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Analysis of some limiting ecological factors on the example of the distribution of the genus *Tilia* L. cultivated in Latvia

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Abstract. The study was performed on the basis of an inventory of the genus *Tilia* in Latvia. A total of 134 dendrological objects were inventoried in order to clarify factors limiting the distribution of linden in the territory of Latvia. During the 2007–2013 inventory 47 taxa of *Tilia* were found. The taxa and their winter hardiness were evaluated according to the Sokolov scale. In the interpretation of the distribution of taxa 16 geographical and climatic factors were used. Spearman's rank correlation indicated a connection with 11 factors, among them distance to the sea, height above sea level, average January temperature, sum of negative temperatures, and amount of annual precipitation. The results of statistical analysis demonstrated an irregular connection between the geographical distribution of the genus *Tilia* and ecological factors. A negative correlation with height above sea level was observed for *T. americana*, *T.* × *moltkei*, and *T. platyphyllos* subsp. *platyphyllos*. Analysis of winter hardiness of trees revealed that trees get frozen in hard winters although they grow in hardiness zones that fit linden.

Key words: linden, Latvia, climate, dendrological objects.

INTRODUCTION

The distribution of plants is a result of the interactions between the environment (abiotic and biotic) and plants (Wang et al., 2006). It is well known that the macro-distribution of plants is primarily controlled by climate (Woodward, 1987; Prentice et al., 1992). The distribution of terrestrial plants and animals depends on different environmental factors, among which climate is of particular importance. Climate involves long-term periodical changes of a set of environmental factors such as temperature, precipitation, wind, etc. As a rule, the geographical distribution of species is determined not by a single climatic factor but by a complex of factors (Laiviņš and Melecis, 2003).

Trees and shrubs of the genus *Tilia* L. are widely distributed and locally important members of the northern temperate mixed forests (Mauriņš and Zvirgzds, 2006; Pigott, 2012). The genus includes 23 species and 14 subspecies (Pigott, 2012). In Latvia, only one species grows naturally, namely *Tilia cordata* Mill., but in plantations 17 species and 3 subspecies have been established. In recent years *Tilia platyphyllos* Scop. has started to grow naturally near plantations (Urševska and Evarts-Bunders, 2010). *Tilia* spp. are widely distributed in three isolated regions: East Asia, Europe and West Asia, and North America (Radoglou et al., 2009; Pigott, 2012). They grow in temperate, subtropical, and tropical climates and occur from moist to dry regions (Muir, 1984). From these regions of distribution, the following taxa have been introduced in the territory of Latvia: European and West Asian species *T. cordata* Mill., *T. dasystyla* Stev., *T. platyphyllos* Scop., *T. tomentosa* Moench; East Asian species *T. amurensis* Rupr., *T. japonica* (Miq.) Simonk., *T. kiusiana* Makino & Shirasawa, *T. mongolica* Maxim., *T. mandshurica* Rupr. et Maxim., *T. sibirica* Fisch. ex Bayer; and North American species *T. americana* L., *T. caroliniana* Mill., *T. heterophylla* Vent. In Latvia also inter-species hybrids *T.* × *euchlora* K. Koch, *T.* × *flaccida* Host ex Bayer, *T.* × *flavescens* A. Braun ex Döll, *T.* × *moltkei* Späth, and *T.* × *vulgaris* Hayne are encountered.

The representatives of these deciduous trees have become increasingly important in municipal parks of large cities and play a central role as avenue trees (Sukopp and Wurzel, 2000). Growing damages of *Tilia* were observed in European cities because of the ubiquitous stress factors such as salt and drought (Helsinki, Warsaw, Budapest) (Liesebach and Sinkó, 2008). In city greeneries in Central, Eastern, and Northern Europe (Sæbø et al., 2003; Sander et al., 2003; Bengtsson, 2005), including in Latvia (Zvirgzds, 1986; Rupais, 1989; Laiviņš et al., 2009), one of the most widely used tree taxa is *T.* × *vulgaris* (Čakstere, 2011).

The natural areas of the species in most cases explain the regularities of their distribution; for example, the distribution of *Fagus* L. in the world (Fang and Lechowicz, 2006), the distribution of *Sorbus torminalis* (L.) Crantz (Maděra et al., 2013), etc. The introduction and acclimatization of trees is not often described in research works. Certain woody plants, such as *Betula pendula* Roth in Canadian prairies, are described in acclimatization studies (Rousi et al., 2012). However, the research on the distribution, acclimatization, and winter hardiness of introduced plants in definite territories, as well as on the determining climatic factors, is insufficient.

One of the most significant limiting factors of the distribution of woody plants is their winter hardiness. Accurate prediction of winter hardiness is a key component to the successful cultivation and survival of long-lived woody plants in many regions of the world (Daly et al., 2012). To prognosticate the survival of plants in winter the United States Department of Agriculture (USDA) focused on winter hardiness in the 1960s; a map of plants hardiness zones was elaborated (Rehder, 1967; Daly et al., 2012). For Europe a map of trees' hardiness zones was elaborated a little bit later (Krüssmann, 1976).

Several researchers from Latvia have attempted to assess the biogeographic parameters that are important for the growth of introduced plants (Kupffer, 1925; Rasiņš, 1962; Laiviņš and Melecis, 2003; etc.). Kupffer (1925) and Rasiņš (1962) developed phytogeographical borders that have a close relationship with sectors of continentality.

Taken together, the studies mentioned above provide useful information also on the genus *Tilia* in the world, including Latvia. Various factors limiting their distribution (for example, height above sea level, distance to the sea, average January temperature, sum of active temperatures, etc.) are more and more often used for the explanation of the distribution area of wild species. Therefore for a successful growth outside its natural area studies on the occurrence and climatological demands of the genus *Tilia* are vital. What physiogeographical and climatic factors determine the distribution of woody plants in a certain territory? Answering this question is not only important in dendrology, but also will provide a firmer basis for predicting the effects of climate change on the future distribution of woody plants, including *Tilia* species.

MATERIALS AND METHODS

Study area

The geographical location of the centre of Latvia, 56°52′48.5″E longitude and 24°36′22.4″N latitude, is situated close to Tīnuži in Ikšķile region. The climate in Latvia is largely determined by its location in the temperate climate zone at the shores of the Baltic Sea and the Gulf of Riga. Further from the sea, the features of continentality become more expressed. The average annual air temperature in Latvia is +5.9 °C. The warmest month is July with the average temperature of 17.0 °C. The coldest months are January and February, their average temperatures are −4.6 and −4.7 °C, respectively. The absolute maximum temperature, +36.4 °C, and the absolute minimum temperature, −43.2 °C, in the whole territory of Latvia were observed only in Daugavpils; thus the range of extreme temperatures here is 79.6 °C (Kļaviņš et al., 2008; Rutkovska et al., 2013). The average annual precipitation is 667 mm. The average relative humidity is 81%. The sun shines 1790 hours a year, which is approximately half of the possible sunshine duration (in clear weather). On the whole, the most frequent winds during a year are southern, southwestern, and western winds. All in all, in the 20th century the average temperature in Latvia rose by 1 °C. In the recent years of the 21st century this temperature growth has increased even more. As to the annual amount of precipitation in the last 100 years, considerable fluctuations with the tendency to increase from the 2nd half of the 20th century have been observed (LEGMC, 2012).

The descriptive statistics for the physiographical, climatic, and general characteristics in the findings of linden taxa are presented in Table 1. The objects inventoried are located from 5 m to 190 m above sea level. Situated in the west of the East European Plain at the Baltic Sea, Latvia is a typical country of lowlands. The highest point in Latvia is Gaiziņš Hill 312 m above sea level (Turlajs, 2007). The farthest from the sea (255 km) location inventoried is Šķaune. In the objects surveyed, the most often encountered soils are turf podzol and pseudo-gley soil, as well as eroded podzol (according to O. Nikodemus's materials) (Turlajs, 2007).

Table 1. Summary of some geographical and climatic characteristics of the inventoried 96 objects that had introduced *Tilia* taxa

Variable	Code	Minimum	Maximum	Average	SD
Longitude		315171	748704	558845.40	111322.12
Latitude		6194467	6423388	6292299.67	54979.547
Altitude, m	ALT	5	190	78.44	49.60
Distance to the sea, km	DS	1	255	97.15	69.60
Soil group	SG	1	8	2.70	1.24
Mean temperature of the coldest month, °C	MTCM	–7.5	–2.5	–5.96	1.20
Mean temperature of the warmest month, °C	MTWM	16.25	17.25	16.91	0.39
Annual precipitation, mm	AP	575	825	685.94	68.16
Sums of negative temperatures, °C	SNT	–700	–200	–504.69	117.72
Sums of active temperatures, °C	SAT	2200	2450	2326.56	71.43
Vegetation period (T > +5 °C), days	VP	175	195	181.82	4.63
Frost-free period, days	FFP	125	175	146.82	9.63
Mean annual sunshine duration, h	MASD	1550	1850	1718.75	85.77
Conrad's continentality index	CCI	22	31	27.7	2.29
Rasiņš's continentality index	RCI	2	10	6.02	2.05

The perennial average temperature in January in the territory of Latvia is –4.6 °C, at the seacoast it is 2.5 °C, but in eastern Latvia (Rēzekne, Ludza, Balvi, Gulbene, etc.), as well as in the Vidzeme Highland, the average temperature is –7.5 °C. The sum of annual negative temperatures fluctuates from –700 °C to –200 °C. The perennial temperature of the warmest month in the territory of Latvia varies by one degree centigrade, on average it is +17 °C; the sum of annual active temperatures is from 2200 °C to 2450 °C.

The annual amount of precipitation in the objects surveyed in the territory of Latvia is from 575 mm to 825 mm. The least amount of precipitation is encountered in the Zemgale Lowland, the greatest in the surrounding areas of Gaiziņš, Limbaži, and Priekule (875 mm).

The vegetation period, when the temperature is over +5 °C in the whole territory, differs by approximately 20 days according to long-term observations: at the sea it is 195 days, while in the eastern part of the country the vegetation period lasts for 175 days. Accordingly, the frost-free period fluctuates from 125 to 175 days. The average annual sunshine duration differs by 300 h. In addition, Conrad's and Rasiņš' continentality indices were analysed.

Climatic data

The values of 15 parameters were used in the present research: the average temperature in January (Turlajs, 2007), the average temperature in July (Turlajs, 2007), the annual amount of precipitation (Turlajs, 2007), the sums of active temperatures (Fomina, 1972), the sums of negative temperatures (Zirnītis, 1968), the duration of the vegetation period (Zirnītis, 1968), the duration of the frost-free period (Turlajs, 2007), the distance to the sea, the height above sea level, the average annual duration of sunshine (Kļaviņš and Andrušaitis, 2008), Conrad's index of continentality (Draveniece, 2007), Rasiņš' index of continentality (Rasiņš, 1962), the changes in the density of the taxa findings in the direction from north to south (Y), the changes in the density of the taxa findings in the direction from west to east (X), the soil groups (Turlajs, 2007).

Distribution of taxa

The previous complete inventory of dendrological features of Latvia (Fig. 1) was carried out mostly during the years 1975–1980 (Laiviņš et al., 2009), but by now it has become obsolete. Therefore, a re-inventory of the richest dendrological collections was carried out during the period 2007–2012 in the whole territory of Latvia. During that inventory all planted taxa of the genus *Tilia* were analysed. A total of 134 dendrological objects, approximately five in each former district, were inventoried in the territory of Latvia (Fig. 2). The selected objects – the

Fig. 1. Location of the research site in Europe.

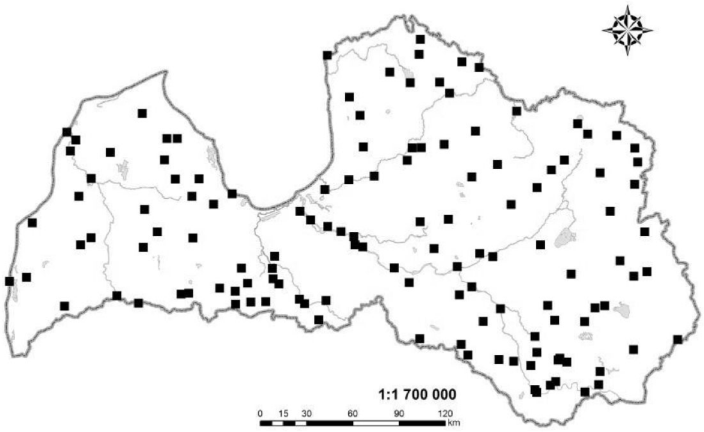

Fig. 2. Map of the inventoried dendrological objects in Latvia.

National Botanical Gardens, Botanical Gardens of the University of Latvia, Kalsnava Arboretum, the plantations of arboreal plants in Jaunbrēdiķi, Skrīveri Dendrarium, Lēdurga Dendrarium, Lāčupīte Dendrarium, and other dendrologically most valuable parks – are possibly the richest in different taxa of *Tilia*. Maps were produced by using GIS software ESRI ArcGis 10.0.

Evaluation of winter hardiness

Winter hardiness of *Tilia* taxa was determined according to Sokolov's (1957) scale:

- I – plant is completely winter-resistant, no damages are observed;
- II – insignificant winter damages are observed;
  - II_0 – frost damages are observed on evergreen leaves and needles;
  - II_1 – frost damages are observed on shoots of the last year, as well as on vegetative and generative buds;
  - II_2 – shoots of the last year are destroyed by frost completely;
  - II_3 – shoots of the last two years are destroyed by frost;
  - II_4 – shoots of the last three years are destroyed by frost;
- III – trunks are damaged by frost or plants are frozen completely;
  - III_1 – arboreal plants are damaged by frost above snow cover;

III_2 – arboreal plants are damaged by frost till ground level or to root collar, but form new shoots during the next vegetation season;
III_3 – plants are destroyed by frost.

Statistical analysis

The data obtained were processed with the statistical software IBM SPSS Statistics 17. The correlation ratios were calculated. The link between two features, as well as its strength and significance, was evaluated by means of Spearman's rank correlation coefficient. Spearman's coefficient was calculated for nine taxa that had been established in four and more findings. PC-ORD 5 software was used to carry out the ordination of the taxa of American origin. Indirect analysis of gradients was done by applying detrended correspondence analysis (DECORANA).

RESULTS

During the research, altogether 47 taxa (15 species, 5 subspecies, 4 hybrids, 1 variety, 22 cultivars) were found; part of them can be traced in the largest dendrological greeneries in Latvia (National Botanical Gardens, Kalsnava Arboretum, etc.). The distribution was described for those taxa for which we had four or more findings (see Fig. 2). The most common native species is *T. cordata* (the number of findings 116). From the cultivated taxa *T.* × *vulgaris* was encountered most often (69), followed by *T. platyphyllos* 'Rubra' (46) and *T. platyphyllos* subsp. *cordifolia* (43).

Spearman's correlation coefficients for the geographical factors are shown in Table 2. The distance to the sea is closely related in 80% of the climatic variables. Of the climatic variables, in turn, 70% vary according to the height above sea level and longitude. Longitude explains the changes in the distribution of taxa in the direction from west to east. Negative correlations were discovered between longitude and the mean temperature of the coldest month (MTCM), the sum of negative temperatures (SNT), the duration of the vegetation period (VP), and the mean annual sunshine duration (MASD), while the correlations are positive with the mean temperature of the warmest month (MTWM), Conrad's continentality index (CCI), and Rasiņš's continentality index (RCI). Latitude, in turn, is useful in clarifying the distribution of woody plants in the south–north direction. A number of negative correlations are related to the decrease in temperature in the direction to the north: MTWM, sums of active temperatures (SAT), duration of the frost-free period (FFP), and CCI, etc. The least expressed correlations were found for the soil groups (SG) and the climatic factors.

From all *Tilia* taxa established in Latvia, Spearman's correlation coefficient was calculated for those species, subspecies, and hybrids that had more than four findings; the cultivars were not analysed separately. All in all, nine taxa were analysed (see Table 3).

Table 2. Spearman's correlation coefficients between geographical and soil variables and climatic variables (see Table 1 for acronyms)

Geographical and soil variables	Climatic variables									
	MTCM	MTWM	AP	SNT	SAT	VP	FFP	MASD	CCI	RCI
Longitude	−0.920**	0.529**		−0.942**		−0.779**		−0.838**	0.973**	0.787**
Latitude		−0.561**	0.385**		−0.722**		−0.585**		−0.378**	
Altitude	−0.773**			−0.807**	−0.273**	−0.688**		−0.729**	0.780**	0.733**
DS	−0.823**	0.457**	−0.210*	−0.842**		−0.625**		−0.756**	0.919**	0.668**
SG			0.352**					−0.246*		

* Significant at $P < 0.05$; ** significant at $P < 0.01$.

Table 3. Spearman's correlation coefficients for *Tilia* taxa and geographical parameters (see Table 1 for acronyms)

Taxon	Longitude	Altitude	DS	SG
T. americana		−0.320**	−0.254*	
T. amurensis				
T. amurensis var. *taquetii*				
T. × *euchlora*		−0.218*		
T. × *moltkei*				
T. platyphyllos subsp. *platyphyllos*	−0.262**	−0.263**	−0.346**	0.210*
T. platyphyllos subsp. *cordifolia*				
T. tomentosa				
T. × *vulgaris*				

* Significant at $P < 0.05$; ** significant at $P < 0.01$.

As to geographical variables, a number of weak and moderate correlations were discovered in the increase of the distribution of *T. platyphyllos* subsp. *platyphyllos* eastwards ($r_s = -0.262$). In three taxa a negative correlation with altitude was found: *T. americana* ($r_s = -0.320$), *T.* × *euchlora* ($r_s = -0.218$), and *T. platyphyllos* subsp. *platyphyllos* ($r_s = -0.263$). The distribution of *T. americana* ($r_s = -0.254$) and *T. platyphyllos* subsp. *platyphyllos* ($r_s = -0.346$) was correlated with the distance to the sea. A weak correlation with soil group was found for *T. platyphyllos* subsp. *platyphyllos* ($r_s = 0.210$). For none of the taxa a correlation of the distribution with latitude was discovered. No correlations were found between the geographical factors and the distribution of *T. amurensis*, *T. amurensis* var. *taquetii*, *T.* × *moltkei*, *T. platyphyllos* subsp. *cordifolia*, *T. tomentosa*, and *T.* × *vulgaris*.

Altogether, 10 climatic parameters were analysed; among them no correlations were found of the distribution of the *Tilia* taxa with the average temperature in July (MTWM), the duration of the frost-free period (FFP), and the mean annual sunshine duration (MASD). The remaining seven climatic variables had correlations with the distribution of four *Tilia* taxa (Table 4). There is a correlation between the average annual amount of precipitation and *T.* × *moltkei* ($r_s = 0.247$) and *T.* × *vulgaris* ($r_s = 0.214$). The findings of *T. americana* correlate with the average sum of active temperatures ($r_s = 0.219$), but *T. platyphyllos* subsp. *platyphyllos* correlates with the average temperature in January ($r_s = 0.317$), the perennial sum of negative temperatures ($r_s = 0.302$), the duration of the vegetation period ($r_s = 0.249$), Conrad's continentality index ($r_s = -0.306$), and Rasiņš' continentality index ($r_s = -0.268$).

DECORANA ordination was carried out for three linden taxa of American origin: *T. americana*, *T.* × *moltkei*, and *T. americana* 'Macrophylla' (Fig. 3). Our results reveal two negative ordinations that may explain the distribution patterns of the *Tilia* taxa of American origin in Latvia: height above sea level ($r = -0.481$)

Table 4. Spearman's correlation coefficients for *Tilia* taxa and climatic factors (see Table 1 for acronyms)

Taxon	MTCM	AP	SNT	SAT	VP	CCI	RCI
T. americana				0.219*			
T. amurensis							
T. amurensis var. *taquetii*							
T. × *euchlora*							
T. × *moltkei*		0.247*					
T. platyphyllos subsp. *platyphyllos*	0.317**		0.302**		0.249*	−0.306**	−0.268**
T. platyphyllos subsp. *cordifolia*							
T. tomentosa							
T. × *vulgaris*		0.214*					

* Significant at $P < 0.05$; ** significant at $P < 0.01$.

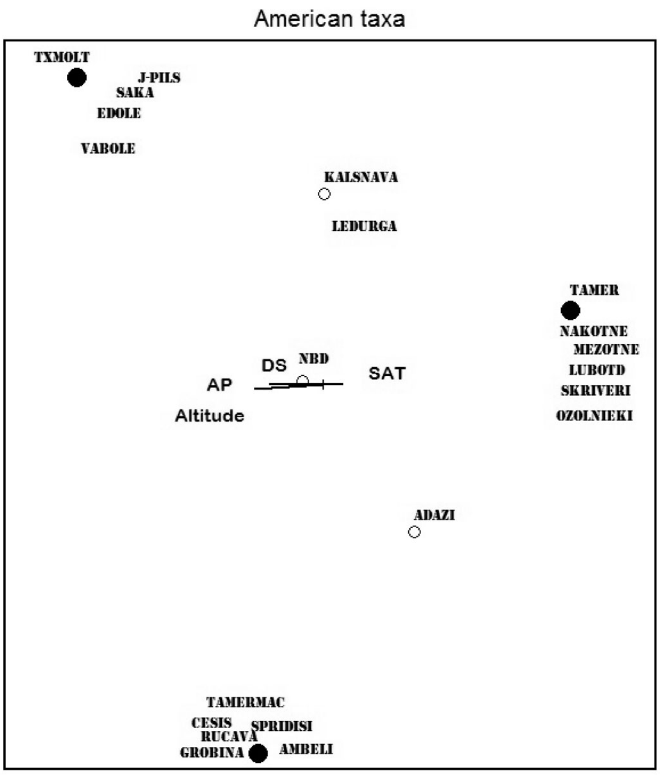

Fig. 3. Ordination of North American taxa of the genus *Tilia* (according to DECORANA); $n = 18$. Critical value of the correlation coefficient $r_a 0.05 = 0.468$. AP – annual precipitation, DS – distance to the sea, SAT – sum of negative temperatures, ALT – altitude, NBD – National Botanical Gardens.

and annual precipitation ($r = -0.393$). The dendrological greeneries situated on the right side of the figure are those where of the analysed American linden taxa only *T. americana* is to be found. These findings are situated 5–50 m a.s.l., and in most cases they are not farther than 80 km from the sea. The highest above sea level is Kalsnava (90 m). Kalsnava is also the farthest point from the sea (114 km) where *T. americana* is to be found. Kalsnava and Lēdurga are indicated separately in the figure because these have two taxa: *T. americana* and *T.* × *moltkei*. In National Botanical Gardens all the three American *Tilia* taxa are found. In Ādaži there are two taxa: *T. americana* and *T. americana* 'Macrophylla'. From seven findings of *T. americana* 'Macrophylla', six are not situated farther than 60 km from the sea, but one has been established even 204 km from the sea, at Ambeļi. Besides, Ambeļi is the place that is the highest above sea level – 140 m. *Tilia* × *moltkei* was found in comparatively more numerous places in eastern Latvia: in Kalsnava (114 km from the sea), Jēkabpils (121 km from the sea), and Vabole (184 km from the sea).

DISCUSSION

Geographical factors limiting the distribution of *Tilia* taxa

What are then the most essential factors that hinder successful introduction of the genus *Tilia* in Latvia? Nature researchers have faced this problem already since the middle of the 16th century, when intentional introduction of North American plants into European botanical gardens began (Golovkin, 1981). The acclimatization and successful introduction of plants out of their natural range are influenced by several geographical and climatic factors (Mauriņš, 1970; Januškevičius et al., 2006). Human role in the development of parks and dendrological greeneries is of great significance as well (Gostev and Yuskevich, 1991). The greater distribution of the genus *Tilia* in the western part of Latvia than in the eastern part of the country is related to the location of parks and gardens in Latvia as a whole. In general, the number of green areas falls in the direction from the west to the east (Rasiņš, 1962; Cinovskis et al., 1974; Laiviņš, 2010). The fact that the greatest number of parks and gardens is found in the west of the country, in Kurzeme, while in the east, in Latgale the number of green areas is smaller, is the result of the historical development of Latvia. There is a statistically valid ($p > 0.01$) negative correlation between the distance to the sea and the density of plantations in Latvia (Laiviņš, 2010). Thus the objects inventoried in Latgale are not very rich in the taxa of the genus *Tilia* (Laiviņš et al., 2009; Jurševska and Evarts-Bunders, 2010). The most frequently found taxa are *T. cordata*, *T.* × *vulgaris*, *T. platyphyllos*, and their most popular cultivars.

Tilia taxa from the Far East were introduced in Latvia in the 1960s (Laiviņš et al., 2009) after the establishment of the National Botanical Gardens in 1956 (NBD, 2014). Far Eastern taxa have been introduced in Latvia less frequently than American ones; they are found mainly in the National Botanical Gardens and Kalsnava Arboretum. Therefore further research is necessary to explain their successful introduction in East Latvia.

The distribution of *T. americana* and *T. platyphyllos* subsp. *platyphyllos* decreases as the distance from the sea increases. There have been separate attempts to plant more exotic taxa, for instance *T. americana* in Vecborne in the Krāslava region and *T. americana* 'Macrophylla' in Kombuļi (Cinovskis et al., 1989). However, during the present research these were not found there any more. Such extinction of trees from public greeneries testifies to the fact that there is a set of ecological features that determine the macrobiota of plantations.

For successful cultivation of exotic trees it is necessary to evaluate the microtopography in the concrete region (Lange et al., 1978). The inspected dendrological greeneries where the American taxa *T. americana*, *T. americana* 'Macrophylla', and *T.* × *moltkei* were found are situated 5–95 (140) m a.s.l. In Latvia the average altitude above sea level of the inspected nine *T. americana* localities is 30 m. The results of the current research indicate that the taxa introduced from America grow much better if planted in lowlands. In lowlands also the influence of winds is less expressed and thus the range of temperatures in winter is not so great (Mauriņš and Zvirgzds, 2006). However, observations made in Great Britain with *T. cordata* indicated that the distribution of *T. cordata* in northwestern England decreases rapidly at altitudes below 160 m (Pigott and Huntley, 1978).

Climatic factors limiting the distribution of *Tilia* taxa

Climate is one of the main factors determining the distribution and growth of tree species (Schweingruber, 1996; Fritts, 2001; Speer, 2010). The most essential climatic factors are the average mean temperature in January, the sum of negative temperatures, the duration of the vegetation period, the annual amount of precipitation, and continentality. A number of these factors are interrelated and affect each other to a certain extent. The obtained Spearman's correlation coefficient shows that the distribution of *T.* × *moltkei* and *T.* × *vulgaris* correlates with the annual average amount of precipitation: these taxa are more often found in places with a higher amount of precipitation. It was established in a research on the forests and tree species distribution of Northeast China that the distribution of *T. amurensis* in the wilderness is controlled by water (growing season precipitation and annual precipitation), annual potential evapotranspiration, and mean temperature of the coldest month (Wang et al., 2006). We did not analyse the coherence with *T. amurensis* and *T. amurensis* var. *taquetii* because during our research only four localities with them were found in the central part of Latvia.

Other authors defined *T. platyphyllos* subsp. *platyphyllos* as winter hardy only in Kurzeme (Mauriņš and Zvirgzds, 2006); however, we established that its distribution is affected by several environmental factors: average January temperature, sum of negative temperatures, duration of the period of vegetation, and Rasiņš' and Conrad's continentality indices.

The main problem might be the climatic differences from its natural area. For example, *T. tomentosa* is naturally distributed in Central Europe, where the average annual temperature is +11 °C, while in Latvia it is about +6 °C (Table 5). The more exotic taxon is being introduced, the longer period of time is necessary for its acclimatization.

Table 5. The average climatic variables at the southern and northern limits of the distribution of *Tilia* species in the world. AMT – annual mean temperature; for other acronyms see Table 1

Species	Southern/northern limits	AMT, °C	MTWM, °C	MTCM, °C	ALT, m	AP, mm
T. americana	Rīga, Latvia	+5.9	+17.0	–4.7	6	670
	Boston, USA	+10.8	+23.0	–1	38	1028
	Winnipeg, Canada	+3.0	+20.0	–17.5	240	540
T. amurensis	Shenyang, China	+8.4	+24.7	–11	43	711
T. platyphyllos	Isola, France	–	+23.5	+9.2	–	–
	Aarhus, Denmark	–	+16	+2	–	575
T. tomentosa	Timisoara, Romania	+11	+21	–1	93	620
	Vicos, Greece	+11.9	+22	+3.7	550–1778	1100

– No data.

Winter hardiness of *Tilia* taxa in Latvia

One of the limiting factors in the growth of trees is their winter hardiness. First observations on the winter hardiness of cultivated woody plants in the territory of Latvia were carried out by J. Cigra after the extremely hard winters of 1798/1799 and 1799/1800, when orchards were frozen out in the whole territory of the Baltic countries (Evarte-Bundere and Evarts-Bunders, 2011). The introduction of plants is definitely hindered by the extreme temperatures during severe winters (Mauriņš, 1962; Zvirgzds, 1962; Igaunis and Bandere, 1983; Pellett, 1994). Winter hardiness of woody plants, including the genus *Tilia*, in the Baltic States has been evaluated several times, especially after the hard winters of 1939/40, 1955/56, 1978/79, and 2009/10 (Lange, 1957; Ozols et al., 1959; Mauriņš, 1962; Igaunis and Bandere, 1983; Cinovskis et al., 1987; Laas, 1987; Tänavots, 1987; Januškevičius et al., 2006; Evarte-Bundere and Evarts-Bunders, 2011). According to these studies *T. americana*, *T.* × *moltkei*, and *T. platyphyllos* were considered as completely winter hardy taxa. In the winter of 1978/79 frost damage was observed for *T. tomentosa* in the north-eastern part of Latvia in Maliena 'Dārznieki' III_1 (Cinovskis et al., 1987); in 2010 the taxon was not found there any more. The winter of 1978/79 damaged also *T. amurensis* in Lāčupīte arboretum III (Mednis, 1987). Mauriņš and Zvirgzds (2006) indicate that it is only in Kurzeme that *T. platyphyllos* subsp. *platyphyllos* and *T. platyphyllos* subsp. *pseudorubra* are winter hardy and are not damaged by frost. During the current research the last year's shoots, on rare occurrence shoots of the last two years, of several taxa, for example *T. americana*, *T.* × *moltkei*, *T. tomentosa*, and *T. amurensis*, were found to be damaged by frost (Table 6).

Every taxon of *Tilia* is attributed to the respective plant hardiness zone (Page and Olds, 1997) (Fig. 4) in which they can grow, as well as the degree of frost damage in the territory of Latvia (according to the author's research) (Table 6).

Table 6. Distribution areas of the genus *Tilia* and plant hardiness zones with hardiness in Latvia

Taxon	Distribution	Plant hardiness zones	Hardiness by Sokolov
T. americana	Eastern part of North America	3–9	I–II_3
T. caroliniana	Southern part of North America	7–9	II_1
T. heterophylla	Eastern part of North America	4–9	I
T. × *flavescens*	Cultivated tree in Central Europe	–	II_1
T. × *flaccida*	Cultivated tree in Central Europe	–	I
T. × *moltkei*	Cultivated tree in Central Europe and North America	5	I–II_3
T. cordata	Temperate lowlands of Europe and western Asia	2–9	I
T. dasystyla subsp. *dasystyla*	Endemic in Crimean mountains		II_1
T. dasystyla subsp. *caucasica*	Crimean mountains and Caucasus region	5	–
T. tomentosa	South-eastern Europe and north-western Asia Minor	5–9	I–II_3
T. platyphyllos subsp. *platyphyllos*	Central Europe and South Europe	5–9	I–II_1
T. platyphyllos subsp. *cordifolia*	North, Eastern, and Central Europe	5–9	I–II_1
T. platyphyllos subsp. *pseudorubra*	South Europe	5–9	II_1
T. × *euchlora*	Cultivated tree in Central Europe	4–9	I–II_1
T. × *vulgaris*	Cultivated tree in Central Europe	3–9	I
T. amurensis	Russian Far East and north-eastern China	4–9	I and II_4 (Ranka)
T. amurensis var. *taquetii*	Russian Far East and north-eastern China	4–9	I and III_1 (Skrīveri)
T. japonica	Eastern China and Japan	6–10	II_1
T. kiusiana	Endemic south-western Japan	6	I
T. mongolica	Mountains of Inner Mongolia, northern Korea	3–9	II_3
T. sibirica	Western Siberia	3–8	III_2
T. insularis	South Korea	–	II_3

The data presented in the table indicate that the plant hardiness zones are rather large and practically all the considered taxa could grow in Latvian conditions, but they would suffer from frost; in some cases they might even be completely damaged by frost before snow cover. Freezing above the snow level was observed with *T. sibirica* in the National Botanical Gardens. It is noteworthy that *T. caroliniana* was found in 16 dendrological objects according to the inventory of Latvian dendroflora carried out in the 1970s (Laiviņš et al., 2009; Jurševska and Evarts-Bunders, 2010). However, having inventoried all these objects we

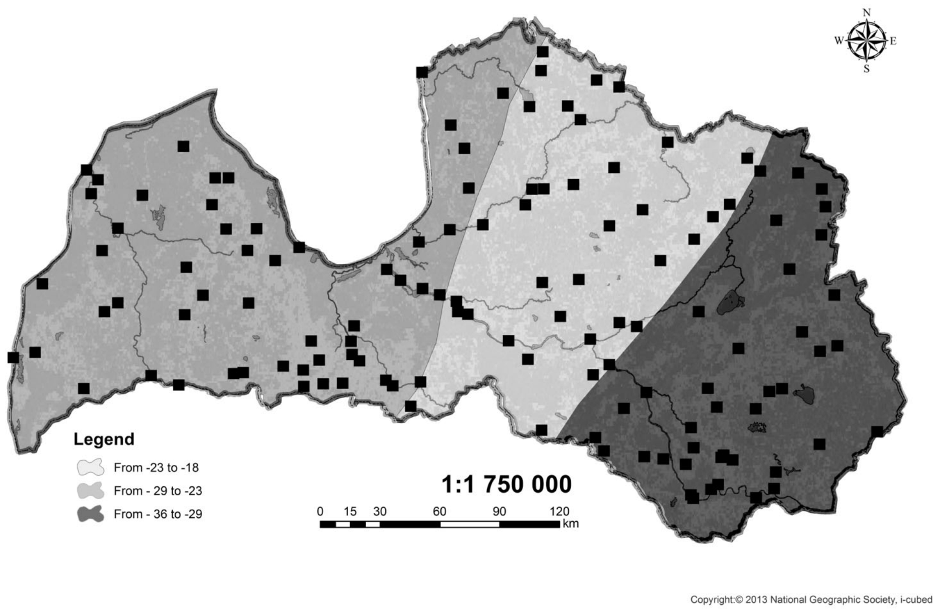

Fig. 4. Map with plant hardiness zones in Latvia with average winter temperatures and the objects inventoried.

found that the species has established only in Pūre, which belongs to the 6th winter hardiness zone. The last year's shoots of *T. caroliniana* had frost damages there. It has not preserved in other dendrological plantations in Kurzeme either. This allows for the conclusion that *Tilia* taxa are practically not able to grow outside the indicated hardiness zones.

The results of this research permit us to draw several important conclusions about the regularities of the factors affecting the distribution of the genus *Tilia* in Latvia. The geographical distribution pattern of *Tilia* taxa is determined by several geographical and climatic factors: average January temperature, sum of negative temperatures, annual amount of precipitation, duration of the vegetation period, altitude above sea level, distance to the sea. The main limiting factor for the growth of linden in Latvia is considered to be distance to the sea, which is closely related to climate continentality and altitude above sea level.

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