Q. robur* stand occurrence in landscape regions of Latvia. We hypothesized that proximity of past manor houses interacting with climatic and soil characteristics were statistically significant factors explaining the occurrence of these stands. We also determined the protection status of these stands, to assess the need for further conservation measures.

Materials and methods

Study area

The study area covered the entire territory of Latvia (64,589 km²). Latvia is located on the Eastern coast of the Baltic Sea, bordering Estonia, Russia, Belarus and Lithuania (Fig. 1). The terrain consists of



Fig. 1 - Location of study area and boundaries of 16 landscape regions (after Ramans 1994) in Latvia: Piejura (Pieju), Rietumkursa (Rkurs), Ventaszeme (Vzeme), Austrumkursa (Akurs), Rietumzemgale (Rzemg), Austrumzemgale (Azemg), Augšzeme (Auzem), Daugavzeme (Dzemg), Dienvidvidzeme (Dvidz), Vidzeme upland (Vaugs), Gaujaszeme (Gzeme), Ziemeļvidzeme (Zvidz), Austrumvidzeme (Avidz), Aiviekstes zeme (Aizem), Austrumlatgale (Alatg) and Latgale upland (Laugs).

mostly flat lowlands separated by glacial upland regions with low hills (150-300 m a.s.l.). The climate in Latvia is temperate, with mild winters (mean temperature in January is -5 °C) and warm summers (mean July temperature is +16 °C). Annual precipitation reaches 600-760 mm. The climate shifts from maritime influence in the Western part to continental in the Eastern part (Draveniece 2007). Soils in Latvia are formed mostly on glacial sediments (clay, loam, loamy sand or sand), which are covered by aeolian, marine, alluvial or peat sediments (Zelčs et al. 2011). The most common soil taxonomy groups in Latvia are Luvisols, Retisols, Arenosols, Podzols, Gleysols, Phaeozems and Stagnosols (Nikodemus et al. 2018).

Latvia is part of the hemiboreal region where southern boreal coniferous forests merge with Central European nemoral forests (Sjörs 1963). Forest covers 52% of the land area. The dominant tree species in Latvia are Scots pine (*Pinus sylvestris*), Silver and Downy birch (*Betula pendula* and *Betula pubescens*), and Norway spruce (*Picea abies*), which together account for 82.8% of the total forested area. Stands dominated by *Q. robur* comprise only 0.3% of the total forested area (State Forest Service 2017).

Spatial datasets

To analyze the regional occurrence of *Q. robur* stands, we used the landscape classification scheme of Ramans (1994) as the basis for defining 16 landscape regions in Latvia. This classification articulates regional differences, based mostly on major geographic features (large-scale landforms like uplands, lowlands, major river valleys and general landscape features like woodland, bog or lake areas). The proportion of forest cover in landscape regions varied greatly, from 14% in Rietumzemgale to 63% in Ventaszeme (Tab. 1).

The Latvian State Forest Register (SFR) geodatabase maintained by the State Forest Service was used as the primary data source of information on *Q. robur* stands. The database is a compilation of data at the stand-level from mensuration surveys. Each management unit contains information on tree species composition, timber volume, stand density, and stand age. This database contains both a tabular component (numeric and textual characterization) and a geometric component (spatial layer with boundaries of stands). In Latvia, the majority of forest stands are small (<2 ha). This data is used in forest management planning and overseeing forest management, including issuing logging permits.

We used climatic maps from the Latvian Centre of Meteorology, Geology and Environment to derive values of mean February temperature as one of limiting factors for survival of *Q. robur* in Latvia (Matisons et al. 2012). Due to the lack of reliable and detailed soil maps in Latvia, we used the Map of Quaternary deposits map of Latvia at

Tab. 1 - Descriptive statistics of *Q. robur* stands in landscape regions of Latvia. (*): the proportion of *Q. robur* is shown as percentage of total forested area in each landscape region.

Landscape region	Area (ha)	Forest cover (%)	<i>Q. robur</i> area (ha)	<i>Q. robur</i> proportion (%)*	No. of manor houses per 100 km ²
Aiviekstes zeme	824,361	45	180.41	0.05	1.25
Augszeme	339,565	45	71.02	0.05	2.94
Austrumkursa	644,634	41	498.63	0.19	4.37
Austrumlatgale	147,116	41	14.75	0.03	1.56
Austrumvidzeme	152,964	44	22.82	0.04	2.81
Austrumzemgale	374,319	58	95.46	0.05	3.02
Daugavzeme	189,823	39	90.53	0.14	3.53
Dienvidvidzeme	289,962	50	103.32	0.08	2.45
Gaujaszeme	390,907	56	166.02	0.08	2.43
Latgale upland	659,105	34	96.97	0.05	3.38
Piejura	716,684	60	125.70	0.03	2.13
Rietumkursa	328,104	36	1030.87	0.94	6.25
Rietumzemgale	223,130	14	111.88	0.40	7.66
Ventaszeme	255,257	63	145.00	0.09	2.90
Vidzeme upland	419,786	52	156.63	0.08	2.81
Ziemeļvidzeme	504,487	45	302.90	0.13	2.83

scale of 1:200,000 (Latvijas Kwartara Noguļumu Karte 1981) as a proxy for characterization of soils. The results from geochemical mapping of Latvia at scale of 1:500,000 (Latvijas Geokimiska Karte 2001) provided information on concentrations of carbonates and texture classes of soil parent material (clay, silt, loam, loamy sand, sand, unsorted material, peat) and bedrock (dolomite, gypsite, limestone). Locations (as points) of all 1984 historical manor houses were derived from a map published by Potapova (1977); this map included all types of feudal rural administrative centers.

Information on protected areas (PA) was obtained from the Nature Conservation Agency (DAP) geoportal OZOLS (<http://ozols.daba.gov.lv/pub/>). This dataset includes all types of terrestrial protected areas in Latvia, i.e., Biosphere Reserves, National Parks, Strict Nature Reserves, Nature Reserves, Nature Parks, Protected Landscape Areas, Microreserves and Natura 2000 sites. Accessory data sources included the "GIS Latvia" cartographic dataset (Envirotech 2015).

Analysis steps

At the data processing stage, we extracted forest stands from the SFR database using criteria of tree species composition and area. Since *Q. robur* rarely forms pure stands, we used a compositional threshold of ≥70% (as the dominant species) of stand timber volume to select stands that were dominated by *Q. robur*. Only stands with area >0.1 ha were considered, excluding sub-stand patches like those formed of large legacy trees. In total 3746 *Q. robur*-dominated forest stands with total area of 3272.2 ha were selected for this study. Data selection and process-

ing were done with ArcMap® ver. 10.3 (ESRI, Redlands, CA, USA) using selection queries in attribute tables and data subsetting. The selected stands were split by landscape regions and converted into raster thematic maps. These maps were analyzed with Fragstats ver. 4.2 (McGarigal et al. 2012) to calculate landscape pattern metrics, i.e., quantitative parameters describing the composition and spatial configuration of *Q. robur* stands. We used the metrics Patch Area (AREA) and Euclidean Nearest-Neighbor Distance (ENN) at the patch level. For the calculation, we prepared thematic raster maps with cell size 10 × 10 m, showing all *Q. robur* stands divided among landscape regions. The eight-cell neighborhood rule was used to determine spatial relationships.

To detect aggregation patterns, multi-distance spatial clustering of *Q. robur* stands was analyzed with the Ripley's K function in ArcMap 10.3 using 99 permutations at 50 distance bands of 500 m. For this, polygons of *Q. robur* stands were converted to points using polygon centroids. Separately, *Q. robur* stand proximity to past manor houses was assessed using the "Buffer" function in ArcMap 10.3 with distance threshold of 3 km.

To determine whether the probability of occurrence of a *Q. robur* stand at a particular point was related to distance from a manor house, and climatic and soil texture factors, an autologistic binary regression model as implemented in software R ver. 3.5.0 (R Core Team 2018) was used. For reference we generated 3746 randomly placed points (to match the number of observed *Q. robur* stands), covering the entire area of Latvia and calculated the same factor values as for the observed *Q. robur* points. To account for spatial autocorrela-

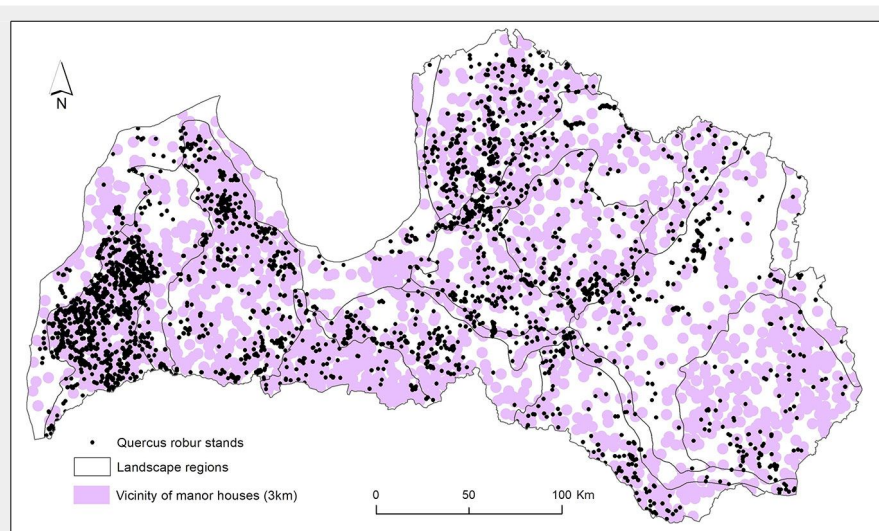


Fig. 2 - Location of *Quercus robur* stands and the vicinity (up to 3 km distance) to past manor houses.

Q. robur stands comprised only 0.03-0.94% of the forested area in the landscape regions (Tab. 1). Two landscape regions contained almost half of all *Q. robur* stands of Latvia and half of the landscape regions together contained only 19.5% of the total *Q. robur* area. The highest total area (1030 ha) of *Q. robur* stands was recorded in the Rietumkursa (Rietumkursa upland) landscape region, twice more than that in the landscape region with the next highest area, Austrumkursa (Austrumkursa upland – 498 ha).

The number of manor houses also differed among landscape regions (1.25-7.66 per 100 km²). From five landscape regions (Rietumzemgale, Rietumkursa, Austrumkursa, Daugavzeme and Latgale upland) with the highest densities of manor houses, four of these also had the highest proportion of *Q. robur* stand area. Proportion of area of *Q. robur* stands showed strong positive correlation with the number of manor houses per 100 km² in landscape regions ($r=0.72$, $p<0.05$).

Geographic pattern of *Q. robur* stands

Multi-distance spatial analysis (Ripley’s K) showed that *Q. robur* stands exhibited a significant spatial clustering (confidence level 99%) in all distance bands compared to the same number of random points. As expected, Ripley’s K analysis also revealed a significant clustering of former manor house locations, but only at distances exceeding 2.5 km.

As shown in Fig. 2, most of the *Q. robur* stands occur in the vicinity of the past manor houses (3 km distance threshold). The proportion of area of *Q. robur* stands in landscape regions was strongly correlated ($r=0.76$) to that of manor houses.

Spatial pattern analysis of *Q. robur* stands revealed a low median patch area (<1 ha) in all landscape regions, with maximum area less than 3 ha (Fig. 3). The ENN metric at patch level indicated that the median distance to nearest neighbor patch was less at 1 km for almost all landscape regions, and lowest for the landscape regions with greater proportional area of *Q. robur* stands (e.g., Rietumkursa). As expected, the median ENN distance was highest in the eastern landscape regions (Austrumlatgale, Latgale upland, Austrumvidzeme) where the area covered by *Q. robur* stands was lowest. In total, only 19.8% of stands were isolated at distances greater than 2 km.

Stand age group distribution

The median age of *Q. robur* stands was 94.8 years. Almost one half (47.3%) of the *Q. robur* stands were older than 100 years and those older than 200 years occurred in 11 of 16 landscape regions. The oldest stand was 305 years old, located in the Gauja National Park in the Gaujaszeme landscape region. More than half (52.7%) of *Q. robur* stands above the age of 90 years (by area) were under some type of protection (strict

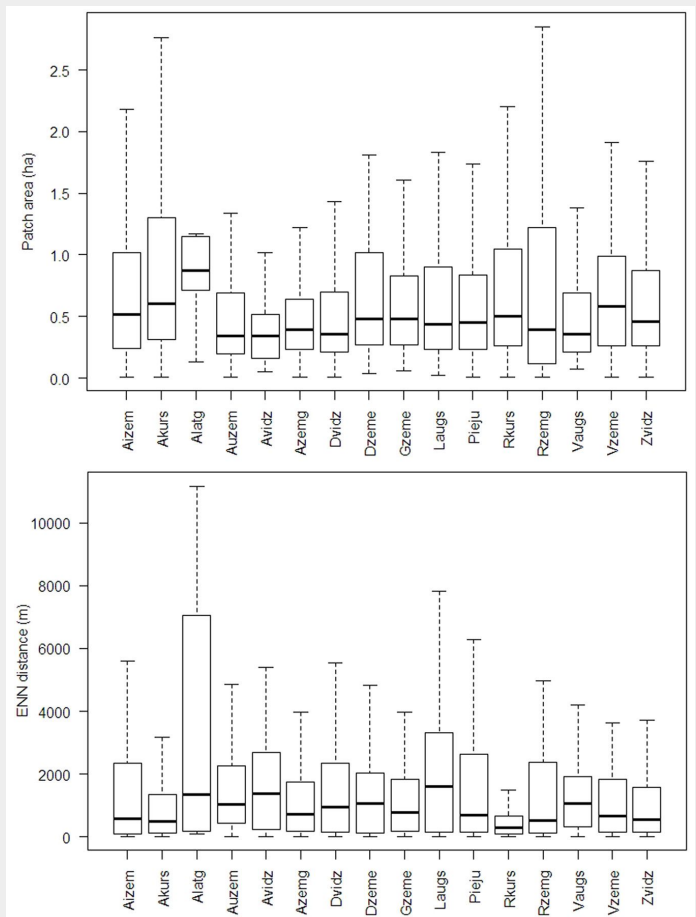
tion, a distance-weighted autocovariate (distance used was 1000 m) was included using the R package “spdep”. Independent variables in the model were distance to nearest manor house (MANDIST), mean February temperature (TEMP) as the main limiting climatic factor in the past, texture type (FRACT) and concentration of carbonates in topsoil (CACONC). We used a confidence level of 0.95. The R package “emmeans” was used to perform a *post-hoc*

test (pairwise comparisons) of occurrence probabilities between FRACT levels. P-value adjustment was done with Tukey’s method for comparing a family of 8 estimates.

Results

Despite the large variation observed across the country, the cover of *Q. robur* stands was very low in all landscape regions – below 1% of the total forested area.

Fig. 3 - Statistical distributions of pattern metrics for *Quercus robur* stands in landscape regions of Latvia. Patch area (top) and Euclidean NN distance (bottom). Outliers are not shown.



nature reserve, nature park, microreserve etc.).

Forest age distribution (grouped by decades) showed two periods of notable increase in area of *Q. robur* stands (Fig. 4). The most recent period corresponds to the establishment in the years 1993-2014, as indicated by the peak of area for stands younger than 20 years. These stands account for 332.8 ha, which is 10.3% of the total *Q. robur* stand area. The second peak in the age distribution (stands with age 101-130 years) suggests a great increase in establishment of *Q. robur* in the period of 1885-1914 (over 60% compared to that in 1865-1874). Stands with this age comprise 42% of all *Q. robur* stands by area. Among age classes, the proportions of *Q. robur* stands located <3 km from manor houses were similar: 69.3%, 75.5%, 75.8% and 70.3% in the age classes 1-30, 31-100, 101-130 and 130 years, respectively.

Predictors of *Q. robur* patch occurrence

The binary regression model applied to explain the spatial distribution of *Q. robur* stands showed that all tested factors had significant independent effect ($p < 0.01$ or $p < 0.001$ – Tab. 2). The spatial autocovariate was also significant ($p < 0.001$) in this model, indicating the aggregation of *Q. robur* stands.

Distance to past manor houses (MANDIST) was inversely related to the probability of occurrence of *Q. robur* stands ($p < 0.001$). February mean temperature (TEMP) was also significant ($p < 0.001$) and positively related to *Q. robur* occurrence. We found that carbonate concentration (CACONC), as an indicator for soil richness, was inversely related to the occurrence of *Q. robur* stands (significance $p < 0.01$). From pairwise comparison of the soil texture types (FRACT), sand and loam significantly differed ($p < 0.01$) as predictors for *Q. robur* occurrence. These two types were the most common soil texture classes for *Q. robur* stands in Latvia (Tab. 3). The proportion of *Q. robur* stands on sand parent material was similar to that predicted by distribution of randomly selected points, while the occurrence on loam was much lower (22.3% of total stands) than expected (34.5% of random points). However, *Q. robur* occurrence on loamy sand was higher than expected (23.0% and 10.2%, respectively).

Protection of *Q. robur* stands

About half of the older *Q. robur* stands (age >150 years) were under protection, while only 20% of the area of *Q. robur* stands that originated in the period of 1885-1914 was under some type of formal protection.

Discussion

Our results reflect the complex history of *Q. robur* forests in Latvia by considering factors like climate, soils and historical management to explain the existing spatial

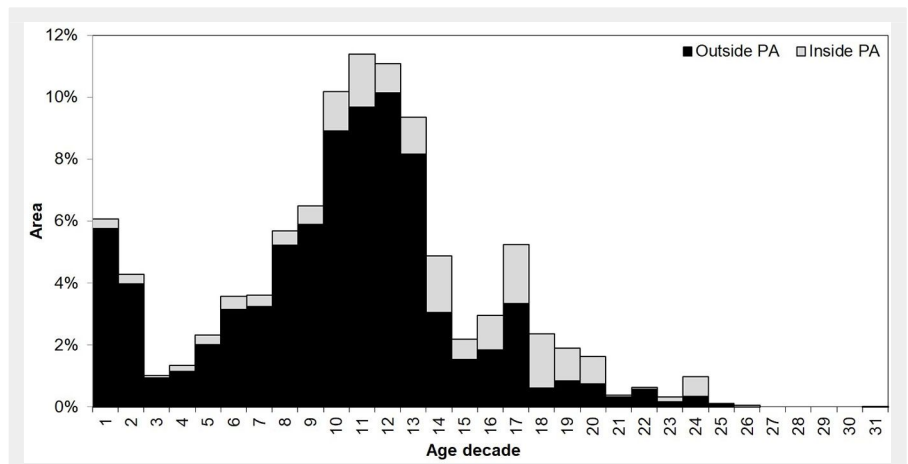


Fig. 4 - Proportional area (%) of *Quercus robur* stands in age classes, inside and outside protected areas (PA).

Tab. 2 - Analysis of Deviance Table (Type II test) for *Quercus robur* stand occurrence in relation to factors of distance to nearest past manor house (MANDIST), mean February temperature (TEMP), type of granular fraction of sediments (FRACT) and concentration of calcium in topsoil (CACONC). The significance of spatial autocovariate is also shown. (df): degrees of freedom.

Factor	χ^2	df	p-value
MANDIST	51.14	1	<0.0001
TEMP	164.75	1	<0.0001
FRACT	26.87	7	<0.0001
CACONC	9.20	1	<0.0001
spatial autocovariate	2304.30	1	<0.0001

Tab. 3 - The distribution of soil texture types of soil parent material for *Quercus robur* stands and random points in Latvia (by number).

Soil texture classes	<i>Q. robur</i> stands (%)	Random points (%)
sand	38.2	38.1
loam	22.3	34.5
loamy sand	23.0	10.2
clay	10.0	10.5
silt	3.5	4.3
unsorted material	2.0	1.2
bedrock	0.4	0.4
peat	0.6	0.7

distributions of these stands. The study showed that distance to past manor houses, soil properties and climate were significant independent predictors of the present geographic distribution of *Q. robur* stands in Latvia. The stands were highly spatially aggregated in areas around the past manor houses, which were mainly established in favorable climate and on fertile soils.

Past land management

Human impact played a major role in the dramatic decrease of broadleaved forests in Latvia during the previous 300 years and influenced the current situation through management legacies (Jögiste et al. 2018). Despite widespread harvesting of *Q. robur*

timber for ship building in 17th century, significant areas of *Q. robur* stands were present in Western Latvia during the first half of the 19th century (Zunde 1999). However, in other parts of present-day Latvia, *Q. robur* stands were rare due to the extensive timber harvesting carried out in previous centuries. Historical records indicate that since 1663, *Q. robur* trees and stands that had remained on agricultural lands were protected in the Dutchy of Courland and Semigallia (as part of Polish-Lithuanian Commonwealth – Strods 1999). This area coincides with the Western and central parts of Latvia. Later, when Latvia was a part of the Russian Empire, forest laws allowed unregulated harvesting in forests of private manor estates, including *Q. robur*

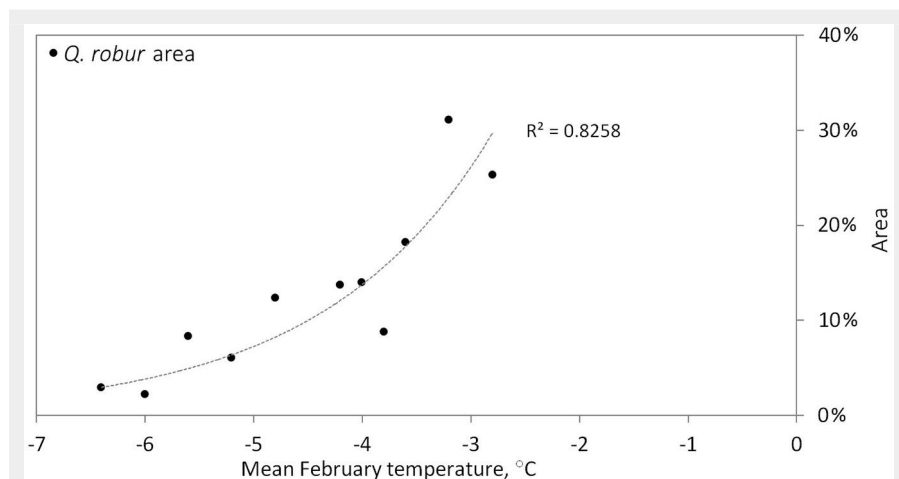


Fig. 5 - The relationship between the proportion of area (% of forested area) of *Quercus robur* stands and mean February temperature in Latvia.

stands. In the Western part of Latvia these regulations were stricter, requiring forest regeneration after harvests in forests of manor estates. This was in contrast to Sweden, where at that time, land use in manor estates was much more strictly regulated (Strods 1999). The history of harvest of *Q. robur* is one of the reasons underlying the current lack of very old stands in Latvia. During this period planting of trees was mostly restricted to gardens and parks of manor estates (Strods 1999). *Q. robur* is usually the oldest remaining tree found in manor parks, but other deciduous trees such as *Tilia cordata* and *Acer platanoides* were also widely planted (Sauliene et al. 2018).

Manor estates firstly were established on fertile land with favorable topography in suitable climate (Potapova 1977), but we found an independent effect of these factors. There was a significant association of location of present day *Q. robur* stands in all age classes with manor estates. The peak in the age distribution of *Q. robur* stands corresponding to the period of 1885-1914 occurred at a time of widespread social unrest and political change in the Russian Empire. With the social turmoil and military conflicts in the beginning of the 20th century, forests in Latvia were rapidly and widely harvested without replanting. Due to uncertainties of the revolutionary situation, many rulers of manors decided to harvest or sell their forests (Zunde 1999). In 1935 only 1150 ha of *Q. robur* stands remained in Latvia, including 500 ha in the Vidzeme region, 150 ha in the Zemgale region and 100 ha in the Latgale region (Kiršteins 1936). The peak in age distribution likely reflects a period favorable for *Q. robur* establishment on previous agricultural land in proximity of the estates, which can also explain the clustered spatial pattern of the stands. At that time, harvest of *Q. robur* was common in manor estates (Strods 1999). Much of the land further from estates was allotted to peasants starting from early 1850s (Boruks 2003),

when the focus was on agricultural land use and not forestry. Similar vicissitudes also occurred in Estonia (Maandi 2010).

In Latvia stands with age over 150 years comprised 534 ha or 16.6% of all analyzed *Q. robur* stands. Nutt et al. (2013) found that in Estonian manor parks around one half of surviving trees (mostly *Q. robur* due to the long lifespan) were trees originally planted at time of establishment of park and thus are at least 150 years old. Similarly, many of the older stands in stands in Latvia likely formed from historical parks.

The recent peak in the age structure has resulted from the increased planting of *Q. robur* in state forests, as well as the use of silvicultural methods promoting oak establishment and survival in clearcuts. Indeed, since 2000 it has been common practice in Latvian state forests to retain *Q. robur* trees in clearcuts, even where *Q. robur* is not the dominant species in the stand. The continuation of this practice, in combination with warming climate, could potentially lead to increased occurrence of *Q. robur* stands in Latvia in the future. Interestingly, the majority of the young stands were also close to former manor houses, i.e., they occur in areas of aggregations of older stands.

Soil

Since reliable soil maps for forested areas in Latvia are lacking, we used carbonates and texture classes of soil parent material to characterize the substrate of *Q. robur* stands, as the respective survey of these variables had been carried out. The high variation observed in forested area among landscape regions (Tab. 1) is the result of historical slash-and-burn cultivation where the most fertile soils were deforested for agriculture (Zunde 1999), as in other areas of Europe (Wulf et al. 2010). Our results showed that higher carbonate concentrations and the presence of loam parent material are linked to a lower probability of *Q. robur* occurrence. This inverse relationship indirectly confirms the historical destruc-

tion of *Q. robur* forests on soils most suited for cultivation (Fescenko et al. 2014). Also, most of the *Q. robur* stands that have survived to this day grow on sandy parent material (Tab. 3), which also confirms that *Q. robur* is an ecologically plastic species (Ikaunieca et al. 2013). However, there was a preference of *Q. robur* stands for loamy sand, likely as these soils, compared to loams, were not the most preferred for agricultural use. We note that soils with double-layered parent material, where the topsoil contains more sand, are common in Latvia (Nikodemus et al. 2018) and in this study the carbonate concentration (CA-CON) values and texture type only characterized the topsoil. Data was not available for deeper soil layers.

Climate

Climatic conditions represent a major factor driving the occurrence of *Q. robur* stands. Sub-oceanic climatic conditions determine the occurrence of *Q. robur* stands in Latvia and also in Europe in general (Schubert & Vent 1990, Krampis 2011). In Latvia, *Q. robur* occurrence decreases with increasing distance from the sea (Krampis 2011). The proportion of area of *Q. robur* stands showed strong ($r^2=0.82$, $p<0.05$) association with mean February temperature (Fig. 5) as a proxy for climate continentality. The Eastern part of Latvia has a continental climate (shorter vegetation seasons, colder winters) and Western part has mostly maritime climatic influences (longer vegetation seasons and mild winters).

Implications for management

The role of past management effects and legacies on the establishment of *Q. robur* stands is understudied and investigations are needed to synthesize perspectives of land use change, cultural and historical studies, landscapes and ecology to explain the complex history and development of these areas. A question remains about the conservation of *Q. robur* stands inside and outside manor parks, as we did not have data on the origin of stands. Today about half of the older *Q. robur* stands (>150 years) are under protection, compared to only 20% (by area) of those established in the period 1885-1914. Many of the older stands in the areas around manor houses are likely relicts of parks and gardens with cultural and historical significance as well as ecological and landscape values (Sauliene et al. 2018). Although more than half of older stands are under some kind of protection, the old trees will continue to deteriorate and die, resulting in the vanishing of this woodland in its current form (Nutt et al. 2013). This will affect the value of traditional rural landscapes in which manor gardens and parks have been crucial elements for centuries. However, conservation of the stands with age 100-130 years by protection to avoid harvest would prevent a temporal gap in the continuity of ecological and social values of these forests. Fur-

ther, the recent establishment of young *Q. robur* stands close to historical manor houses is expected to promote the spatial continuity of these stands, thereby reducing their current fragmentation and favoring their biological and conservation values (Lohmus et al. 2014). *Q. robur* stands in protected and production forests in Latvia will increase their coverage due to policy of retention of young *Q. robur* trees in clearcuts and climate change effects. Conservation of *Q. robur* woodland should focus on the identification of clusters of stands with age 101 years or more (which is the harvesting age threshold in Latvia) that have dispersal connectivity with the typical nemoral vascular plant communities and epiphytes associated with *Q. robur*. Additional protection for older stands with age >150 years is crucial.

Conclusions

The occurrence of *Q. robur* stands analyzed in this study was well explained by substrate, climatic and historical management as independent factors. Proximity to past manor houses was a strong predictor for the occurrence of *Q. robur* stands. In landscape regions Rietumkursā (upland), Austrumkursā (upland) and Rietumzemgale (lowland) where a high number of manorial estates occurred, *Q. robur* stands cover relatively high proportions of forested areas, due to favorable soil, climatic and scenic conditions. The peak in *Q. robur* age group distribution indicated successful establishment of the stands around manor estates in a time of social and political turmoil. Management should focus on clusters of stands, particularly when ageing veteran trees have high occurrence, to retain their cultural and ecological value.

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