Further East: Eutrophication as a major threat to the flora of Vladimir Oblast, Russia

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Abstract

Eutrophication remains a major threat to the flora of western Europe despite measures to reduce nitrogen emissions. Although nutrient enrichment has been recorded for both inland waters and adjacent seas, there is almost no evidence from Russia for large-scale anthropogenic eutrophication of soils and its impact on terrestrial biota. I used the distribution grid data (337 grid squares, ca. 96 square km) on 1384 vascular plants of Vladimir Oblast for two periods (1869–1999 vs. 2000–2012) to estimate the shifts in mean Ellenberg's indicator values for nitrogen and soil reaction. Decadal changes in the flora of acid sandy Meshchera Lowlands were observed directly during two grid surveys of 2002 and 2012 based on a coarser grid (50 squares, ca. 24 sq km). Despite the spatial correlation of Ellenberg's indicator values for soil reaction and nitrogen, mean grid values for nitrogen are growing in areas with both acid and neutral soils. The changes in mean grid indicator values for nitrogen are caused by either local extinctions of species from nutrient-poor habitats or spread of nitrophilous plants. I found that nutrient-poor habitats are declining rapidly within the eutrophic loamy landscapes. In contrast, changes in landscapes with acid sandy soils are caused by increasing number of records of nitrophilous species, both invasive and native. These two processes have different spatial patterns caused by varying levels of geochemical buffer capacity and should be considered separately. Fragmentary historical data on Vladimir Oblast flora agrees with the overall European picture of eutrophication in the 20th century.

Keywords—eutrophication, Russia, flora, Ellenberg's indicator values, grid mapping, grid survey.

1. Introduction

Eutrophication has been identified as the main driving force of shifts in spatial patterns in the European flora over the last decades. Cardinal changes in vascular plant flora caused by nutrient enrichment have been shown for the United Kingdom, Belgium, the Netherlands, and Germany (e.g. Hodgson, 1986; Kowarik, 1990; McCollin et al., 2000; Godefroid, 2001; Tamis et al., 2005ab; Braithwaite et al., 2006; Van Landuyt et al., 2008). As a general rule, eutrophication causes two interconnected processes, i.e. decline or local extinction of oligotrophic species and spread of plants typical of nutrient-rich habitats. Changes in the nitrogen cycle in terrestrial ecosystems have been described in general and in detail (for instance, see reviews by Jordan & Weller, 1996; Vitousek et al., 1997; Galloway, 1998; De Jonge et al., 2002; Matson et al., 2002; Gruber & Galloway, 2008).

The Russian Federation currently holds 8.8% of the world's arable lands. During 2008, Russian agriculture consumed 1.9 million tonnes of mineral fertilizers (FAO, 2010). Recently, some large-scale studies have revealed nutrient enrichment of the adjacent seas and inland freshwater bodies (e.g. Korneva & Mineeva, 1996; Trifonova, 1998; Rumyantsev et al., 1999; Pogozhev & Gerasimova, 2001; Golubkov et al., 2003; Rukhovets et al., 2003; Selifonova, 2009; Aleksandrov, 2010). Ironically, there is little evidence from Russia to support the proposition that anthropogenic eutrophication affects terrestrial biota (e.g. Puzachenko et al., 2010; Avetov & Shishkonakova, 2013). Moreover, some published results suggest that eutrophication accompanies natural successions in pine forests (Polyakova et al., 2011).

Indicator values are widely used for assessing of floristic spatial patterns. Ellenberg's indicator values and their regional adjustments (Ellenberg et al., 2001; Hill et al., 1999; Böhling et al., 2002; Pignatti et al., 2005) are the most popular indicator values in both national and local studies, although results of these studies are sometimes considered as *"too good to be true"* (Zelený & Schaffers, 2012). When analysing grid square floristic data, various authors have used

Ellenberg's indicator values in different ways either for species pools or for grid squares (Godefroid, 2001; Schmidtlein, 2004; Tamis et al., 2005b; Braithwaite et al., 2006; Petřík & Wild, 2006; Piessens & Hermy, 2006; Van Landuyt et al., 2008, 2011; Otýpková et al., 2011).

Russian terrestrial ecologists are paying little attention to differences between acidity and soil nitrogen, because nutrient-poor calcareous sands or any nutrient-rich acid habitats are extremely rare in Russia. Combined indicator values for fertility and salinity proposed by Ramensky et al. (1956) are widely used in Russian literature instead of separate ones. Ramensky's indicator values arrange the habitats from nutrient-poor ones with $pH < 4.5$ (peatbogs) via nutrient-rich ones with $pH = 7.0$ (steppes on chernozem soils) back to nutrient-poor solonchaks with $pH > 9.1$. Ellenberg's indicator values could help us to separate fertility and reaction.

An overall decline in the distribution of species from nutrient-poor habitats throughout Europe has been detected using Ellenberg's indicator values for soil pH (R-values) and nitrogen (N-values) (Braithwaite et al., 2006; Tamis et al., 2005b; Van Landuyt et al., 2008). Van Landuyt et al. (2008, 2011) presented maps of changes in mean grid N-values over the last decades and calculated mean grid values for various phytogeographic floristic groups within northern Belgium.

There are no regional grid mapping projects in Russia beside collaboration in *Atlas Florae Europaeae*. The density of both published records and herbarium collections is low even in the vicinities of Moscow and St. Petersburg, areas that are considered to be well-studied. Thus, virtually no quantitative data exist for historical analysis.

Grid mapping of Vladimir Oblast flora was launched in 1999 (Seregin, 2000). Thirteen years of intensive recording effort resulted in recently published *Flora of Vladimir Oblast, Russia* (Seregin et al., 2012). This includes 1361 distribution maps of vascular plants. The territory was considered fairly well studied in the past starting from the standard *Flora des Gouvernements Wladimir* (Fleroff, 1902), a comprehensive data book of local plant diversity.

Careful consideration of all available historical data allowed reconstruction of the overall picture of local plant extinctions. Furthermore, maps of endangered and extinct plants in Vladimir Oblast are similar to maps from national atlases with larger historical data (Kukk & Kull, 2005; Van Landuyt et al., 2006; Floron, 2011; BSBI, 2013; FloraWeb, 2013).

Van Landuyt et al. (2008) showed that the largest shifts in indicator values for nitrogen in northern Belgium were observed in areas with nutrient-poor acid sandy soils. However, previous study of the changes in distribution of two louseworts (*Pedicularis palustris* and *P. sceptrum-carolinum*) in Vladimir Oblast derived the opposite result—species from nutrient-poor habitats have disappeared in many localities throughout naturally eutrophic landscapes (Seregin, 2011). These areas were widely used for agriculture in the 20th century with extensive organic and mineral fertilizing, and small plots of nutrient-poor habitats (like *Nardus* heaths, spring fens, or coniferous woodlands) became exposed to modified geochemical cycles.

Thereby, the aim of this study is to reveal spatial patterns of eutrophication impact on flora of Vladimir Oblast using historical data. I hypothesised that floral shifts could be controlled by either local extinctions of oligotrophic species or penetration of nitrophilous plants. To check this assumption, it has been important to estimate an intensity of these shifts in various landscapes within the Oblast like wet acid nutrient-poor Meschera Lowlands, wet neutral nutrient-rich Klin-Dmitrov Ridge, dry acid nutrient-poor Oka-Tsna Ridge, and dry neutral nutrient-rich Opolye. A key issue of this study is to define species with the highest extinction rates and the most successful invaders.

2. Materials and methods

2.1. Study area

Vladimir Oblast is situated in the centre of East European Plain ca. 100–400 km east of

Moscow. It stretches ca. 190 km from north to south and ca. 290 km from west to east covering 29 084 square km. Mean January temperature is –8.5°C, mean July temperature is +18.8°C, and mean annual temperature is +4.7°C (Pogoda i klimat, 2013). Mean annual precipitation is 585 mm with the highest precipitation in summer months. Continentality is more pronounced along the eastern border of Vladimir Oblast.

Figure 1 shows the prevailing soil conditions determined by mean grid indicator values for moisture, nitrogen and soil reaction. Wet, acid, nutrient-poor soils are peculiar for sandy alluvial and fluvioglacial lowlands (3). Dry, neutral, nutrient-rich soil conditions dominate in agricultural Opolye region and areas along the major rivers (6). Dry, acid, nutrient-poor soils are located in axial zone of a carbonate fold covered by fluvioglacial sand and sandy loam (7). Wet, neutral, nutrient-rich soils cover Klin-Dmitrov Ridge, the highest upland of Vladimir Oblast reaching 271 m above sea level (2). Other types of soil conditions are typical for ca. 20% of grid squares (1, 4, 5, and 8).

Vladimir Oblast is situated in the ecotone between boreal coniferous and temperate broadleaf forests. Distribution of forest types within the region is clearly determined by soil conditions. Both boreal coniferous forests dominated by *Pinus sylvestris* and *Picea abies* on various nutrient-poor substrata and temperate broadleaf forests with *Quercus robur*, *Tilia cordata*, and *Ulmus glabra* on loamy eutrophic soils are the main components of original (pre-man) vegetation. Other native plant communities of Vladimir Oblast are peatbogs, xeric meadows on steep slopes, and alder stands along lesser streams, as well as meadows, marshes, and willow thickets on flood plains. Currently, 29.9% of land is used for agriculture, while 55% is covered by forests (official data).

Floristic divisions of Vladimir Oblast (fig. 2) are based on UPGMA cluster analysis of grid data (Seregin, 2014). The characteristic species of divisions with the highest *IndVal* score (Dufrêne & Legendre, 1997) are indicated in the figure legend. This scheme corresponds to some extent to landscape divisions (Gvozdetsky & Zhuchkova, 1963; Seregin, 1994). Balakhna

Lowland is the most distinct region with pine forests of *Pyrolo–Pinetea* class and *Oxycocco–Sphagnetea* peatbogs. Three spatially separated divisions (Meshchera Lowlands, Nerl district, and Lower Oka district) have similar flora and vegetation consisted of *Vaccinio–Piceetea* boreal coniferous woods and variable wetland vegetation. In contrast, Oka-Tsna Ridge with similar boreal forests has almost no species from wet habitats due to the proximity of limestone. Klin-Dmitrov Ridge has the most eutrophic conditions and is characterised by *Querco–Fagetea* and *Galio–Urticetea* classes, while in the adjacent Opolye *Querco–Fagetea* woodlands are enframed by *Trifolio–Geranietea sanguinei* communities. Gorokhovets Ridge and Oka Plain are covered by *Querco–Fagetea* woods and xeric meadows with some diagnostic species of *Festuco–Brometea* class. Sudogda Upland is the only region where both *Querco–Fagetea* and *Vaccinio–Piceetea* communities are equally present.

2.2. Grid scheme and floristic dataset

The Vladimir Oblast coordinate grid 5×10 minutes (ranging from 94.7 to 98.2 square km) is based on WGS84 datum. In 1999–2012, each of 337 grid squares was sampled at least once from 5 July to 15 September when the highest number of species could be observed. Grid squares with a low proportion of Oblast’s land were not studied. Topographic maps and satellite images were studied to reveal areas of potential botanical interest before the field survey. A list of the 680 most common species was used during field recording. 452 species were recorded during one day in the most diverse grid square.

Maps of the *Flora of Vladimir Oblast* (Seregin et al., 2012) include ca. 118 000 grid-based records. Additional records are resulted from field excursions during 2012. As of May 2013, there were 120 883 records of 1 384 species in the database, excluding records for aggregates based on records of microspecies and erroneous records. If a species was recorded in a grid square several times, only the latest record is considered. On average, 359 species were recorded in each grid square.

The majority of records (93.5%) were collected since 1999. Historical block includes 7 236 records made before 1999 by various authors and not confirmed later. They are based on herbarium collections, published data, and manuscripts. The most important collections from Vladimir Oblast are deposited in the Moscow University herbarium (MW), the Komarov Institute herbarium in St. Petersburg (LE), and Murom Art Museum (ca. 3 700 historical records). Locally published floristic data include ca. 2 800 historical records. Additionally, ca. 700 historical records were extracted from unpublished manuscripts.

A list of extinct vascular plants of Vladimir Oblast (table 1) includes 40 native species and archaeophytes. There are no confirmed records of these plants since 1951. Native plants and archaeophytes recorded from at least five localities were considered declining if an extinction rate calculated as a proportion of pre-1949 records is higher than 30%. Fourty species listed below meet these criteria (table 2). Nomenclature follows Seregin et al. (2012).

2.3. Ellenberg's indicator values and statistical analysis

The third edition of Ellenberg's indicator values (Ellenberg et al., 2001) includes data on 1 005 species of Vladimir Oblast vascular plant flora out of the 1 384 species. No species with missing values were considered in the calculations, including some widespread species, namely, *Heracleum sibiricum*, *Malus domestica*, *Carex acuta*, etc. Hopefully, this will not significantly affect the results because 379 species with missing values hold only 9.3% of the records. Also, no species with wide ecological amplitude (i.e. with "x" values for the considered variable) were included in the analysis. As a result, 61.9% of records from the database including 4 914 historical records have values for soil reaction (R) and 80.5% of records including 5 562 historical records possess values for nitrogen (N). It should be stressed, that mean Ellenberg's indicator values are rather robust with respect to the number of species involved in floristic studies (Ewald, 2003; Otýpková, 2009; Otýpková et al., 2011).

I compiled separate maps of mean grid N-values for recent and unconfirmed historical records, as done by Van Landuyt et al. (2008). These mean values are based on species presence with no reference to abundance and therefore unweighted. The superimposed resulting map shows the difference between current and historical average values (fig. 4). This is based on data from 50.5% grid squares with more than six historical records with values for nitrogen.

Statistical analysis was performed in *MS Excel* environment using *StatistiXL* (www.statatistixl.com) and *Real Statistics* (www.real-statistics.com) software which extends *MS Excel*'s built-in statistical capabilities.

In this study, the coefficient of determination (r^2) of simple linear regression is the square of the sample correlation coefficient between mean grid indicator values for soil *pH* and nitrogen ($p < 0.001$). Mean values are accompanied with standard error of the mean.

A nonparametric Mann-Whitney U-test was used to compare a difference in Ellenberg's indicator values for the whole dataset and for historical records only. A t-test was performed for comparison of mean grid values.

2.4. Experimental tracking of short-term changes in flora of the Meshchera Lowlands

Meshchera Lowlands with nutrient-poor landscapes which are presumably sensitive to eutrophication, have virtually no historical floral records (fig. 4). The most pronounced oligotrophic acid sandy landscapes are situated in the Meshchera National Park on south east corner of Vladimir Oblast (fig. 1). Typical features of the national park vegetation are pine forests on fluvioglacial and alluvial sands, large bogs either survived or drained for peat mining, marshes and alder forests along slow rivers, and areas deforested due to frequent fires.

In order to test conjecture by Van Landuyt et al. (2008) for vulnerability of flora of nutrient-poor acid sandy landscapes two grid surveys were performed in decadal interval within the Meshchera National Park. These studies were based on a finer grid 2.5×5 minutes (ca. 24 square km). In 2002, the first survey describing 57 grid squares was performed by me and my wife Irina Privalova, and the resulting maps were published in the atlas (Seregin, 2004). Ten years later, the same grids and 23 supplementary ones were described (Seregin, 2013). Seven grid squares with the lowest number of 2002 records (<56%) were excluded from further analysis. Thereby, the species dynamics in Central Meshchera was revealed using data from 50 grid squares with 10 132 records made in 2002 and 13 515 records in 2012 (33% increase). Successful invaders have rates of increase far beyond 33%. Relative Change index (*RC*) between 2002 and 2012 and its 90% confidence limits were calculated following Braithwaite et al. (2006) for species with more than three records. Unfortunately, *RC* is not applicable for species with no confirmed records from at least one grid square.

3. Results

3.1. Mean Ellenberg's indicator values of the dataset and spatial shifts of N-values

Mean grid Ellenberng's indicator values for soil *pH* (R-values) and nitrogen (N-values) show similar spatial patterns with $r^2 = 0.6245$ ($p < 0.001$) (fig. 5). Grid squares of Klin-Dmitrov Ridge are more acidic than those in Opolye, although these floristic divisions are both have eutrophic conditions. Both being oligotrophic, Oka-Tsna Ridge is, on the average, more neutral (and dry) than the Meshchera Lowlands (fig. 1).

Mean R-values demonstrate virtually no shift in time with 5.92 ± 0.01 for the whole dataset (n = 74 823) and 5.98 ± 0.03 for historical records only (n = 4 914). Mean N-values have changed over time more than R-values—4.96 ± 0.01 (n = 97 297) and 4.30 ± 0.03 (n = 5 562) respectively. There are significant differences according to the Mann-Whitney U-test in both cases ($p < 0.001$), but the median R-value has not changed (fig. 3).

Mean grid N-values for unconfirmed historical records were lower in 148 grid squares, while mean values increase in 22 squares (fig. 3). The median grid shift is 0.79 vs. 0.66 for the whole dataset. Historical mean grid N-values are significantly different from overall mean grid N-values according to t-test ($t = –12.9186$, $df = 338$, $p < 0.001$). Unfortunately, no solid assumptions on environmental shifts could be made for grid squares excluded from the analysis, but there is no other basis because merely all historical records were considered.

Map of shifts in mean N-values (fig. 4) shows pronounced spatial peculiarities. Dry acid landscapes in the axial zone of Oka-Tsna Ridge have the most considerable shifts to nutrient-poor scores in the past. Eutrophic neutral landscapes of Klin-Dmitrov Ridge and Opolye have only two green scores. There are virtually no data from wet acid sandy landscapes like central part of the Meshchera Lowlands or Lower Oka district. On the contrary, grid squares along the major watercourses like the Klyazma River or the Oka River have the lowest negative shifts. Dry eutrophic landscapes of Oka Plain in the southeastern corner of Vladimir Oblast demonstrate no pronounced changes. This is likely to be true, because this green cluster includes grid squares with both large and fragmentary historical datasets.

3.2. Species assessment: extinct and declining natives vs. successful neophytes

Plants considered extinct in Vladimir Oblast (table 1) are declining all over Middle Russia, especially on range fringes, and they would have been most unlikely to be rediscovered. However, tiny populations of *Lithospermum officinale* and *Hammarbya paludosa*, previously considered extinct (Seregin et al., 2012), were recently recorded in new localities.

We may roughly estimate an extinction rate in Vladimir Oblast vascular plant flora as 0.7 species per year. It is based on the last records of species in 1891–1951. Assuming the same extinction rate for subsequent 60 years, ca. 40 species recorded in 1952–2012 will not be rediscovered. For instance, there are no confirmations since mid-1970s of *Arabis sagittata*, *Bromus arvensis*, *B. secalinus*, *Epilobium collinum*, *Filago minima*, *Hypericum hirsutum*, *Senecio vernalis*, and *Xanthium strumarium* listed in table 2.

Grid data collected in 1999–2012 have only a limited suitability for study of plants progress over the last century. For each neophyte species, I have only two variables—current number of grid squares and a year of the first record (if known). Table 3 includes the 40 most widespread neophytes with the earliest records in Vladimir Oblast since mid-19th century.

Figure 6 shows fairly even distribution of extinct and declining species across R-indicator values with two peaks (3–4 and 7–8). The majority of successful neophytes prefer neutral conditions (7). Indicator values for nitrogen exhibit significant difference between species pools—the median N-value for extinct species is 4, for declining is 3, while for the top 40 neophytes is 6 (Mann-Whitney U-test for extinct species vs. neophytes and declining species vs. neophytes, $p < 0.001$). The difference is even more pronounced in grid calculations due to wide distribution of selected neophytes.

3.3. Distributional changes in species over the last decade: the Meshchera case-study

Many plants in the Meshchera National Park significantly changed their distribution over the last ten years. For instance, 44 increasing species and a dozen of decreasing plants were recorded.

A list of the most successful invaders includes ten species with the highest *RC* indexes (table 4). Evidently, many of them are rapidly spreading in temperate regions all over the world. The list should be supplemented by plants lacking confirmations from at least one grid square. Showy *Jacobaea vulgaris* (25 squares in 2012) and *Epilobium tetragonum* (24 squares in 2012) were definitely absent in the park ten years ago, while annual vetches *Vicia angustifolia* (1 grid square in 2002 vs. 9 squares in 2012) and *V. hirsuta* (1 square in 2002 vs. 8 squares in 2012) were rare casuals here. These four plants prefer sandy abandoned fields, a clear evidence of a decline in Russian agriculture.

Species with the highest extinction rates as revealed by *RC* indexes are also listed in table 4. Few other species like *Salix lapponum* (10 grid squares in 2002 vs. 5 squares in 2012), *Lepidium ruderale* (8 squares in 2002 vs. 2 squares in 2012) and *Leontodon hispidus* (6 squares in 2002 vs. 2 squares in 2012) also have a pronounced decline, but no confirmations from at least one grid square exist. Since 2002, a decline in the Meshchera Lowlands of three oligotrophic species, namely *Pedicularis palustris*, *Eriophorum angustifolium*, and *Salix lapponum*, was detected.

4. Discussion

Mean Ellenberg's indicator values for nitrogen have changed significantly throughout Vladimir Oblast. The shifts were detected in the areas with various soil conditions throughout the region. The majority of extinct and declining species are typical for nutrient-poor habitats, whereas the most common neophytes are nitrophilous plants. In the Meshchera Lowlands, six out of the top ten spreading species are typical for nutrient-rich conditions. In contrast, only three out of the ten most declining species are oligotrophic plants, but their reduction could be caused by a series of hot summers during the last decade (Black et al., 2004; Barriopedro et al., 2011).

Although mean indicator values for nitrogen and soil reaction were spatially correlated in Vladimir Oblast (fig. 5), they are not shifting simultaneously through time. Species from nutrient-poor habitats are declining in Vladimir Oblast irrespectively to soil reaction values. For instance, declining (or extinct) species like *Herminium monorchis, Scabiosa ochroleuca*, *Liparis loeselii*, *Polygala amarella*, *Pedicularis sceptrum-carolinum*, and *Eriophorum latifolium* are typical for basic soils while *Potentilla collina*, *Neottia cordata*, *Scheuchzeria palustris*, *Epilobium collinum*, *Polygala vulgaris*, and *Radiola linoides* are indicators of acid habitats. Both Tamis et al. (2005b) for the Netherlands and Van Landuyt et al. (2008) for Flanders pointed out that changes in mean grid R-values are highly correlated with changes in mean N-values, causing a problem of correct data interpretation. On the contrary, Godefroid (2001) demonstrated that from 1940 onwards the flora of the Brussels area, Belgium has become more nitrophilous, while it does not differ with respect to soil reaction. The flora of Vladimir Oblast has shown the same trends.

Total eutrophication of the environment affects both sandy and loamy areas regardless of the current agricultural development. Spatial examination of the results from the current study for declining and invasive species shows a complex picture of the changes in Vladimir Oblast flora. These results do not contradict conclusions by Van Landuyt et al. (2008) for large-scale changes in the flora of nutrient-poor landscapes in Flanders and assumptions on rapid decline of nutrient-poor habitats and species throughout eutrophic landscapes of Vladimir Oblast (Seregin, 2011). Contrary to Van Landuyt et al. (2008), the results from the current study suggest separation of the two processes of extinction of oligotrophic species and the penetration of eutrophic species, as these processes have resulted in different spatial patterns. Tamis et al. (2005ab) reported that in the Netherlands both processes are almost equally pronounced, but no spatial differentiation within the country was investigated.

Mean grid N-values have showed an increase on loamy neutral soils of Klin-Dmitrov Ridge and Opole mainly due to the extinction of species typical for oligotrophic habitats. For instance, in 2009 a dense spruce woodland with *Lamiastrum galeobdolon* was described in place of a pine forest with *Trifolium montanum, Antennaria dioica, Myosotis stricta*, and *Anthoxanthum odoratum* recorded in 1894 (Fleroff, 1902). Similar changes are evident throughout the moraine landscape of Klin-Dmitrov Ridge. *Chimaphila umbellata, Moneses uniflora,* and *Pyrola chlorantha, Pedicularis palustris, P. sceptrum-carolinum* are considered extinct in this area as well as *Potentilla alba*, *Rubus arcticus*, and *Orchis militaris* (Seregin et al., 2012). It is assumed that eutrophication provides competitive advantages to species with prominent vegetative mobility from nutrient-rich habitats (for example, Wedin & Tilman, 1993;

Grime, 1994; Sammul et al., 2003).

A decline of species from nutrient-poor habitats is almost unnoticeable on the vast sandy plains of the Meshchera Lowlands and Oka-Tsna Ridge, areas with low proportion of currently used arable land and an unexhausted geochemical buffer capacity (Glazovskaya, 1983; Annenskaya et al., 1997). Therefore, the distribution of many oligotrophic species has shrunk towards the Meshchera Lowlands and Oka-Tsna Ridge over the last century. The Meshchera Lowlands provide a secure shelter for species from acid habitats, while the ridge is a refuge for plants from weakly acid to weakly basic conditions.

The shifts in mean grid values for nitrogen in the Meshchera Lowlands are controlled by penetration and rapid spread of eutrophic species. *Bidens frondosa*, *Galinsoga parviflora*, *Echinocystis lobata*, *Chelidonium majus*, *Epilobium hirsutum* and *Erigeron septentrionalis* (i.e. six out of eight species with N-values listed in table 3) were rated 8 in indicator values for nitrogen (Ellenberg et al., 2001). It means that these plants often found in richly fertile places and, furthermore, might be indicators of extremely rich situations, such as cattle resting places or banks of polluted rivers. Damp roadside ditches, drainage lines of peat harvesting fields, and private gardens are the most favourable habitats for establishing eutrophic plants in Central Meshchera.

The similar tendencies of local plant extinctions throughout Europe are even more obvious on a species level (fig. 7). Extinct and declining plants of Vladimir Oblast are evidently threatened in both Northern Germany and Estonia, the nearest areas where grid atlases with clearly marked historical records were published (Kukk & Kull, 2005; FloraWeb, 2013). Similar species scenarios have resulted from the same changes in environment and land use throughout Europe.

The loss of oligotrophic species is compounded by the direct destruction of some nutrient-poor habitats. Few major peatbogs were drained for mining in 1930–1980’s or replaced by poor pastures in Vladimir Oblast. Thus, some local populations of bog species were demolished.

The main decadal change recorded in the Meshchera flora has been a gradual increase in number of species both in the national park and in grid squares. This may be explained by a bias of sampling intensity, but this is not relevant for both increasing and declining plants (table 4), as they are noticeable and easy recognisable. A list of species which are increasing in their distribution may be expected and composed mainly of recently introduced neophytes. *Nuttalanthus canadensis* (first recorded in 1995), *Bidens frondosa* (1997), or *Aronia mitschurinii* (2002) are still colonizing suitable new habitats throughout Vladimir Oblast.

A list of declining species in the flora of Meshchera is more surprising, particularly a rapid mass extinction of railway plants like *Artemisia sieversiana*, *Ribes uva-crispa*, *R. aureum*, *Agropyron pectinatum*, *Fagopyrum tataricum*, *Hyoscyamus niger* and *Carlina biebersteinii*. These declines have been caused by permanent use of powerful herbicides by the *Russian Railways*.

A decline of *Lepidium ruderale* was already reported from Kaluga Oblast (Reshetnikova et al., 2010). There was a persuasive argument that it was outcompeted by recently introduced American *L. densiflorum* (Vinogradova et al., 2009; Reshetnikova et al., 2010) but this assumption is questionable. *Lepidium ruderale* and *L. densiflorum* have different ecological preferences in Vladimir Oblast. They have not been recorded growing together beside railway beds. The former species prefers residential areas, weedy places, and field margins being typical for heavy and manured soils. The latter species prefers open soils, either sandy or stony, pine forest margins and road verges.

Rapid spread of *L. densiflorum* since the first record in 1967 coincided with the beginning of *L. ruderale* decline. Local extinction of *L. ruderale* in rural areas is a consequence of changes in the rural lifestyle and reduction of private livestock. The streets and outskirts of Russian villages are now lacking fresh manure deposits, a favourite habitat of the species. A similar decline in distribution was recorded for *Urtica urens*, *Amaranthus blitum*, *Asperugo procumbens* and *Geranium pusillum*. Local extinctions of plants typical for heavily manured soils are apparently the only example of nutrient-rich habitats destruction.

Presented results seem to be important for outworking of conservational strategy in Vladimir Oblast as well as in adjacent regions with similar physical conditions. Undoubtedly, some issues of plant protection should be reconsidered. For instance, the regional Red List applies throughout the Oblast without any local differentiation. Due to this, many vulnerable plants of nutrient-poor habitats do not have any legal protection at all, because they are fairly common in the Meshchera Lowlands. For example, *Antennaria dioica* and *Nardus stricta* are still abundant throughout oligotrophic landscapes of Vladimir Oblast, but rapidly decreasing in nutrient-rich Opolye and Klin-Dmitrov Ridge.

In contrast, few nitrophilous species typical for broadleaf forests of Klin-Dmitrov Ridge were included into the regional Red List due to overall rarity of habitats. Nonetheless, within this area such species like *Brachypodium sylvaticum*, *Bromopsis benekenii*, *Carex sylvatica*, *Vicia sylvatica*, *Daphne mezereum*, *Campanula latifolia* and *Hepatica nobilis* are locally common and currently do not need any conservational measures.

Probably due to expansion of nutrient-rich habitats some species from the regional Red List become more common in the last decades. Dozens of new localities of *Alliaria petiolata*, *Arabis pendula*, *Cardamine parviflora*, *Chaerophyllum bulbosum*, *Mycelis muralis* have been reported from the Oblast since 2000, and most likely these species should be excluded from legal protection acts.

5. Conclusions

Fragmentary historical data on Vladimir Oblast flora agrees with the overall European picture of eutrophication in the 20th century. Despite the spatial correlation of Ellenberg’s indicator values for soil reaction and nitrogen, mean grid values for nitrogen are growing in areas with both acid and neutral soils.

The changes in mean grid indicator values for nitrogen are caused by either local extinctions of species from nutrient-poor habitats or increase of nitrophilous plants. These processes have different spatial patterns and should be considered separately. Both nutrient-poor habitats and their characteristic species are declining rapidly within the eutrophic loamy landscapes. In contrast, local extinctions of oligotrophic species are invisible on grid-scale in landscapes with acid sandy soils, and shifts in indicator values for nitrogen are caused here by increasing number of records of nitrophilous species, both invasive and native.

Decadal changes in the flora of oligotrophic acid sandy lowlands observed directly during two grid surveys show that six out of the top ten spreading species are typical for nutrient-rich habitats. In contrast, only three out of the ten most declining species are oligotrophic plants, but their reduction could be caused by a series of hot summers.

The regional strategy of plant protection should be elaborated with a consideration of species rarity within a certain landscape. The Red List of Vladimir Oblast flora could be supplemented with a list of species which needs local conservational efforts.

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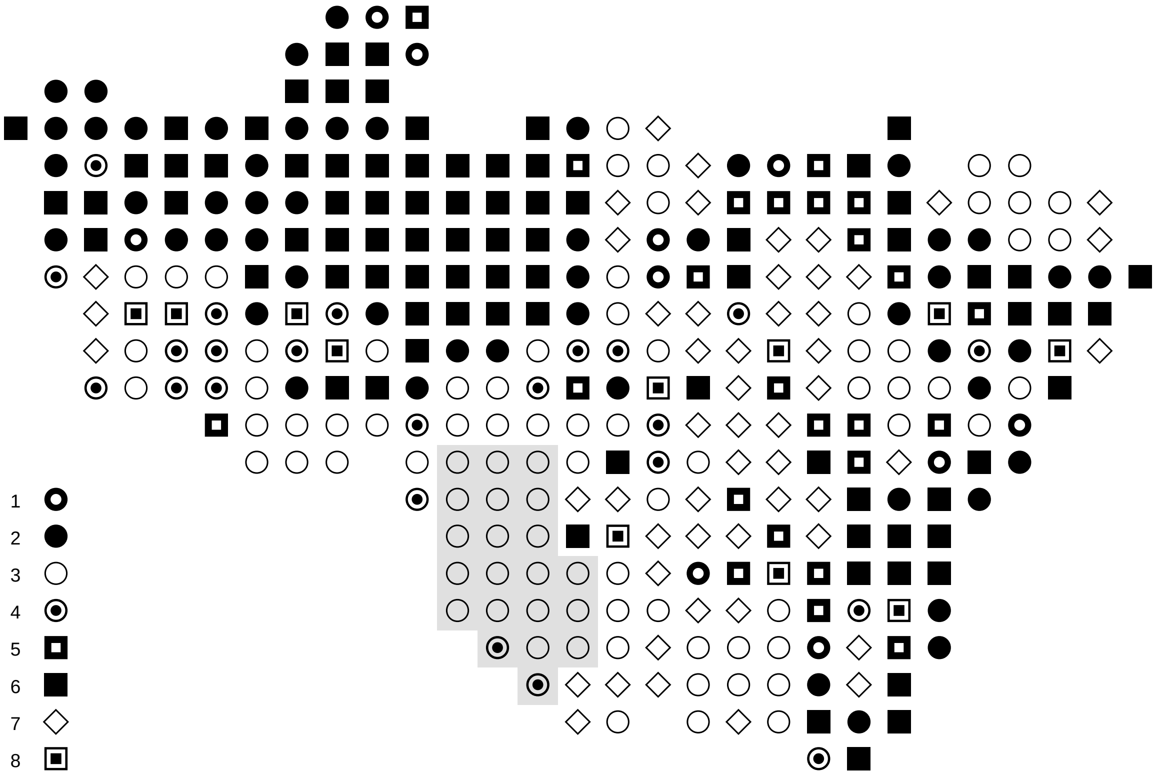

Fig. 1. Dominant soil conditions of Vladimir Oblast determined through 0.5-quantile three mean grid indicator values (for moisture, soil *pH*, and nitrogen supply).

1 – wet neutral nutrient-poor (10 grid squares); 2 – wet neutral nutrient-rich (52 grid squares); 3 – wet acid nutrient-poor (83 grid squares); 4 – wet acid nutrient-rich (23 grid squares); 5 – dry neutral nutrient-poor (24 grid squares); 6 – dry neutral nutrient-rich (82 grid squares); 7 – dry acid nutrient-poor (52 grid squares); 8 – dry acid nutrient-rich (11 grid squares). Gray background for the Meshchera National Park.

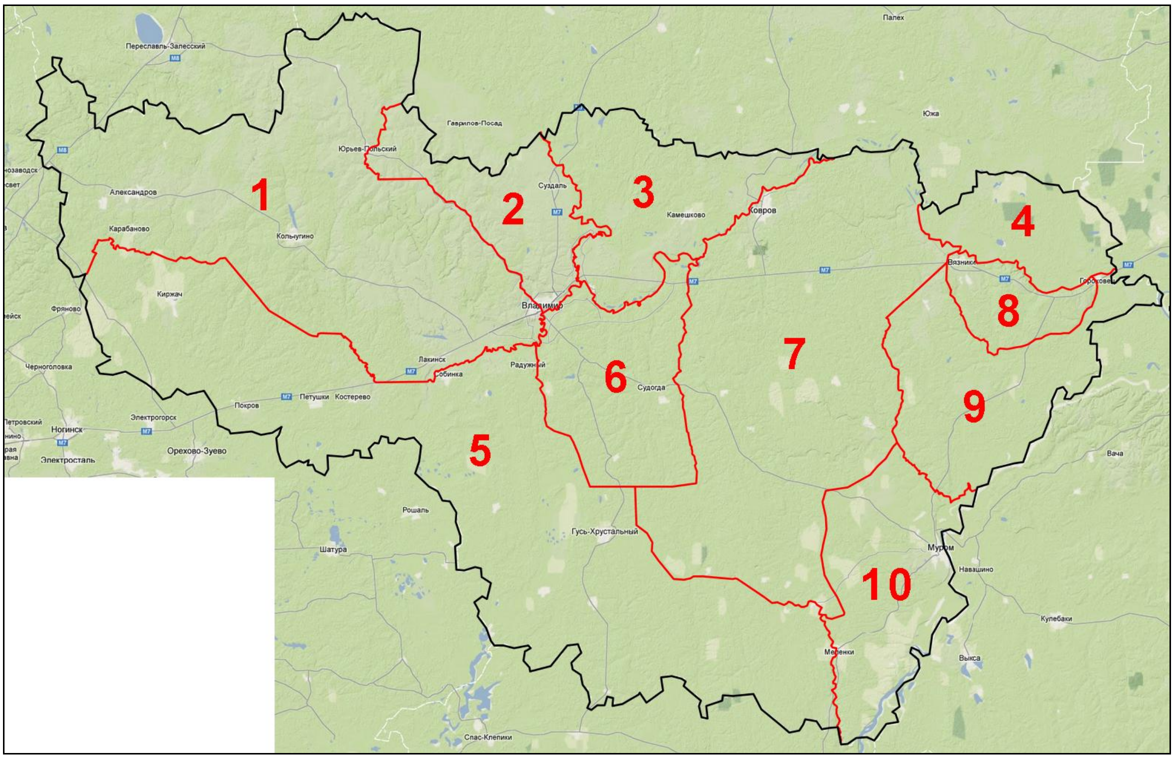

Fig. 2. Floristic divisions of Vladimir Oblast based on UPGMA cluster analysis of grid data (Seregin, 2014).

Floristic divisions and a species with the highest *IndVal* score (Dufrêne & Legendre, 1997): 1 – Klin-Dmitrov Ridge (*Alnus incana*); 2 – Opolye (*Phleum phleoides*); 3 – Nerl district (*Dactylorhiza fuchsii*); 4 – Balakhna (Frolishcheva) Lowland (*Jurinea cyanoides*); 5 – Meshchera Lowlands (*Viola palustris*); 6 – Sudogda Upland (*Lamiastrum galeobdolon*); 7 – Oka-Tsna Ridge (*Salix rosmarinifolia*); 8 – Gorokhovets Ridge (no counts); 9 – Lower Oka district (*Erigeron annuus* s. str.); 10 – Oka Plain (*Anthyllis macrocephala*).

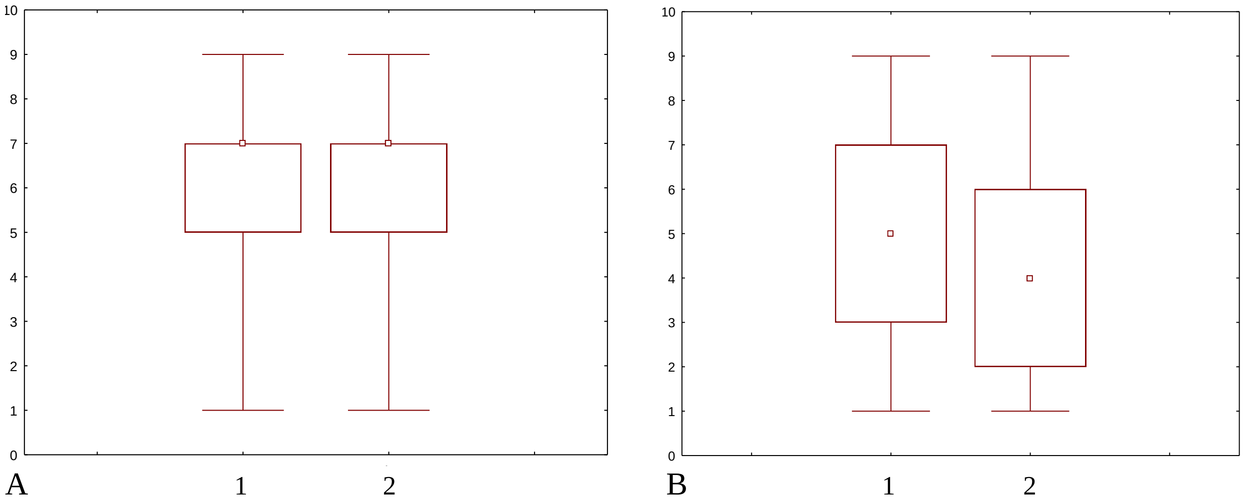

Fig. 3. Median Ellenberg's indicator values for (A) soil reaction and (B) nitrogen for the whole dataset (1) and historical records (2).

Box and whiskers represent 25–75% interval and extreme values respectively. Ellenberg's indicator values are shown on Y-axis. There are significant differences according to the Mann-Whitney U-test in both cases ($p < 0.001$).

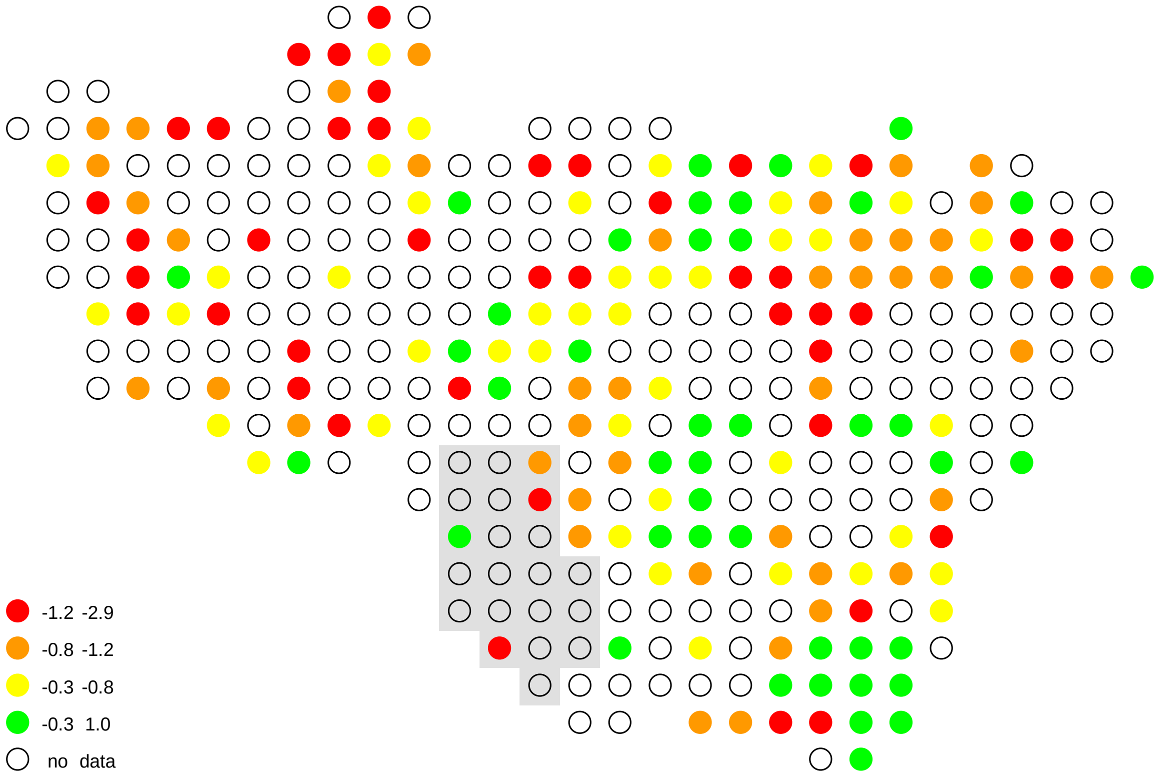

Fig. 4. The difference in mean Ellenberg's indicator values for nitrogen between recent and unconfirmed historical records (four equal classes for 170 grid squares with more than six historical records with N-values).

Gray background for the Meshchera National Park.

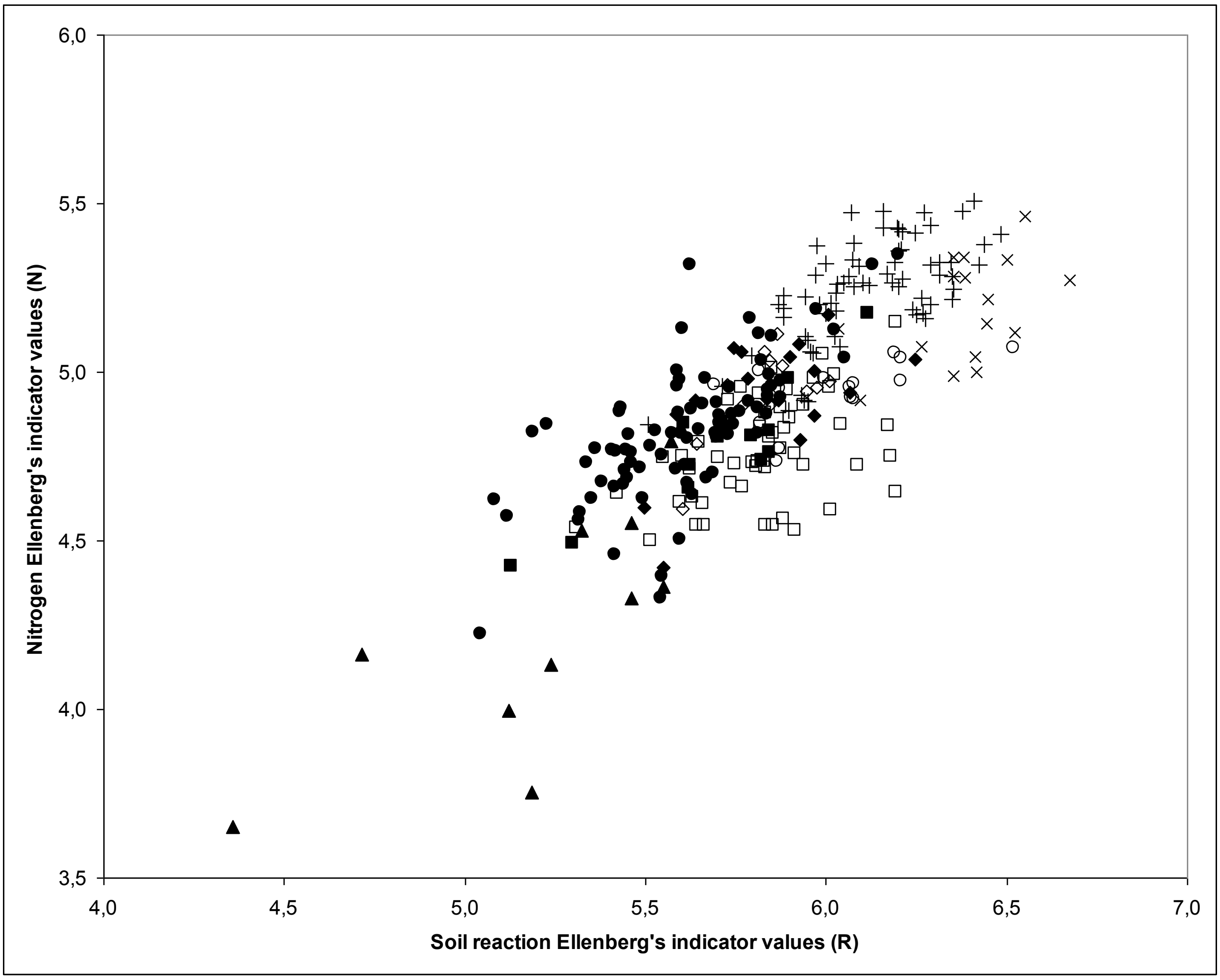

Fig. 5. Ordination scheme showing correlation of mean grid Ellenberg's indicator values for soil reaction and nitrogen with reference to floristic divisions of Vladimir Oblast.

Floristic divisions of Vladimir Oblast (fig. 2): + Klin-Dmitrov Ridge (69 grid squares); × Opolye (16 grid squares); □ Oka-Tsna Ridge (53 grid squares); ○ Sudogda Upland (12 grid squares); ◇ Oka Plain (15 grid squares); ● Meshchera Lowlands (82 grid squares); ■ Nerl district (12 grid squares); ♦ Lower Oka district (17 grid squares); ▲ Balakhna (Frolishcheva) Lowland (10 grid squares).

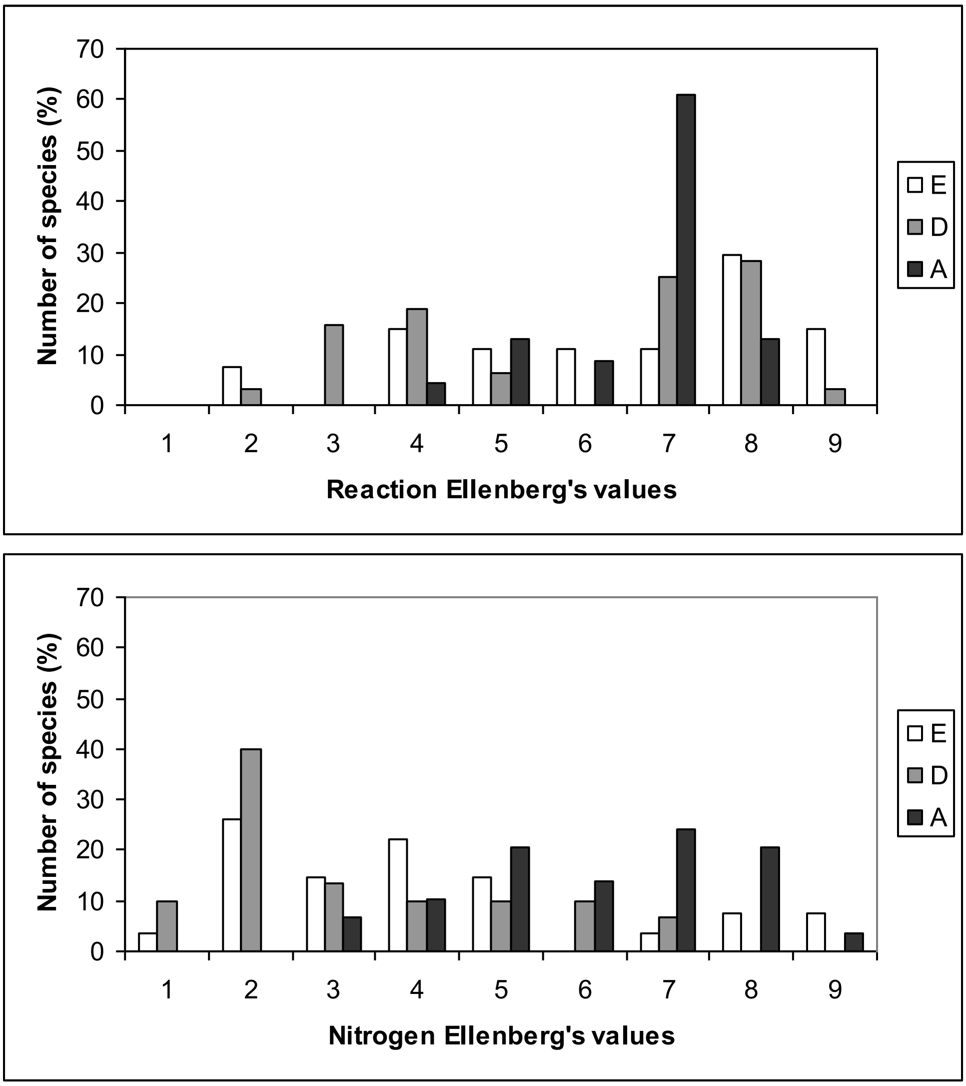

Fig. 6. Distribution of Ellenberg's indicator values compared for extinct species (E), declining species (D), and the most widespread neophytes (A).

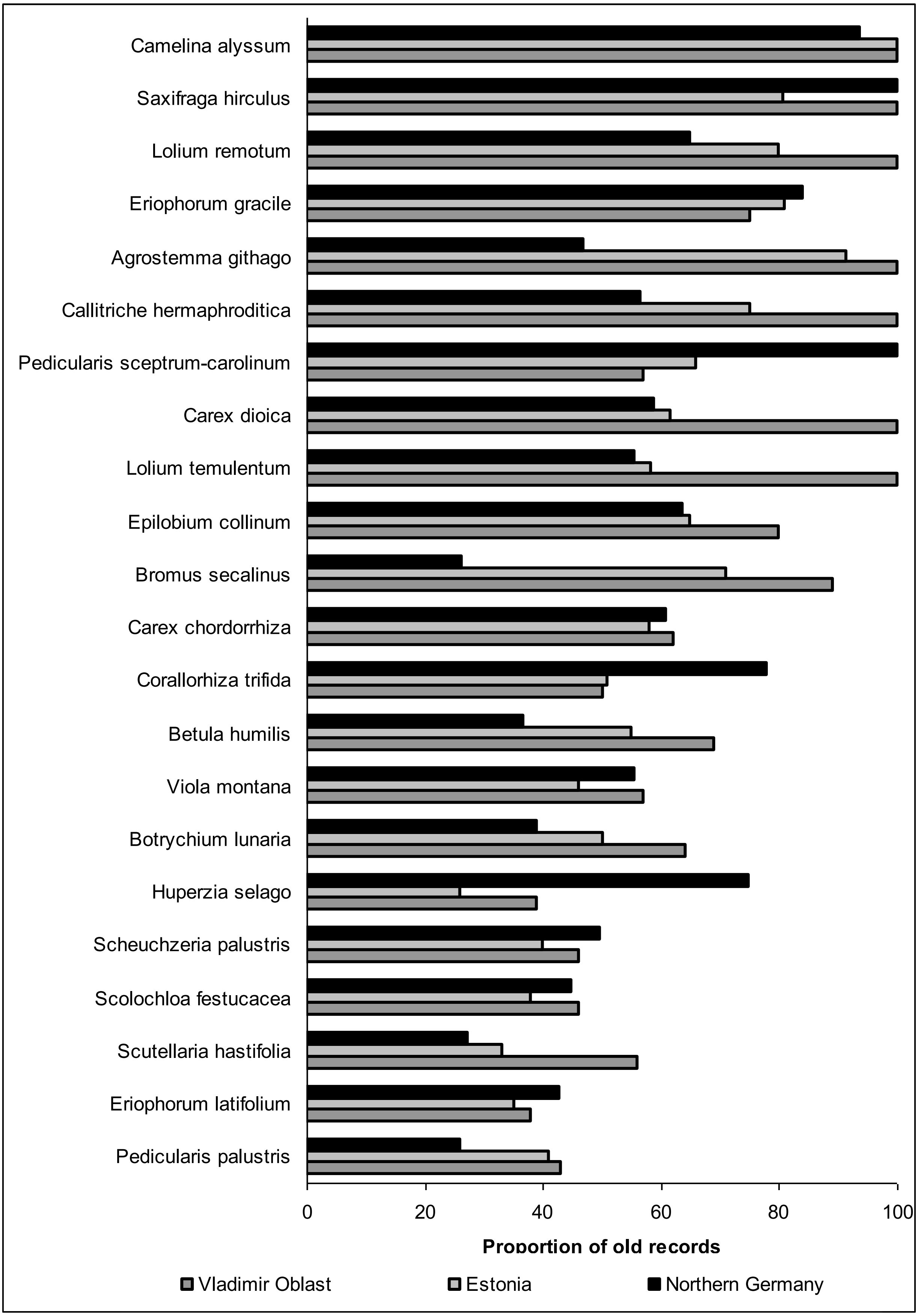

Fig. 7. Declining rate of threatened species calculated as a proportion of grid squares with unconfirmed old records for Vladimir Oblast, Estonia and Northern Germany (north of 52°N). Old records are pre-1949 records in Vladimir Oblast, pre-1970 records in Estonia, and pre-1950 records in Germany.

Table 1. Extinct plant species of Vladimir Oblast flora (natives and archaeophytes).

Species	Number of grid squares	Year last recorded	Typical habitats in Vladimir Oblast
Potentilla alba	1	1894	Dry pine forests
Zannichellia palustris	2	1901	Oxbows
Potentilla collina	1	1901	Floodplain dry meadows
Prunus fruticosa	1	1901	Floodplain oak forests
Chenopodium foliosum	4	1901	River banks
Malva verticillata	3	1903	Weed of nutrient-rich grounds
Carex heleonastes	2	1905 (1907?)	Peatbogs
Herminium monorchis	2	1907	Fens
Neottia cordata	2	1907	Spruce forests
Liparis loeselii	1	1908	Peatbogs
Ranunculus gmelinii	5	1910	Oxbows
Montia fontana	2	1912	Stream banks
Coeloglossum viride	4	1913	Broadleaf forests
Bolboschoenus yagara	1	1913	River banks
Diplazium sibiricum	1	1914	Broadleaf forests
Carex dioica	7	1914	Fens
Saxifraga hirculus	5	1915	Fens
Lolium remotum	5	1916	Flax weed
Pycreus flavescens	2	1916	Stream banks
Galium spurium s. str.	4	1916	Flax weed
Cuscuta epilinum	2	1916	Flax weed
Polystichum braunii	3	1918	Broadleaf forests
Malva neglecta	2	1918	Weed of nutrient-rich grounds
Asperugo procumbens	4	1918	Weed of nutrient-rich grounds
Vaccaria hispanica	8	1920s	Cereal weed
Juncus atratus	5	1922	Floodplain low meadows
Callitriche hermaphroditica	5	1923	Millponds
Laserpitium latifolium	1	1927	Calcareous woods
Rubus arcticus	4	1928	Fens
Crepis biennis	2	1928	Floodplain dry meadows
Camelina alyssum	18	1933	Flax weed
Lolium temulentum	10	1935	Cereal weed
Agrostemma githago	13	1935	Cereal weed
Ranunculus polyphyllus	2	1938	Oxbows
Myosotis alpestris	3	1939	Floodplain dry meadows
Crypsis schoenoides	1	1947	River banks
Corydalis marschalliana	2	1949	Broadleaf forests
Scabiosa ochroleuca	1	1949	Xeric meadows
Arabis gerardii	4	1951	Calcareous woods
Silene noctiflora	6	1951	Floodplain oak forests

Table 2. Declining plant species of Vladimir Oblast flora (natives and archaeophytes) with the highest proportion of pre-1949 records (at least five records).

Species	Number of grid squares	Proportion of records by periods			Typical habitats in Vladimir Oblast
		pre-1949	1950–1999	2000–2012	
Bromus secalinus	9	89	11	0	Cereal weed
Senecio vernalis	15	87	13	0	Pine forest clearances
Platanthera chlorantha	7	86	14	0	Broadleaf forests
Xanthium strumarium	6	83	17	0	River banks
Gentianella amarella	20	80	15	5	Short grass meadows
Epilobium collinum	5	80	20	0	Dry pine forests
Arabis sagittata	5	80	20	0	Calcareous woods
Silene procumbens	9	78	11	11	River banks
Eriophorum gracile	20	75	15	10	Fens & peatbogs
Najas minor	5	60	20	20	Oxbows
Bromus arvensis	12	75	25	0	Cereal weed
Filago minima	10	70	30	0	Open sands
Polygala vulgaris	13	69	23	8	Short grass meadows
Betula humilis	13	69	23	8	Fens & peatbogs
Botrychium lunaria	14	64	21	14	Short grass meadows
Matricaria chamomilla	11	64	27	9	Weed of nutrient-rich grounds
Carex chordorrhiza	13	62	8	31	Peatbogs
Dactylorhiza traunsteineri	5	60	20	20	Fens
Lathyrus palustris	17	59	18	24	Floodplain low meadows
Dracocephalum ruyschiana	12	58	25	17	Dry pine forests
Viola montana	7	57	29	14	Floodplain oak forests
Pedicularis sceptrum-carolinum	28	57	21	21	Fens
Gratiola officinalis	18	56	11	33	Floodplain low meadows
Scutellaria hastifolia	18	56	44	0	Floodplain low meadows
Radiola linoides	11	55	36	9	Open sands
Salix myrtilloides	24	54	33	13	Peatbogs
Corallorhiza trifida	16	50	50	0	Spruce bogs
Galium triflorum	17	47	12	41	Spruce forests
Scolochloa festucacea	11	46	36	18	Lakesides
Scheuchzeria palustris	28	46	14	39	Peatbogs
Salix lapponum	46	46	15	39	Peatbogs
Salix phylicifolia	22	46	18	36	Fens
Ophioglossum vulgatum	9	44	44	11	Fens
Pedicularis palustris	42	43	36	21	Fens
Polygala amarella	12	42	33	25	Short grass meadows
Neottia ovata	27	41	33	26	Broadleaf forests
Huperzia selago	13	39	31	31	Spruce forests
Eriophorum latifolium	16	38	50	13	Fens
Gymnadenia conopsea	20	35	45	20	Short grass meadows
Hypericum hirsutum	6	33	67	0	Broadleaf forests

Table 3. The most widespread neophytes of Vladimir Oblast flora (casuals and relics of former cultivation excluded).

Species	Number of grid squares	Year of the first record
Erigeron canadensis	316	before 1885
Juncus tenuis	311	1971
Matricaria discoidea	308	early 1880s
Epilobium adenocaulon	274	1912
Lupinus polyphyllus	273	end of 1960s
Melilotus officinalis	244	before 1885
Schedonorus arundinaceus	256	1999
Epilobium pseudorubescens	253	1967
Elodea canadensis	226	1886
Acer negundo	225	mid-1970s
Puccinellia distans	214	before 1885
Lactuca serriola	201	before 1885
Erigeron septentrionalis	194	1967
Sambucus racemosa	184	before 1885
Medicago sativa	174	1902
Amelanchier spicata	156	before 1904
Amaranthus retroflexus	153	before 1885
Bidens frondosa	151	1997
Solidago gigantea	144	before 1987
Caragana arborescens	143	before 1904
Medicago varia	142	1995
Echinocystis lobata	127	mid-1970s
Lepidium densiflorum	123	1967
Calystegia inflata	116	before 1904
Symphyotrichum salignum	115	before 1987
Heracleum sosnowskyi	111	mid-1970s
Atriplex sagittata	100	before 1885
Vicia tetrasperma	100	1912
Lolium perenne	99	before 1885
Galium spurium var. *vaillantii*	98	before 1885
Oenothera rubricaulis	97	before 1987
Geranium sibiricum	94	before 1885
Sisymbrium loeselii	89	before 1885
Epilobium tetragonum	87	2006
Impatiens parviflora	87	before 1980s
Ribes uva-crispa	84	before 1902
Fraxinus pennsylvanica	84	before 1987
Aquilegia vulgaris	83	1896
Trifolium campestre	82	1912
Solidago canadensis	77	before 1987

Table 4. The species with the highest and the lowest *Relative Change* indexes (*RC*) over the last decade in the Meshchera National Park.

Species	Number of grid records 2012 only	2002 only	Confir-mations	Total	*RC*, %	90% confidence limits
Increase						
Aronia mitschurinii	21	0	2	23	88	±8
Bidens frondosa	30	0	6	36	81	±8
Galinsoga parviflora	12	1	1	14	79	±15
Echinocystis lobata	11	0	2	13	79	±13
Impatiens parviflora	6	0	1	7	76	±17
Nuttalanthus canadensis	6	0	1	7	76	±17
Chelidonium majus	18	1	5	24	72	±12
Epilobium hirsutum	19	0	8	27	69	±10
Lathyrus tuberosus	7	1	1	9	69	±17
Erigeron septentrionalis	30	1	12	43	68	±9
Decline						
Artemisia sieversiana	1	7	2	10	–62	±17
Ribes uva-crispa	2	7	1	10	–58	±11
Eriophorum angustifolium	4	13	2	19	–58	±8
Agropyron pectinatum	0	2	1	3	–55	±24
Fagopyrum tataricum	0	2	1	3	–55	±24
Hyoscyamus niger	0	2	1	3	–55	±24
Ribes aureum	0	2	1	3	–55	±24
Pedicularis palustris	1	4	1	6	–54	±18
Rumex maritimus	3	7	1	11	–47	±7
Carlina biebersteinii	2	5	1	8	–46	±11