DISSERTATIONES
BIOLOGICAE
UNIVERSITATIS
TARTUENSIS
306

POLINA DEGTJARENKO

Impacts of alkaline dust pollution on biodiversity of plants and lichens: from communities to genetic diversity

DISSERTATIONES BIOLOGICAE UNIVERSITATIS TARTUENSIS

306

DISSERTATIONES BIOLOGICAE UNIVERSITATIS TARTUENSIS
306

POLINA DEGTJARENKO

Impacts of alkaline dust pollution on biodiversity of plants and lichens: from communities to genetic diversity

UNIVERSITY OF TARTU
Press

Department of Botany, Institute of Ecology and Earth Sciences, Faculty of Science and Technology, University of Tartu, Estonia

Dissertation was accepted for the commencement of the degree of *Doctor philosophiae* in botany and mycology at the University of Tartu on August 25, 2016 by the Scientific Council of the Institute of Ecology and Earth Sciences University of Tartu.

Supervisors:	Assoc. Prof. Tiina Randlane, University of Tartu, Estonia
	PhD Liis Marmor, University of Tartu, Estonia
Opponent:	Assist. Prof. Stefano Loppi, University of Siena, Italy
Commencement:	Room 218, 40 Lai Street, Tartu, on 16 November 2016 at 10.15 a.m.

Publication of this thesis is granted by the Institute of Ecology and Earth Sciences, University of Tartu

ISSN 1024-6479
ISBN 978-9949-77-259-9 (print)
ISBN 978-9949-77-260-5 (pdf)

University of Tartu Press
www.tyk.ee

TABLE OF CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications that are referred in the text by Roman numerals:

I Paal, J., **Degtjarenko**, **P**., Suija, A. & Liira, J. (2013) Vegetation responses to long-term alkaline cement dust pollution in *Pinus sylvestris*-dominated boreal forests – niche breadth along the soil pH gradient. *Applied Vegetation Science* 16: 248–259. doi: 10.1111/j.1654-109X.2012.01224.

II Marmor, L. & **Degtjarenko**, **P** (2014) *Trentepohlia umbrina* on Scots pine as a bioindicator of alkaline dust pollution. *Ecological Indicators* 45: 717–720. doi: 10.1016/j.ecolind.2014.06.008.

III **Degtjarenko**, **P**., Marmor, L. & Randlane, T. (2016) Changes in bryophyte and lichen communities on Scots pines along an alkaline dust pollution gradient. *Environmental Science and Pollution Research* 23: 17413–17425. doi: 10.1007/s11356-016-6933-5.

IV **Degtjarenko**, **P**., Marmor, L., Tõrra, T., Lerch, M., Saag, A., Randlane, T. & Scheidegger, C. (2016) Impact of alkaline dust pollution on genetic variation of *Usnea subfloridana* populations. *Fungal Biology* 120: 1165–1174. doi: 10.1016/j.funbio.2016.05.010.

Published papers are reproduced with the permission of the publishers.

Author's contribution to the publications:

I. participated in developing the idea, had the main responsibility in data collection, participated in data analysis and manuscript preparation;

II. participated in developing the idea, participated in data collection and analysis, and manuscript preparation;

III. had the main responsibility in developing the idea, data collection and analysis, as well as manuscript preparation;

IV. had the main responsibility in developing the idea, data collection and analysis, as well as manuscript preparation.

1. INTRODUCTION

1.1. General introduction

Environmental pollution (including air pollution) is a consequential global threat to overall biodiversity. Air pollution impacts on all levels of biological organization, from individuals to ecosystems (Grantz et al. 2003; Lovett et al. 2009). For instance, changes induced by air pollution can disturb the composition, function and structure of ecosystems (Vitousek et al. 1997), triggering the loss of sensitive species or inducing the succession by pollutant-tolerant species. Moreover, environmental pollution could influence the genes and genetic diversity of organisms from different species groups (DiBattista 2008; Holloway et al. 2012). Therefore, there are multiple tasks for air pollution management. In order to control, monitor and, consequently, mitigate damages caused by air pollution, the influence of air pollution on different levels of biodiversity should be estimated and the potential sources of pollution and their extension detected (Guerreiro et al. 2015). Additionally, it is required to improve the mitigation technologies and set the new possible methods for complementing the data from air monitoring stations.

The total emission and concentrations of many air pollutants (e.g., SO_2, CO, C_6H_6) have decreased and, generally, air quality has improved in Europe for now, while particulate matter (PM) is still an acute and problematic pollutant as EU limits for PM have continued to be exceeded in large parts of Europe (Guerreiro et al. 2015). PM is air pollutant, which represents the heterogeneous mixture of solid particles, differing in size (ca. 0.1−10 µm), origin and chemical composition, and has been suspended in the air (Grantz et al. 2003). PM pollution is usually defined by size fraction (Grantz et al. 2003). Coarse PM (or larger dust particles, hereafter dust pollution) is released to the environment e.g., through rock quarrying, combustion processes, kiln grinding, directly from surfaces of unpaved roads by intensive traffic or from biogenic sources e.g., from surfaces of deserts or from wildfires. Anthropogenic dust pollution usually disperses by the wind and, therefore, deposits generally in the vicinity of emission sources, e.g., power plants, cement industries, limestone quarries, and unpaved roads (e.g., Farmer 1993; Mandre 1995; Paoli et al. 2014; Rai 2016). The chemical composition of dust pollution is variable, depending on properties of raw material and particular source of emission. In general, dust emission from aforementioned industrial pollution sources contains a high amount of $CaCO_3$, MgO, K_2O, small amount of SiO_2, Al_2O_3, Fe_2O_3, and heavy metals like Mn, Zn, Cu (Mandre 2000; Reinsalu 2008), and is extremely alkaline. For instance, the pH of cement dust in water suspension is 12.3−12.6 (Mandre 2000). The alkaline dust pollution has always been essential environmental issue in Estonia since over the years the large part of industrial pollution was formed by alkaline dust, and remarkable changes of local environment have been detected in northern region of Estonia due to high presence of alkaline dust pollution (e.g., Laasimer 1958; Annuka 1995; Kask et al. 2008; Reintam et al. 2011).

The effects of alkaline PM on biodiversity have been less studied (Farmer 1993; Zvereva et al. 2008; Rai 2016) in comparison with the effects of acidifying pollutants (i.e., SO_2, NO_x, NH_3). Dust emission can effect vegetation directly, causing negative changes in physiology and biochemistry or indirectly, through the environment. Considerable dust pollution causes visible injuries of plant tissue (Farmer 1993) or necrotic disrupt of lichen thalli (Jóźwiak and Jóźwiak 2009), damages spruce needles (Mandre et al. 2002; Ots et al. 2009; Lukjanova et al. 2013), disturbs stomatal function (Siqueira-Silva et al. 2016), reduces transpiration and degrades photosynthetic pigments that results in inhibition of photosynthetic activity (Zaharopoulou et al. 1993; Lepeduš et al. 2003; Maletsika et al. 2015), consequently causing cell plasmolysis and death of entire plants (Saha and Padhy 2011; Siqueira-Silva et al. 2016). Dust pollution can also change element concentration of vascular plants (Mandre and Korsjukov 2007; Kupcinskiene et al. 2008), mosses (Liiv and Kaasik 2004), and lichens (Kortesharju and Kortesharju 1989) or decrease the level of carbohydrates leading to decrease of plant biomass (Mandre and Klõšeiko 2000; Klõšeiko 2005; Ade-Ademiula and Obalola 2008). Moreover, dust pollution can disturb the radial increment and height growth of conifers, and cause defoliation of trees (Mandre et al. 1998; Ots and Rauk, 2000; 2001; Ots et al. 2009). However, the negative effect of dust pollution on vegetation could be counterbalanced to some extent through a fertilizing effect on plants (Annuka and Rauk 1990; Kask et al. 2008; Rizvi and Khan 2009); for example, dust increases the graminoid biomass closer to the calcareous dusty roads (Auerbach et al. 1997).

Indirect effects through the increasing pH and hypertrophication of habitats (changes in chemical properties of soil) provoke the alteration of nutrient cycling and, thus, imbalance nutrient uptake or cause deficiencies (Farmer 1993; Nanos and Ilias 2007) and damage soil biota, e.g., mycorrhizal and bacterial communities involved in nutrient cycling of plants (Grantz et al. 2003; Bilen 2010). The response to dust pollution of individual species consequently leads to the changes at population, community and, finally, at ecosystem level. Those indirect impacts can alter the total species richness, abundance and community structure, changing species composition (e.g., Marmor et al. 2010; Stravinskienė 2011; Vellak et al. 2014). For example, the soil long-term alkalization provokes the successional changes in forest communities (Brandt and Rhoades 1972) or induces the disappearance of *Sphagnum* mosses from sensitive to alkaline dust bogs (Paal et al. 2010) and tundras (Auerbach et al. 1997). Several studies have shown the replacement of acidophytic lichens by basiphytic and neutrophytic lichenized taxa along a dust pollution gradient (e.g., Gilbert 1976; Loppi and Pirintsos 2000; Paoli et al. 2014). The impact intensity of dust pollution depends on the distance from pollution sources, frequency and continuation of emission, dominant wind direction, the amount of deposited dust particles, and particular responses of species groups (Farmer 2000; Grantz et al. 2003). Among other items, PM pollution poses a remarkable harm to human health, particularly in urban areas, provoking the respiratory and cardiovascular diseases and increasing risks of mortality (Brook et al. 2010; World

Health Organization 2013; Yorifuji et al. 2016). For instance, traffic-released PM can cause damage of airway epithelial cells that lead to the production of pro-inflammatory cytokines (Kumar et al. 2015) playing important role in pathogenesis of asthma (Barnes 2008).

Air monitoring stations can provide the real-time information about pollutant concentrations in the surrounding area; however, such data collection is usually performed in a limited number of monitoring stations. Bioindication is a potential tool for complementing the data from air monitoring stations, supplying information about the pollution status and its cumulative impacts in areas that are not covered with direct measurements (Conti and Ceccheti 2001; Sujetovienė 2015). Bryophytes and lichens are widely used as effective indicators for monitoring air quality and surrounding environment (e.g., Gilbert 1968; Hawksworth and Rose 1970; Nimis et al. 2002) due to their particular physiology (e.g., lack of a root system and protective waxy cuticles), metabolic peculiarities (e.g., poikilohydry) and distinctive sensitivity to particular air pollutants (Barkman 1958; Nash 2008; Zvereva and Kozlov 2011). Several studies consider indicator values of lichens and bryophytes for monitoring the atmospheric deposition of different pollutants (e.g., Pakarinen and Hasanen 1983; Branquinho et al. 2008; Sujetovienė 2015); however, simultaneous changes in abundance and species richness or possibilities to use other organisms, for instance epiphytic algae, as bioindicators of dust pollution are poorly investigated.

The majority of studies considering the effects of environmental pollution (including PM pollution) on vegetation have concentrated on responses of individual species or communities (Smith 1990; Farmer 1993; Ellenberg 2009; Rai 2016), while pollution impact on genetic diversity of species has received much less attention (van Straalen and Timmermans 2002). The genetic diversity within populations results from cumulative effects of both historical and present processes (Hewitt 2000; Frankman 2010). Present processes include changes in environmental conditions and, finally, in species habitat, which may influence growth, dispersal and vitality of species. The variation at the genetic level is important part of biodiversity as it initiates evolutionary processes, provides the raw material for adaptation to changing environments, and ensures healthy populations (Lacy 1997; Helm et al. 2009; Frankham et al. 2010). Therefore, the changes in genetic structure and loss of genetic diversity, caused by anthropogenic disturbances, could be a serious threat to natural populations. Moreover, the knowledge of changes or declines in genetic diversity of populations may be used as a warning to vulnerability and sustainability of populations to environmental changes (Bickham et al. 2000).

1.2. Objectives of the thesis

The main objective of the present thesis was to contribute to the knowledge about the response of pine forest ecosystems (**I**), epiphytic communities (algae, lichens, bryophytes) on pines (**II**, **III**), and genetic diversity of populations of a common lichen-forming fungus (**IV**) to changed environmental conditions induced by a long-term alkaline dust pollution.

In summary, the aims of the current thesis were:

- To investigate the successional response of the *Vaccinium myrtillus* site type Scots pine forest communities to changed pH conditions induced by long-term cement dust pollution (**I**). This study particularly aimed to investigate (1) how much the chemical properties of soil litter horizon have been changed by over century persisted alkaline dust pollution; (2) the niche breadth along the soil pH gradient; (3) how resilient the forest community was considering the responses of core species to the changed pH conditions.
- To find out the potential bioindicators of air quality near sources of alkaline dust pollution (**I**, **II**, **III**), and, especially, to shed light on the possibilities to use *Trentepohlia umbrina* (Kützing) Bornet as an indicator of alkaline dust pollution (**II**). To our knowledge, no direct measurements of the abundance of *T. umbrina* or any other *Trentepohlia* species have been made in habitats with different level of alkaline dust pollution so far.
- To evaluate the response of two cryptogamic groups, lichens and bryophytes, including their diversity and cover, in relation to alkaline dust pollution emitted by the processes connected with limestone quarrying (**III**). To our knowledge, no direct measurements of the species richness and cover of epiphytic bryophytes on pine trees have been made so far in sites with different limestone dust pollution level.
- To estimate the effects of limestone dust pollution from unpaved roads on the genetic diversity of *Usnea subfloridana* Stirt. populations using fungus-specific microsatellite markers (**IV**). No previous study has considered the microsatellite variation of lichen-forming fungus populations under long-term air pollution, particularly under alkaline dust pollution.

2. MATERIALS AND METHODS

2.1. Study area and sample plots

The studies were carried out in Estonia (Fig. 1), northern Europe. Estonia has temperate climate; the mean annual temperature is 5°C, and the total annual precipitation is 770 mm (Estonian Weather Service 2016). The vegetation of Estonia belongs to the hemiboreal subzone of the boreal forest zone, lying in the transitional area, where southern taiga forest subzone changes into spruce-hardwood subzone (Ahti et al. 1968; Laasimer and Masing 1995).

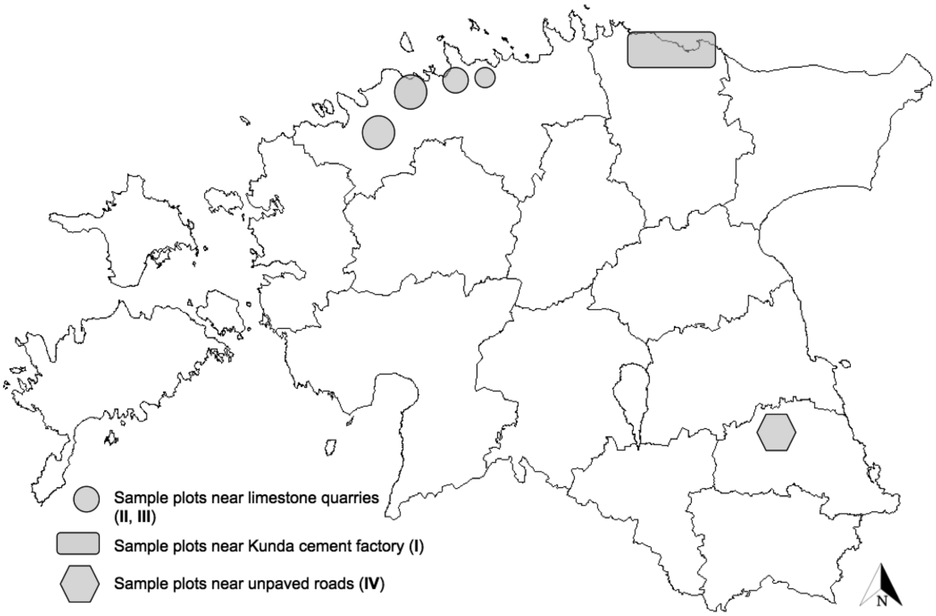

Figure 1. Study areas and location of sample plots in the vicinity of different sources of alkaline dust pollution in Estonia (papers **I–IV**).

The studies were carried out in the surroundings of three different sources of alkaline dust pollution; cement plant (**I**), limestone quarries (**II**, **III**), and limestone unpaved road (**IV**; Fig. 1; Table 1). The extraction and using of limestone have a long tradition in Estonia, beginning already in the 13th century (Ministry of the Environment 2011). The study **I** was performed in the vicinity of Kunda cement factory (Fig. 1; Fig. 2; Fig. 1 in **I**). The Kunda cement factory was established in 1871, and since that time has emitted alkaline dust in substantial amount into the surrounding area. The emissions of cement kiln dust have been varying greatly during the years, reaching the level of about 100 000 tons per year in the late 1980s and early 1990s (Estonian Environment 1995). For now, after the installation of powerful dust filters in 1996, the dust emission considerably decreased – to 34 tons per year (Kunda Nordic Tsement 2016), and stayed within allowed permits (Environmental Board 2016). However, the dust pollution impact is still detectable, for example, in 2008 the Ca content in the snowmelt water exceeded the unpolluted measures by ten-fold in Mahu bog (about 4.5 km NE of Kunda cement plant; Paal et al. 2010). In papers **II** and **III**, the study sites were situated in the surroundings of four major limestone quarries in northern Estonia: Vasalemma, Harku, Väo, and Maardu (Fig. 1; Fig. 1 in **II**; Fig. 1 in **III**). The mean quantity of quarried limestone in Estonia per year is 2.6 million m^3, and about half of it is extracted from the aforementioned quarries, which have been functioning during last 50–60 years (Geoguide Baltoscandia 2012). The unpaved road, which is the source of dust pollution in paper **IV**, has been marked as a road on the map at least from the end of 19th century (earlier maps are not available), however, serious pollution started ca. 60 years ago, in 1960s when motors vehicles, including agricultural machines, became widely used.

The study sites were located in *Pinus sylvestris*-dominated boreal forests (**I**−**IV**) and forested parks (**II**, **III**). The studies were conducted in forests belonging to the *Vaccinium myrtillus* site type (**I**, **IV**), the *Oxalis-Vaccinium myrtillus* site type (**IV**), and the *Vaccinium vitis-idaea* site type (**IV**). Those forest site types are also widely distributed in other Baltic states (Kairiūkštis 1966; Bušs 1997), in Fennoscandia (Dierßen 1996), and in northwest Russia (Fedorchuk et al. 2005). In undisturbed conditions, soil from those forest site types is naturally acidic; pH_{KCL} of the litter and humus horizon ranges between 2.5 and 5.5 (Paal 1999; Lõhmus 2004). The study sites were selected using the maps of Estonian State Forest Management Centre (**I**), Estonian Forest Public Registry (**I**−**IV**), and the soil maps of the Estonian Land Board (**I**). The sample plots were located at different distances from the pollution sources (Kunda cement plant in **I** and the nearest limestone quarry in **II** and **III**), representing thus the pollution gradient (Fig. 1; Fig. 2; Fig. 1 in **II**; Fig. 1 in **III**). Furthermore, the sample plots were situated in more than 100 m from the nearest paved or gravel road for minimizing the potential impact of traffic pollution (**I**, **II**, **III**). In **IV**, where genetic diversity of *Usnea subfloridana* populations was studied, eight sample plots were investigated: four of them were within polluted forest stands, which were located close to unpaved roads, and four within undisturbed forest stands, which were situated more than 180 meters from the source of dust pollution, as reference data (Table 1 in paper **IV**). Lichen populations were delimited according to the boundaries of forest sites having different average age of the lichen phorophyte (Forest Public Registry 2012).

Table 1. Short overview of study objects, sources of pollution, total number of studied species/samples, total number of sample plots, and applied statistical and molecular analyses

Papers	**Study objects**	**Source of pollution**	**Total number of studied species/ samples**	**Total number of sample plots**	**Statistical analyses**	**Molecular analyses**
I	Vascular plants, epigeic bryophytes	Cement factory	86 species (including 25 bryophytes)	20	PCA, ANOVA, Tukey post hoc test, MRPP, ISA, GRM, GLZ	–
II	Epiphytic green alga on Scots pine	Limestone quarries	1 species (*Trentepohlia umbrina*)	32	Spearman's rank correlation analysis, logistic regression, Kruskal-Wallis test	–
III	Epiphytic bryophytes and lichens on Scots pine	Limestone quarries	34 bryophytes, 84 lichens	32	Spearman's rank correlation analysis, Kruskal-Wallis test, ANOVA, Tukey post hoc test, GLZ	–
IV	Lichenized fungi on Norway spruce	Limestone unpaved road	1 species (*Usnea subfloridana*), 274 specimens	8	GLZ, AMOVA, Wilcoxon signed-rank test, allele frequency distribution test	Fungus-specific micro-satellites (9 loci)

2.2. Field methods and data collection

Fieldworks were carried out between summer 2008 and summer 2014. To estimate the vegetation changes under long-term cement pollution, twenty 65–90 years old pine stands were selected, and a circular sample plot of 0.1 ha was set in the centre of the each pine stand (**I**). We characterised the tree layer by crown closure, tree basal area, average height, and age of trees (**I**). The basal area was measured for each tree species as an average of three to five measurements (**I**). The density of shrub layer species was the average stem count on five randomly placed 2 m radius subplots (**I**). Cover of vascular plant species in the herb layer and moss layer was registered in 12 randomly located 1 m × 1 m sample squares in a radius of 10 m within the centre plot (**I**). Species outside sample squares were also recorded and included in the analyses as cover 0.01% (**I**). The composite sample of the soil litter horizon was collected from three randomly selected pits around plot centre within a radius of 10 m (**I**). The pH_{H2O}, Ca, Mg, N, P, K, and ash content of soil samples were estimated in laboratory (see methods in paper **I**). In papers **II** and **III** five random Scots pine (*Pinus sylvestris* L., hereafter 'pine') trees were examined in a 25-m radius circle of 32 sample plots; only trees with more than 50 cm circumference were included. The line cover method was used to estimate the cover of *Trentepohlia umbrina* (**II**), lichens (**III**), and bryophytes (**III**) on pine trunks. A measuring tape was attached round each sample tree trunk at the height of 120 cm; all the millimetres, where any species was crossing the lower edge of the tape, were recorded. Sample tree circumference was measured for later calculating of the cover of *T. umbrina* (**II**), the cover of lichens (**III**), and the cover of bryophytes (**III**). Additionally, the occurrence of all epiphytic lichen and bryophyte species was registered on trunk of every sample tree from 0.5 to 2 m above ground (**III**). In paper **IV**, shrubby *Usnea* thalli were randomly collected from Norway spruces (*Picea abies* (L.) Karst., hereafter 'spruce') in forest stands with different average age (between 70–114 years) of spruces from eight sample plots. The specimens (three specimens per tree on average) were sampled up to six meters from the ground using tree pruner. If there were less than three thalli, only one or two specimens were sampled while in other cases more than three (but not more than five) specimens were collected per tree to balance sampling.

2.3. Bark pH measurement

The pine bark pH was measured *in situ* at breast height (DBH of at least 90 cm) on three stems in three repeats at each sample plot in study **I**. In studies **II**, **III**, and **IV**, two bark pieces were collected at the height of 120 cm from the ground from every studied pine tree (**II**, **III**), and from five random spruces from polluted and unpolluted forest stands (**IV**). In studies **II** and **III**, one piece of pine bark was gathered from the side of the quarry and another from the opposite side of tree. In paper **IV**, in polluted forest sites one piece of bark was taken from the northern side (N), which was adjacent to unpaved road, and second piece from the opposite, southern, side (S) of tree. In unpolluted forest sites (**IV**), bark pieces were analogously collected, keeping the same cardinal direction. Then bark pH of collected bark pieces was measured in laboratory (**II, III, IV**). The flathead pH meter Consort C532 was used for all bark pH measurements (**I**−**IV**). To allow rapid solution of hydrogen ions, 0.5 mL of 0.1 M KCl was dripped on the bark 1 min before the measurement following Schmidt et al. (2001). The mean bark pH of every tree was expressed as an arithmetic mean of two (**II**, **III, IV**) or three (**I**) measurements of bark pH values (all calculations of mean pH were based on mean hydrogen ion concentrations and then transformed back into pH value).

2.4. Species identification

The species that were difficult to identify in the field were collected for later determination (**I**, **III**). Additionally, in study **II**, at least one sample was taken for examination and confirming the identification under a light microscope from every sample plot, where epiphytic green alga *Trentepohlia umbrina* occurred. Thin layer chromatography (TLC) with solvent A (Orange et al. 2001) was performed for those lichen specimens that were difficult to identify by morphology or by chemical spots (**III**), and for confirming the identification of *Usnea subfloridana* (**IV**). In paper **I**, the bryophyte nomenclature follows Hill et al. (2006) and the nomenclature of vascular plants follows Tutin et al. (1964–1980), in paper **III**, the bryophyte nomenclature follows Vellak et al. (2015), and in papers **III** and **IV**, the lichen nomenclature follows Randlane et al. (2013).

2.5. Molecular analyses

In study **IV**, the total DNA of *Usnea subfloridana* specimens was isolated using PowerPlant® Pro DNA Isolation Kit (MO BIO Laboratories, Inc., USA) according to the manufacturer's protocol. Nine unlinked fungus-specific microsatellite loci (Tõrra et al. 2014) were analyzed and amplified in three different multiplex PCR following the protocol described in Tõrra et al. (2014) except the reverse primer sequences, which had erroneously been presented as direct sequences from the genome. Therefore, we used the modified set of the reverse primer sequences (Table 2 in paper **IV**). Additionally, the final primer concentration of Us01 (multiplex I) was increased to 0.05 μM to get PCR amplification (see Tõrra et al. 2014 for other primer concentrations). Fragment lengths of PCR products were determined on a 3730xl DNA Analyzer (Applied Biosystems, Zurich, Switzerland). The electropherograms were analyzed using GENEMAPPER ver. 5 (Applied Biosystems) using LIZ-500 (all multiplexes) as size standard.

2.6. Statistical analyses

The collected data (e.g., bark pH values, soil chemical characteristics, abundance and occurrence of species) were averaged per sample plot (**I**–**IV**), and statistical analyses were performed on the plot level (Table 1; **I**–**IV**).

In paper **I**, the principal component analysis (PCA) with Varimax rotation was applied on variables describing the alkaline pollution; litter horizon pH, logCa, logK, logMg, and logAsh content were included. The first principal component was defined as the compound pollution factor (CF). The variation in soil chemistry and forest structure measures between pollution zones were estimated with a one-way ANOVA; Tukey post hoc test was used to test the significant difference between the pollution zones (**I**). The multiple response permutation procedure (MRPP) was used to estimate the difference on species composition between pollution zones (Bonferroni correction was applied for p-values). Indicator species analysis (ISA; Dufrêne and Legrendre 1997) was applied to find out indicator species for each pollution zone (**I**). The statistical significance of the indicator values was estimated with a Monte Carlo permutation test. The indicator value pattern between pollution zones was used to outline niche width for species having indicator value >15 in at least one pollution zone (**I**). Species were classified into six groups: acidophilous, acido-neutrophilous, neutrophilous, neutrophilous-calcicolous, and calcicolous. Species with high indicator values through three zones or at least in the unpolluted and heavily polluted zones were classified as generalists.

The two-way step-wise general regression model (GRM) analysis was applied to estimate plant species reaction to the alkaline pollution. Some species had sharply asymmetric abundance distribution (i.e., observation included of too many zeros), and the assumption of the normal error distribution could not be applied (**I**). Therefore, the generalized linear model (GLZ) with binominal distribution and 'logit' link function analysis was carried out on presence-absence data of these species (**I**). The GRM analysis was also applied to test the effect of litter chemical properties on species richness and on the variables of tree layer structure (**I**). Spearman's rank correlation analysis was used to find the relationships between the cover of *Trentepohlia umbrina* and distance from the quarry (**II**), between the cover of bryophytes and the cover of lichens (**III**), between the number of bryophytes and the number of lichens (**III**), between the mean tree circumference and the cover of lichens and bryophytes (**III**), between the mean tree circumference and the number of lichens and bryophytes (**III**), and between the mean tree circumference and the cover of *Trentepohlia umbrina* (**II**). Logistic regression was used for describing the occurrence probability of *T. umbrina* in relation to bark pH (**II**). Kruskal-Wallis test was applied for checking the differences in the cover of *T. umbrina* (**II**), and in the cover and species richness of bryophytes and lichens between the quarries (**III**, separately for lichens and bryophytes). One-way analysis of variance (ANOVA, type III) was used for estimating the effects of distance from the nearest quarry (distance groups 0–500, 501–1000, 1001–2000, >2000 m) on the cover of bryophytes and lichens, on the bryophyte richness, and on pH value of pine bark (**III**). Two-way ANOVA (type III) was applied for checking the effects of distance on the lichen richness; the type of quarry was taken as additional categorical independent variable (**III**). Additionally, Tukey post hoc test was used to test the significant statistical differences between the distance groups (**III**). GLZ analysis with binominal distribution and 'logit' link function was used to describe the relationships between the presence of species and bark pH (taken as a continuous independent variable); species that were recorded in only one sample plot were excluded from this analysis, and species that were recorded on genus level were also excluded (**III**). PCA, ISA, and MRPP were performed in PC-ORD 5 (McCune and Mefford 1999). The Kruskal-Wallis test, ANOVA, Tukey test, t-test, Spearman's rank correlation analyses, logistic regression, GRM, and GLZ analyses were performed in STATISTICA 7 (Statsoft 2004).

In paper **IV**, the total number of alleles, the mean number of alleles, the maximum and the minimum number of alleles, the number of private alleles (P), heterozygosity, i.e., genetic diversity (H), allelic richness (A), and Shannon's information index (I) for eight *Usnea subfloridana* populations were estimated in the GenAlEx ver 6.5 software (Peakall and Smouse 2012) and the Microsatellite Analyzer (MSA) software (Dieringer and Schlötterer 2003). The number of multilocus genotypes (G), the percentage of multilocus genotypes, and the minimum number of colonisation events (C) per population were calculated in the R software (R Core Team 2012) using the script written by Werth et al. (2006). GLZ analysis with normal distribution and "identity" link function was applied to find an effect of dust pollution on the G, M, C, A, I, H, and P of *U. subfloridana* populations. To estimate genetic differentiation among populations from polluted and unpolluted habitats, hierarchical analyses of molecular variance (AMOVA) with 999 permutations was performed using the GenAlEx ver 6.5 software (Peakall and Smouse 2012). T-test was used for detecting the differences between polluted and unpolluted forest stands (according to bark pH value of spruces). To measure bottlenecks of population (to undergone the significant reductions in size or bottleneck effect), the Wilcoxon signed-rank test and the allele frequency distribution test (mode-shift test) were performed using the software BOTTLENECK (Piry et al. 1999).

3. RESULTS

3.1. Environmental variables and pollution zones

Three pollution zones around cement plant in Kunda were distinguished using primarily the pine bark pH, and refined considering CF scores: (1) unpolluted (bark pH≤3; CF<−0.5); (2) moderately polluted (bark pH=3−4; CF −0.5−0.2); (3) heavily polluted (bark pH>4; CF>0.2) zone (Fig. 2; **I**). The pH of the forest litter horizon around the cement plant gradually decreased with increasing distance form cement plant from 7.1−7.4 to 3.6−4.5 at 30 km distance (Table 1 in paper **I**). The content of K, Ca, and Mg of soil samples followed a similar gradient (**I**). The absolute pH values on pines in the vicinity of limestone quarries varied between 2.9 and 6.6, and the mean values per sample plot between 3.2 and 6.3 (**II**, **III**). The bark pH depended significantly on the distance from quarries (F(3, 28)=19.5; p<0.000001; Fig. 2 in paper **III**) and also gradually decreased with increasing distance from the quarries (**II**, **III**). The bark pH gradually decreased with increasing distance from the limestone quarries, being ca. 3.5 at the distance of 1001–2000 m from the quarry, and reaching the mean minimum value, ca. 3.4, further than 2000 m from the quarry (Fig. 2 in paper **III**). The mean bark pH of spruces per forest site varied between 3.5 and 6.6 (Table 1 in paper **IV**) and significantly differed between polluted and unpolluted forest stands (t=14.6; df=6; p<0.00001; **IV**).

The closure of tree stands and shrub layer density were highest in the moderately polluted zone and lowest in the unpolluted zone in vicinity of Kunda cement plant (**I**). The average height of the tree layer and the basal area of pines and spruces were rather similar between zones (Table 1 in paper **I**).

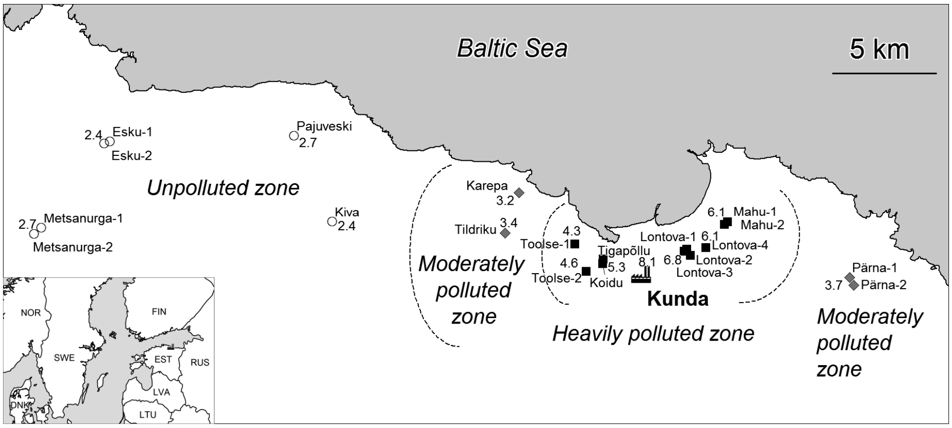

Figure 2. The grading of study area around the Kunda cement plant by three pollution zone: (1) unpolluted zone, marked with open (white) symbols; (2) moderately polluted zone, marked with partly filled (grey) symbols; (3) heavily polluted zone, marked with filled (black) symbols.

3.2. Species richness and cover

Altogether, we recorded 86 species (including 25 epigeic bryophytes; Table 1; Appendix S1 in paper **I**) in the study concerning boreal forest communities in the vicinity of Kunda cement plant (**I**), and 34 epiphytic bryophytes and 84 lichens on pines near limestone quarries (Table 1; Tables 1 and 2 in paper **III**). Comparing the three pollution zones near Kunda cement plant, the pooled species richness was lowest in unpolluted forests (average = 31, SD = 3 species in 0.1-ha sample plot), it increased considerably in the moderately polluted zone (44 ± 14) and was almost two times higher in the heavily polluted zone (63 ± 7; **I**). The variation in species number (SD) was highest in the moderately polluted zone (**I**). The MRPP test showed that the species composition of ground vegetation (herb and moss layer) in the heavily polluted zone was significantly different from that in unpolluted and moderately polluted zones (P=0.001; P=0.006), but species compositions in unpolluted and moderately polluted zones did not differ (P=0.254).

The cover of bryophytes per tree varied between zero and 12%, and mean value per sample plot between zero and 4% near limestone quarries (**III**). The species richness of bryophytes per tree ranged between zero and 8 bryophyte species, and between zero and 11 species per sample plot (**III**). The cover of lichens per tree varied between zero and 75%, and mean value per sample plot between 3 and 60% near limestone quarries (**III**). The species richness of lichens per tree ranged between zero and 18 species, and between 8 and 31 species per sample plot (**III**). The results of Kruskal-Wallis test did not indicate significant differences in the species richness and the cover of epiphytic bryophytes between the four quarries (H(3,32)=3.8, p=0.28; H(3,32)=1.0, p=0.80; **III**), in the cover of *Trentepohlia umbrina* between the four quarries (H(3,32)=1.54; p=0.67; **II**), and in the cover of epiphytic lichens between the four quarries (H(3,32)=0.9, p=0.84; **III**). However, this test revealed a significant difference in species richness of lichens between the four quarries (H(3,32)=12.1, p=0.01; **III**).

3.2.1. Factors influencing species richness and cover

Results of analyses revealed that species richness and cover were correlated with pollution intensity, but various species groups differently responded to pollution impact. According to the GRM analyses, the number of species in the herb and moss layers of boreal forest communities near Kunda cement plant was positively correlated with pollution intensity (**I**). Herb layer richness was well described by the model consisting of three environmental variables (adj R2 = 91.0%). The herb layer richness increased most clearly along the pH gradient (standardized slope estimate b=0.707, p=0.0001; Fig. 3 in paper **I**); moreover, it increased together with the P content (b=0.360, p=0.0002), whereas N content of the litter horizon had a significant negative relationship to the species richness (b=0.281, p=0.0055 in paper **I**). Species richness of epigeic bryophytes was dependent on pollution gradient via Ca content (b=0.643, P=0.0022; adj R2=38.1%; Fig. 3 in paper **I**).

The GRM analyses also revealed that abundance of frequent plant species depended mainly on the litter horizon pH (Table 2 in paper **I**). The significant impact of the litter horizon N content was observed only for a restricted number of species; the P content affected only the abundance of *Alnus incana* and moss species *Cirriphyllum piliferum*. The increase of litter horizon pH was positively associated with the abundance of several shrub layer species (*Corylus avellana*, *Ribes alpinum*, and *Sorbus aucuparia*) and *Quercus robur* saplings. The increased pH of the litter horizon had different impacts on the herb and moss layer species: abundance of species that were natural to boreal pine forests (e.g., *Calluna vulgaris*, *Vaccinium myrtillus*, and *V. vitis-idaea,* and bryophytes *Hylocomium splendens*, *Pleurozium schreberi*, and *Ptilium crista-castrensis*) decreased, while abundance of nemoral species (e.g., *Mycelis muralis*, *Vicia sepium*, *V. sylvatica*, and bryophytes *Cirriphyllum piliferum* and *Rhytidiadelphus triquetrus*) increased (**I**).

According to the results of one-way ANOVA, the species richness of epiphytic bryophyte per sample plot depended significantly on the distance from quarry (F(3,28)=9.9; p=0.0001): the species richness of bryophytes was higher near quarries and decreased gradually at increasing distances from quarries (Fig. 3; **III**). The bryophyte cover also depended significantly on the distance from quarries (F(3,28)=21.7; p<0.00001; Fig. 3; **III**). The cover of epiphytic lichens per sample plot depended significantly on the distance from the quarry (F(3,28)=10.0, p<0.001) being lower near limestone quarries and increasing gradually with increasing distances from quarries (Fig. 3; **III**). The results of two-way ANOVA showed that the distance from the quarry had effect on the number of epiphytic lichens (F(3,25)=4.3, p=0.01): species richness was lowest near quarries, increased gradually till 2000 m from quarries, and started to decrease further than 2000 m from quarries (Fig. 3; **III**). According to two-way ANOVA, the type of quarry had an effect on the number of lichens (F(3,25)=6.9, p=0.01). The results of Spearman's correlation demonstrated no significant effect of mean tree circumference per plot on the number and the cover of bryophytes (N=32: Rs=-0.1, p=0.46; Rs=-0.03, p=0.89 in **III**), on the number and the cover of lichens (N=32: Rs=-0.3, p=0.07; Rs=-0.3 p=0.13 in **III**), and on the cover *of Trentepohlia umbrina* on pines (N=32: Rs= −0.06; p=0.75 in **II**).

The cover of *T. umbrina* was strongly correlated with pine bark pH (Fig. 2 in paper **II**). The results of logistic regression analysis revealed that the occurrence probability of *T. umbrina* reached 50% at pH 3.4 and 90% at pH 3.9−4.0 (**II**).

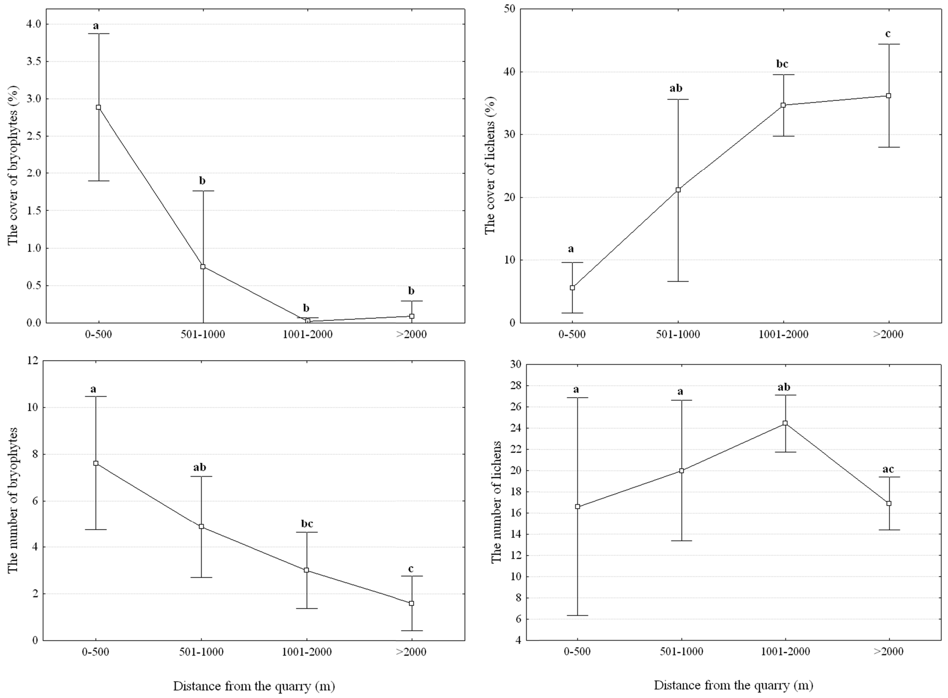

Figure 3. The mean percentage of bryophyte and lichen cover (±0.95 confidence interval) and the mean number of bryophyte and lichen species (±0.95 confidence interval) on Scots pines per sample plot at different distances from the quarries; the significant differences between the groups are marked with letters *a–c* according to Tukey' HSD test.

3.3. Bioindicators of dust pollution

According to results of ISA, 12 species (among them two orchids − *Neottia ovata* and *Neottia nidus-avis*) appeared to be significant indicators for the heavily polluted zone, and six species – for the moderately polluted zone around Kunda cement factory (Appendix S1 in paper **I**).

Spearman's correlation analyses confirmed a significantly higher cover of *Trentepohlia umbrina* in the vicinity of limestone quarries (Fig 2 in paper **II**). The cover of this species decreased steeply at the distance of 800–900 m from the quarry; further than 1000 m from the quarry the maximum cover value of *T. umbrina* was already less than 4%, and further than 2000 m less than 1% (Fig. 2 in paper **II**).

The GLZ analysis revealed that six epiphytic bryophyte species (*Orthotrichum pallens*, *O. speciosum*, *Pylaisia polyantha*, *Radula complanata*, *Schistidium apocarpum*, and *Syntrichia calcicola*) preferred a higher bark pH of pines in the vicinity of limestone quarries (Table 1 in paper **III**). No bryophyte species were significantly associated with lower bark pH (**III**). Thirteen lichen species favoured a higher bark pH of pines in the vicinity of limestone quarries, and 21 lichen species preferred a lower bark pH of Scots pines (Table 2 in paper **III**).

3.4. Niche width along the soil pH gradient (I)

We categorized the species using their indicator value patterns between pollution zones near Kunda cement plant (Appendix S1 in paper **I**); 17 species were defined to acidic soils, 48 species were associated with calcareous soils, and 13 species were related to neutral soils (Fig. 4). Eight species (having frequency ≥10%) were common species with no preference pH, and were considered as pH generalists. The species reactions measured with the parametric model (GRM and GLZ; Tables 2 and 3 in paper **I**) were in good agreement with the non-parametric niche definitions based on the indicator species analysis (Appendix S1 in paper **I**), particularly for the species at the extreme ends of pH/Ca gradients. The exceptions were two generalists (*Vaccinium vitis-idaea* and *Hylocomium splendens*), but as shown by GLM, their abundance decreased along the pollution gradient linearly, and indicator values also indicated this. We revealed that niche width classes, which were generated using species indicator value patterns were acceptable, because parametric models did not allow evaluation of species with lower frequencies or species with a neutrophilous niche. The number of narrow and wide niche species increased from the acidophilous-neutrophilous niche class in both directions according to species counts in each niche class, but particularly toward calcicolous species (Fig. 4).

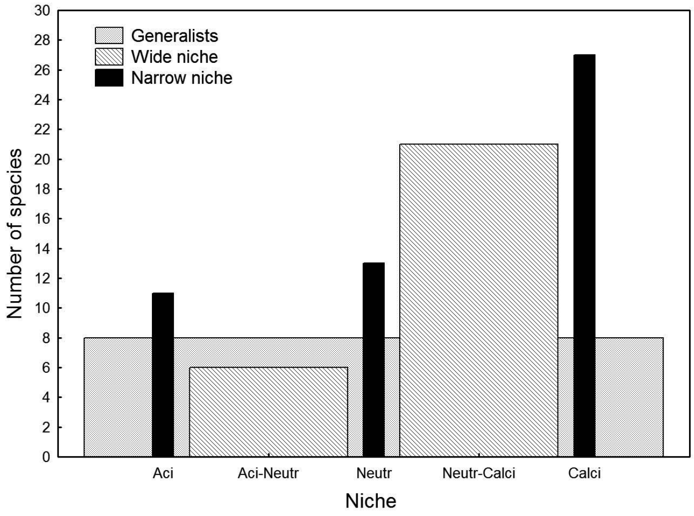

Figure 4. Number of common species (frequency ≥ 10%) in pH-based niche classes: Aci, acidophilous; Aci-Neutr, acidophilous-neutrophilous; Neutr, neutrophilous; Neutr-Calci, neutrophilous-calcicolous; Calci, calcicolous. pH generalist species are shown as background bar. The combined summary of these species by pollution zone describes the major pattern of species richness along the pH gradient.

3.5. Genetic diversity of *Usnea subfloridana* populations (IV)

In total, 274 specimens of *Usnea subfloridana* were analysed and genotyped using nine microsatellite fungus-specific markers. We found 72 alleles at studied loci that provided 168 different genotypes across eight populations of lichen-forming fungus. All microsatellite loci were highly polymorphic. Detailed genetic estimates and number of alleles per each marker and population are given in Tables 1 and 3 in paper **IV**.

The GLZ demonstrated that the presence of dust pollution and number of collected samples or sample size (sqrt N) revealed significant impact on allelic richness (A); this measure was higher in unpolluted forest sites than in polluted forest sites (Table 2). The presence of dust pollution showed the same significant effect on the Shannon's information index (I) and genetic diversity (H) per population, but sqrt N revealed significant influence only on I (Table 2). GLZ also demonstrated that the number of multilocus genotypes (G) and the number of private alleles (P) were significantly contingent on the sample size (sqrt N), but did not differ between polluted and unpolluted forest sites (Table 2). There was no statistically significant relationship between C and the presence of dust pollution (data not shown). There was also no significant interaction between clonal diversity (M) and dust pollution, and M did not correlate with sqrt N (Table 2). The average age of spruces in forest sites (sqrt AGE) did not show significant effect on any measures of genetic diversity of *U. subfloridana* populations in all CLZ analyses (Table 2, results of analyses shown partially).

Hierarchical analyses of molecular variance (AMOVA) revealed no genetic differentiation between studied *U. subfloridana* populations from polluted and unpolluted forest sites (1% differentiation; PhiRT=0.01; P=0.06). The proportion of alleles showed a ‘shifted mode’ distribution in population 4 and 5 (Table 5 in paper **IV**). The results of Wilcoxon signed-rank test under all tree mutation models per population are given in Table 5, in paper **IV**.

Table 2. Results of generalized linear model (GLZ) for the allelic richness (A), the Shannon's information index (I), the genetic diversity (heterozygosity) (H), the number of multilocus genotypes (G), the clonal diversity (M), and the number of private alleles (P) in examined *Usnea subfloridana* populations. df, degrees of freedom; F, Wald-type F-statistic; p, significance level; sqrt Age, the square root of average age of spruces in each forest site; sqrt N, the square root of number of collected thalli in each population; Pollution, the presence of dust pollution. Bold-faced values represent significant effect

Effect	**A**			**I**			**H**		
	df	**F**	**p**	**df**	**F**	**p**	**df**	**F**	**p**
sqrt Age	1	1.60	0.21	1	1.26	0.26	1	0.32	0.57
sqrt N	1	**16.86**	**<0.001**	1	**18.41**	**<0.001**	1	1.89	0.17
Pollution	1	**10.03**	**0.002**	1	**12.30**	**<0.001**	1	**4.17**	**0.04**
Effect	**G**			**M**			**P**		
	df	**F**	**p**	**df**	**F**	**p**	**df**	**F**	**p**
sqrt Age	1	0.18	0.67	1	0.21	0.64	1	0.09	0.76
sqrt N	1	**247.6**	**<0.001**	1	1.75	0.19	1	**10.68**	**0.001**
Pollution	1	0.10	0.75	1	0.06	0.81	1	1.30	0.25

4. DISCUSSION

4.1. Environmental variables under alkaline dust pollution

Effect of long-term alkaline dust pollution from various pollution sources (viz., cement plant, limestone quarries, and unpaved road) on different organism groups was studied in boreal forest ecosystems. According to our results, the long-term dust pollution had a remarkable neutralizing effect on natural substrates in pine forest ecosystems; both, the pH value of litter horizon (Table 1 in paper **I**) and pine bark (**I**, **II**, **III**) significantly decreased along an increasing distance from the sources of dust pollution. Additionally, the pH value of spruce bark had also increased (up to 5.9–6.6) in polluted habitats that were adjacent to limestone unpaved road, and significantly differed between polluted and unpolluted forest stands (**IV**).

Similarly, several studies have showed the noticeable decrease of soil and bark acidity (e.g., Gilbert 1976; Farmer 1993; Cutillas-Barreiro et al. 2016), and increase of Ca, Mg, and K content (Mandre 1995; Haapala et al. 1996a) in the vicinity of sources of alkaline air pollution. We also found that Ca, Mg, and K content of soil litter horizon followed the similar decreasing tendency along the dust pollution gradient (**I**). The Ca content of soil litter horizon was ten times higher near Kunda cement plant than in unpolluted areas. Previous studies from the early 1990s in the vicinity of Kunda factory had detected a 15-fold increase in Ca content from the unpolluted to the heavily polluted zone (Annuka and Mandre 1995). Comparing our results with previous 20-yr-old monitoring (Annuka and Mandre 1995), we can observe that the soil litter is recovering after the drastic reduction of alkaline emissions from the cement plant, but the over a century accumulated dust and its impact are still evident and persisted nowadays. Amarell (2000) also noticed the delayed recovery of soil in the pine forests of Central Germany. The observed delay in soil recovery may be explained by the saturation of pollution impacts, where increasing Ca content does not increase the pH above a certain level (Fig. 2 in paper **I**), and consequently, after the reduction of pollution, the Ca level in soil can decrease over a long time before pH will reduce. The natural self-restoration of soils and pine forest ecosystems at whole is possible but it will last for decades. There have been no controlled studies that consider the restoration of pine ecosystems after long-term alkaline cement dust accumulation. Therefore, further continuing observations are required to evidence when total recovery processes will occur.

4.2. Bioindication of alkaline dust pollution

Bioindicators are biological species, biological processes or communities, which are used to evaluate the quality of environmental conditions (Holt & Miller 2010). Comparing with monitoring stations and directly measured physical parameters, the using of bioindicators has several advantages as they allow assessing the cumulative impacts of chemical pollutant, habitat changes over time, and could provide the monitoring data about environment that is not covered with direct measurements (Conti and Ceccheti 2001; Sujetovienė 2015). The good bioindicators should have some features, for instance, they should be well-studied, common in studied geographical region, and have measurable indicator ability (Holt & Miller 2010).

The present study confirms some previously known, and suggests a few new bioindicators of dust pollution among algae, lichens, bryophytes, and vascular plants. The results of paper **II** confirm that green alga *Trentepohlia umbrina*, if growing on pines, could be used as an ecological indicator of alkaline dust pollution. Our results revealed that the abundance of *T. umbrina* on pine trunks was clearly higher near the limestone quarries, its maximum cover values reaching ca. 30% (mean of five trees studied per sample plot). We suggest that ≥10% cover of *T. umbrina* on pines indicates considerable dust pollution (Fig. 2 in paper **II**). These results are in agreement with those obtained by Haapala et al. (1996b), who also observed high abundance of *T. umbrina* on pine trunks in dust-polluted areas in Leningrad Oblast, Russia. Such reddish powdery cover of *Trentepohlia* on pine bark is easily recognizable at field (Appendix A in paper **II**); however, further separating between the species without microscopical examination might be challenging.

The cover and species richness of epiphytic bryophytes also responded to limestone dust pollution (**III**). The cover of bryophytes had the highest mean values (2.9 %) up to 500 m from limestone quarries; further from the quarries, the cover of bryophytes decreased significantly, being 0.02 % at the distance range between 1001 and 2000 m and 0.1 % further than 2000 m (Fig. 3). The number of bryophyte species on pines was significantly higher near the limestone quarries and decreased steadily along an increasing distance from the source of limestone dust pollution (Fig. 3). In the same way, we detected the inflated species richness of epigeic mosses and vascular plants in *Vaccinium myrtillus* site type pine forests in vicinity of Kunda cement plant (**I**). The number of species in the herb and moss layer was positively correlated with pollution intensity, but expressed via different indicators, pH of litter horizon for vascular plants and litter logCa content for bryophytes, which were more significant predictors than combined pollution factors (Fig. 3 in paper **I**). However, the pollution intensity has a different impact on abundance of vascular plants and epigeic mosses. For example, the increase of litter horizon pH was positively correlated with abundance of several shrub layer species (Table 2 in paper **II**) and negatively correlated with abundance of species that were natural to boreal pine forests (Table in paper **II**).

Lichen cover responded to dust pollution in a different way compared with alga *Trentepohlia umbrina* (**II**) and epiphytic bryophytes (**III**); correlation analysis confirmed the negative association between the bryophyte cover and lichen cover, while the maximum cover of bryophytes was considerably lower than lichen cover (viz., 12 and 75% per tree, correspondingly, in paper **III**). The lichen cover on pines increased considerably with the increasing distance from quarries up to 3340 m; the lichen cover was ca. 35% at the distance range between 1001 and 2000 m and further than 2000 m continued to increase slightly (Fig. 3). The number of lichen species was lowest near the source of pollution, increased at the distance of 1001–2000 m, and then started to decrease, being almost at the same level as in the closest vicinity near quarries (Fig. 3). In general, we revealed the shift of natural communities along a pollution gradient (**I**, **III**). These results are in agreement with the previous findings concerning the effect of alkaline dust pollution, for instance, on lichens, where the number of species was altered due to the change of bark pH from acidic to subneutral, and increased bark pH favoured the occurrence of basiphytic and neutrophytic species and even saxicolous species on the originally acid-barked trees (Gilbert 1976; Loppi and Pirintsos 2000; Marmor et al. 2010). The monitoring of cryptogamic communities (Rola and Osyczka 2014) and communities of vascular plants could be useful in bioindication studies. At the same time, the community structure could be an even better predictor of environmental conditions than occurrence or absence of a specific species (van Haluwyn and van Herk 2002). Therefore, we suggest that increased bryophyte diversity and cover on pines due to invasion of species typical for nutrient-rich communities (**III**), diversification effect (to some extent) of lichens (**III**), the appearance of typical species for mesotrophic and meso-eutrophic habitats and increased abundance of shrub species in vegetation of *Vaccinium myrtillus* site type forests (**I**), as well as replacement of acidophilious/acido-tolerant species by neutrophilous and calciphilous (**I**, **III**) could provide useful and promising tool for detecting environmental changes and, particularly, monitoring the dust pollution and its extent in dust-impacted areas. However, the relation between species richness and dust pollution may not be universal and simply linear in all cases (Marmor and Randlane 2007). Therefore, such findings need to be interpreted with caution, taking into account the initial environmental conditions and variation among different taxonomic groups and ecosystems.

We also found that the occurrence of six epiphytic bryophytes was strongly correlated with the pH of their substrate: *Orthotrichum pallens*, *O. speciosum*, *Pylaisia polyantha*, *Radula complanata*, *Schistidium apocarpum*, and S. *calcicola* preferred a higher bark pH of pines (Table 1 in paper **III**). Some of them have been already proposed as indicator species of polluted areas with different dust pollution level: *P. polyantha* and *R. complanata* as indicators for moderate dust-polluted zones, and *S. calcicola* for heavy dust-polluted zones (Paal and Degtjarenko 2015). Here, we proposed that *O. pallens*, *O. speciosum*, and *S. apocarpum*, if growing on pines, can be regarded as new additional indicators of alkaline dust pollution (**III**). Conifers, especially pines, are commonly colonized by few epiphytic mosses in natural conditions (Király and Ódor 2010) due to the fact that Scots pines have an extremely acidic and oligotrophic bark, which is a rare habitat for bryophytes (Barkman 1958). Therefore, the occurrence of epiphytic calcicolous bryophytes on pines could serve as a very good indicator of dust pollution in dust-impacted areas. Our results in paper **I** also revealed that some epigeic bryophyte species can be indicators of alkaline dust pollution in pine forests (Appendix S1 in paper **I**), however many of them were in low abundance in the pollution areas and so they should be pooled for analyses and used as an indicator species complex.

Several lichens were also correlated with the pine bark pH according to our results (**III**). Thirteen lichens (e.g., *Lecania cyrtella*, *Lecania naegelii*, *Lecanora hagenii* etc.) favoured a higher bark pH of Scots pine (Table 2 in paper **III**). Several of them were previously known as alkaline dust indicators if growing on pines (Marmor and Randlane 2007; Smith et al. 2009). *Alyxoria varia*, *Caloplaca cerinelloides*, *Lecania cyrtella*, and *Lecidella elaeochroma* have been repeatedly recorded in areas impacted by dust pollution that was released from limestone quarries (Loppi and Pirintsos 2000; Smith et al. 2009; Paoli et al. 2014). Hence, the presence of these species on Scots pines can be considered as a further indication of alkaline dust pollution. In addition, changes and loss of genetic diversity observed in *Usnea subfloridana* populations (**IV**) could be used as an additional sign to highlight environmental disturbances induced by alkaline air pollution.

4.3. The impact of alkaline dust pollution on natural communities in boreal ecosystems

Local long-term dust pollution has led to destruction of natural communities in pine forests, including epiphytic communities on pines. We outlined the process of ‘nemoralization’ in the vegetation of the studied *Myrtillus* site type pine forests (**I**). The ‘nemoralization’ of this habitat was expressed as step-by-step replacement of acidophilous/acidotolerant species by several neutrophilous and then by calcicolous species. In the heavily polluted zone near Kunda cement factory, numerous herb layer species and bryophytes typical of unpolluted *Myrtillus*-type forests were absent (**I**). The most indicating was the loss of dwarf-shrub species (*Vaccinium myrtillus* and *Calluna vulgaris*), a specific plant growth form of oligotrophic habitats (**I**). However, the species-poor undergrowth and ground vegetation of unpolluted *Vaccinium* site type forests was diversified by invasion with non-typical species for local communities along the cement pollution gradient (**I**). The characteristic arrival species, including several orchid species, were typical for mesotrophic and meso-eutrophic habitats and for boreo-nemoral woodlands. These arrival species are generally common in calcareous habitats with nutrient-rich soils, but as in the present study the addition of nutrients was not noticed (cement dust did not contain much N and P). Therefore, we outlined that pH was the most limiting factor for these species (**I**).

Similarly, dust pollution and its alkalization effect for pine bark provoked the shift of cryptogamic communities along a pollution gradient (**III**). The structure of cryptogamic communities clearly responded to changing habitat conditions along the pollution gradient. For instance, the increased bark pH of pines promoted increased diversity of epiphytic bryophytes, including the occurrence of tolerant bryophyte species, which withstand or even favour alkalinity of substrates, and typically occur on limestone outcrops (e.g., *Anomodon longifolius*, *Ditrichum flexicaule*, *Fissidens dubius*, and *Pseudoleskeella catenulata*), concrete substrates (e.g., *Amblystegium serpens*, *Brachythecium salebrosum*, and *Syntrichia calcicola*) or on nutrient-rich bark (e.g., *Orthotrichum diaphanum* and *Leskea polycarpa*) (Ingerpuu and Vellak 1998; Ignatov and Ignatova 2004; Atherton et al. 2010). The increased bark pH from acidic to subneutral also favoured lichens that commonly occur on basic nutrient-rich bark of deciduous trees (e.g., *Lecania cyrtella*, *Lecania naegelii*, and *Lecanora hagenii*) (Smith et al. 2009).

Besides species-specific reactions, dust pollution caused the ‘diversification effect’ of vascular plant (**I**) and bryophyte (**I**, **III**) communities and increased the total species richness (including several protected and rare species). The air pollution is considered as environmental stress to vegetation and other biota, and it commonly leads to the decrease of overall biodiversity and impoverishment of natural communities (Zvereva et al. 2008). However, the increase of species richness can occur in low-diversity oligotrophic habitats in the response to stress (Odum 1984). Indeed, the alkaline dust pollution through increasing the soil and bark pH and nutrient input (e.g., Ca, Mg, and K) has a positive effect (to certain extent) on species richness in studied pine forests or on pine barks near the source of alkaline dust pollution. The rise of vascular species richness (e.g., Ksenofontova and Zobel 1987; Annuka 1995; Stravinskiene 2011) and increased diversity of epiphytic bryophytes (Kannukene 1995; Paal and Degtjarenko 2015) induced by alkalization of environment has been noted in several previous studies; other studies, however, have indicated the negative impact and the loss of species richness among vascular plants (Stravinskiene et al. 2004; Sujetovienė 2008), epigeic bryophytes (Meininger and Spatt 1988; Auerbach et al. 1997), *Sphagnum* mosses among others, in naturally acidic ombrotrophic bogs (Paal et al. 2010; Vellak et al. 2014). This difference might be explained by the immigration time, initial natural conditions, pollution load, and variation in regional species pool size or availability of alternative species in the region, accumulated in communities with different environmental conditions. Indeed, in the neighbourhood of studied pine forest communities in Kunda (**I**), there were boreo-nemoral and limestone escarpment forests, which are characterized by high richness of vascular plant species and bryophytes, among them several red-listed species (Paal 2001; Ingerpuu et al. 2003).

Therefore, those adjacent forests may also contribute to availability of alternative species in Kunda region (**I**).

We also revealed that species responded with different sensitivity to the changes in the environment, revealing their different ecological niche width along the pH gradient (Fig. 4). The niche width of species along the pollution gradient ranged among species and only a few species acted as pH generalists. The pH specificity of species, and the species niche widths along the dust pollution gradient, demonstrated that the species pool of calcicolous species was several times larger than species pool of acidophilous species, which was presumed according to large-scale analyses (Pärtel 2002; Ewald 2003). We also proposed that species filtering success is regulated, as suggested by Tilman (1988), by a critical level at the one end of the niche width along the limiting gradient (Lawesson 2003; Lõhmus and Kull 2011). In general, the study in paper **I** supported the classical individualistic approach of community assembly (Gleason 1926; Tilman 1988). According to that theory, species arriving in the community are filtered from the available species pool (Zobel 1997) not by their environmental average tolerance, but by niche thresholds or niche location and width along the limiting factor gradients. The species ecological niche space boundaries could be useful and could be kept in long-term database for future floristic studies.

Moreover, we found that alkaline dust pollution revealed a 'parapositive' effect on species diversity. We recorded several locally rare species [(e.g., bryophytes *Leskea polycarpa*, *Orthotrichum diaphanum*, and *Pseudoleskeella catenulata*, red-listed in Estonia as NT (Vellak et al. 2015), and e.g., lichens *Agonimia tristicula*, *Strangospora pinicola*, and *Caloplaca ulcerosa* (red-listed in Estonia as VU; Randlane et al. 2008)], two woodland key habitat bryophyte indicators (*Anomodon longifolius* and *Ulota crispa*), and two woodland key habitat lichen indicators (*Alyxoria varia* and *Pseudoschismatomma rufescens*) on pines at the closest distance from the pollution source (Estonian Acts of Law 2016). In the areas heavily polluted by cement dust, several orchids species having conservation value in Estonia were also recorded. The altered environment, e.g., increased bark pH of Scots pines or soil, dust cover and other changed environmental conditions, such as drier microclimatic conditions (Loppi and Pirintsos 2000), in dust-polluted areas could eventually shape a particular and alternative habitat for species, contributing to diversification of communities and the distribution of locally rare species. Although some rare species can even benefit from these environmental changes induced by pollution, the alkaline dust pollution has heavily disturbed the natural communities (**I**, **III**) and affected the genetic diversity of lichen populations (**IV**) in the vicinity of pollution sources. Those artificial communities containing rare or protected taxa are temporary phenomena, depending strongly on the continuation of pollution (Gilbert 1976). Consequently, those disturbed areas have a scientific importance as long-term ecological experiments but they do not contribute permanently to the local species richness.

4.4. The effects of dust pollution on genetic diversity of *Usnea subfloridana* populations (IV)

Little is known about impacts of environmental pollution on the genetic pattern of cryptogams. For example, extensive urban pollution lowered the genetic diversity of the epiphytic bryophyte *Leptodon smithii* (Spagnuolo et al. 2007); moreover, gene diversity was correlated with airborne trace element content in moss tissue (Spagnuolo et al. 2009). No studies have been performed concerning the genetic variation of populations of lichenized fungi in air polluted conditions; however, lower genetic diversity of the photobionts of the lichenized fungus *Parmotrema tinctorum* was demonstrated in the urban area compared to that in suburbs and mountainsides (Ohmura et al. 2006).

We compared the variables of genetic diversity of eight *Usnea subfloridana* populations, a common lichen-forming fungus, from different habitats (polluted vs unpolluted) and defined that several variables of genetic variation were significantly different in *U. subfloridana* populations. Populations that developed under road dust pollution revealed significantly lower values of the allelic richness (A), Shannon's information index (I), and genetic diversity (H) than populations in unpolluted forest sites (Table 2). Previous studies have demonstrated that habitat quality was a crucial factor shaping the genetic variation of lichenized fungi populations (Werth et al. 2006; Jüriado et al. 2011; Otalora et al. 2011). At the same time, long-term dust pollution can change drastically local environmental conditions in the vicinity of the source of dust pollution (**I**, **II**, **III**), and influence the natural composition of epiphytic lichen communities and alter the species richness of lichens (Marmor et al. 2010; Paoli et al. 2014; **III**). The habitats located near the dusty roads suffer from similar changes (Marmor and Randlane 2007; Madl et al. 2010). Results of this study also indicated the increased mean bark pH value (5.9–6.6) of spruces growing in polluted habitats, while natural pH value of spruce bark is about 3.3–3.8 in unpolluted sites of Estonia (Marmor et al. 2010; 3.5–3.6 in our sites without dust pollution). Furthermore, *Usnea* species are usually sensitive to alkaline dust pollution (Martin and Nilson 1992) and generally prefer a lower bark pH (Marmor and Randlane 2007). Additionally, alkaline dust pollution contributes to drier microclimatic conditions (Loppi and Pirintsos 2000), and thus decreases the habitat quality for *Usnea* species even more. Hence, we suggest that reduced habitat quality increased *Usnea* mortality, which could cause a decline in population size (not directly measured in this study). Therefore, studied *Usnea* populations in polluted habitats may have experienced a continuing bottleneck reducing the allelic richness (A) of *Usnea* populations in polluted habitats but not yet other examined measures of genetic variation (e.g., M or P) in this study. The measure of A is usually more sensitive to the impact of bottleneck and is reduced by bottlenecks faster than other commonly reported variables of genetic variation (Leberg 2002; Kalinowski 2004). The observed measures of I and H support our results (Table 2), although, those measures were not corrected for sample size as A. The bottleneck analysis showed a strong evidence of the bottleneck only in one lichen population from polluted habitat in this study (Table 5 in paper **IV**). Still, it has been recently demonstrated that microsatellite-based bottleneck tests often either failed to recognize bottleneck in populations known to have experienced reductions or detected bottlenecks in putatively stable populations (Peery et al. 2012). For example, the significant heterozygosity excess was also detected under infinite alleles mutation model (IAM) in stable populations (Luikart and Cornuet 1998). Taking into account the insufficiency of microsatellite-based bottleneck tests, we hypothesize that probable population bottleneck (although detected only in one population from polluted habitat), which is caused by considerable changes of local environment due to the presence of alkaline dust pollution, may have reduced the genetic variation of studied *U. subfloridana* populations.

The observed changes in genetic diversity in *U. subfloridana* populations that were exposed to dust pollution may theoretically have also experienced the negative edge effect of habitat, which could disrupt spore dispersal and exchange of individuals or genes among populations, resulting in genetic drift, increasing the genetic differentiation between populations, and reducing the genetic variation (Frankham et al. 2010; Holderegger and Di Giulio 2010). However, exchange of individuals still exists between the populations according to AMOVA analysis that showed no genetic differentiation (1% differentiation; PhiRT=0.01; P=0.06) among the lichen populations from polluted and unpolluted habitats. Therefore, we consider population bottleneck more reasonable cause than negative edge effect for the reduced genetic variation in the studied populations of *Usnea subfloridana* in polluted habitats.

CONCLUSIONS

The current study reviewed long-term influence of alkaline dust pollution emitted from different sources (cement plant, limestone quarry, and unpaved road) on species diversity, including vascular plants, bryophytes, lichens, and alga; and, additionally, on the genetic diversity of populations of a common lichen-forming fungus in Estonia. The results of this thesis demonstrate considerable local contamination and destruction of natural communities around the sources of alkaline dust pollution, and provide different approaches of bioindication of dust pollution.

In general, the results of this thesis can be summarized as follows.

1. Long-term dust pollution had a remarkable neutralizing effect on natural substrates in forest stands; both, the pH value of soil litter horizon and pine and spruce barks significantly decreased along an increasing distance from the sources of dust pollution. We also found that Ca, Mg, and K content of soil litter horizon followed the similar decreasing tendency along the dust pollution gradient. The resilience of soil litter horizon was observed but accumulated (over century persisted) pollution impact was still evident in the vicinity of Kunda cement plant.
2. The long-term alkaline pollution has caused destruction of natural communities and formation of novel communities in the vicinity of dust pollution sources. The alkaline pollution has induced remarkable and long-lasting successional changes in pine forest ecosystems and has caused the 'nemoralization' of the studied *Vaccinium myrtillus* site type pine forests close to Kunda cement plant. Dust pollution and its alkalizing effect on pine bark also provoked the shifts of epiphytic cryptogamic communities along a pollution gradient. The linear increase of species richness among vascular plants, epigeic and epiphytic bryophytes from unpolluted to newly formed polluted habitats was detected. The diversification took place by invasion of non-typical and pollution-tolerant species for local communities, including calcicolous species and species characteristic for nutrient-rich habitats. The increased bark pH from acidic to subneutral also favoured lichens that commonly occur on basic and nutrient-rich bark of deciduous trees or even limestone outcrops, while cover of lichens responded to dust pollution in a different way compared with cover of epiphytic bryophytes and *Trentepohlia umbrina*. We provided, for the first time, one-time inventory of the two cryptogamic groups (epiphytic bryophytes and mosses) growing on pine trees in the vicinity of limestone quarries.
3. The results of this study confirmed usability of several previously proposed bioindicators and suggested new, additional bioindicators of alkaline dust pollution among algae, lichens, bryophytes, and vascular plants. The presence of species being typical for mesotrophic and meso-eutrophic habitats (e.g., several orchid species) in vegetation of *Vaccinium myrtillus* site type forests or of cryptogams typical for basic nutrient-rich bark of

deciduous trees on originally acid-barked phorophytes could be used as bioindication of dust pollution. We also outlined that total community changes, species richness and abundance of selected species groups could be also useful and helpful indicators of alkaline dust pollution in biomonitoring studies around sources of similar pollution.

4. Our results revealed ‘parapositive’ impact of alkaline dust pollution on natural communities, suggesting that pollution might, besides disturbing natural communities, temporarily also contribute to the distribution of rare and protected species. Despite the fact that some rare and protected species can even benefit from these drastic environmental changes induced by alkaline dust pollution, the dust pollution has heavily destroyed the natural communities in the vicinity of pollution sources. Such polluted areas with disturbed communities had a high scientific importance as long-term ecological experiments, but they are temporary phenomena, depending strongly on the continuance of pollution and are certainly not suggested as a tool for supporting rare taxa.
5. We revealed that species grouping along the alkaline dust pollution gradient indicates the existence of different ecological association in terms of ecological niche use, and establishment of a new community is defined by the tolerance level of each species. This result also supports the classical individualistic approach of community assembly. We also conclude that for future floristic studies to predict community changes and species coexistence, the species ecological niche space boundaries should be evaluated and kept in long-term data sets.
6. We recorded for the first time that long-term alkaline dust pollution released from unpaved roads had a negative impact on the genetic variation of *Usnea subfloridana* populations, a common species of lichen-forming fungi. We suggest that studied *Usnea* populations in polluted habitats may have experienced a continuing bottleneck reducing the allelic richness (A) of populations, but not yet other examined measures of genetic variation (e.g., M or P) in this study. The loss of genetic diversity and changes in genetic structure of populations of common lichen-forming fungi may serve as a warning to the vulnerability of lichen-forming fungi populations to environmental disturbances caused by air pollution.

REFERENCES

Ade-Ademilua, O. E. & Obalola, D. A. (2008) The effect of cement dust pollution on *Celosia argentea* (Lagos Spinach) plant. *Journal of Environmental Science and Technology* **1**: 45−55.

Ahti, T., Hämet-Ahti, L. & Jalas, J. (1968). Vegetation zones and their sections in northwestern Europe. *Annales Botanici Fennici* **5**: 169−211.

Annuka, E. (1995) Influence of air pollution from the cement industry on plant communities. In *Dust pollution and forest ecosystems. A study of conifers in an alkalized environment* (M. Mandre, ed): 124–133. Tallinn: Institute of Ecology.

Annuka, E. & Mandre, M. (1995) Soil responses to alkaline dust pollution. In *Dust pollution and forest ecosystems. A study of conifers in an alkalized environment* (M. Mandre, ed): 33–43. Tallinn: Institute of Ecology.

Annuka, E. & Rauk, J. (1990) Männikute radiaaljuurdekasv ja vitaalsus mõnedes tööstuspiirkondades. In *Tootmine ja keskkond: teaduslik-rakendusliku konverentsi (19.-20. apr. 1990. a.) ettekannete kokkuvõtted, Tallinn, Eesti,* p. 38–43.

Amarell, U. (2000) *Kiefernforste der Dübener Heide. Ursachen und Verlauf der Entstehung und Veränderung von Forstgesellschaften. Dissertationes Botanicae.* Berlin-Stuttgart: J. Cramer.

Atherton, I. D. M., Bosanquet, S. D. S. & Llawley, M. (2010) *Mosses and liverworts of Britain and Ireland: a field guide*. Plymouth: British Bryological Society.

Auerbach, N. A., Walker, M. D. & Walker, D. A. (1997) Effects of roadside disturbance on substrate and vegetation properties in Arctic tundra source. *Ecological Applications* **7**: 218–235.

Barkman, J. J. (1958) *Phytosociology and ecology of cryptogamic epiphytes*. Assen: Van Gorcum.

Barnes, P. J. (2008) The cytokine network in asthma and chronic obstructive pulmonary disease. *The Journal of clinical investigation* **118**: 3546–3556.

Bickham, J. W., Sandhu, S., Hebert, P. D., Chikhi, L. & Athwal, R. (2000) Effects of chemical contaminants on genetic diversity in natural populations: implications for biomonitoring and ecotoxicology. *Mutation research* **463**: 33–51.

Bilen, S. (2010) Effect of cement dust pollution on microbial properties and enzyme activities in cultivated and no-till soils. *African Journal of Microbiology Research* **4**: 2418–2425.

Brandt, C. J. & Rhoades, R. W. (1972) Effects of limestone dust accumulation on composition of a forest community. *Environmental Pollution* **3**: 217–225.

Branquinho, C., Gaio-Oliveira, G., Augusto, S., Pinho, P., Máguas, C. & Correia, O. (2008) Biomonitoring spatial and temporal impact of atmospheric dust from a cement industry. *Environmental Pollution* **151**: 292–299.

Brook, R. D., Rajagopalan, S., Pope, C. A., Brook, J. R., Bhatnagar, A., Diez-Roux, A. V., Holguin, F., Hong, Y., Luepker, R. V., Mittleman, M. A. & Peters, A. (2010) Particulate matter air pollution and cardiovascular disease an update to the scientific statement from the American Heart Association. *Circulation* **121**: 2331–2378.

Bušs, K. (1997) Forest ecosystem classification in Latvia. *Proceedings of the Latvian Academy of Sciences* **51**: 204–218.

Conti, M. E. & Cecchetti, G. (2001) Biological monitoring: lichens as bioindicators of air pollution assessment – a review. *Environmental Pollution* **114**: 471–492.

Cutillas-Barreiro, L., Pérez-Rodríguez, P., Gómez-Armesto, A., Fernández-Sanjurjo, M.J., Álvarez-Rodríguez, E., Núñez-Delgado, A., Arias-Estévez, M. & Nóvoa-

Muñoz, J. C. (2016) Lithological and land-use based assessment of heavy metal pollution in soils surrounding a cement plant in SW Europe. *Science of The Total Environment* **562**: 179–190.

DiBattista, J. D. (2008) Patterns of genetic variation in anthropogenically impacted populations. *Conservation Genetics* **9**: 141–156.

Dieringer, D. & Schlötterer, C. (2003) Microsatellite analyser (MSA): a platform independent analysis tool for large microsatellite data sets. *Molecular Ecology Notes* **3**: 167–169.

Dierßen, K. (1996) *Vegetation Nordeuropas*. Stuttgart: Eugen Ulmer.

Dufrêne, M. & Legrendre, P. (1997) Species assemblages and indicator species: the need for flexible asymmetrical approach. *Ecological Monographs* **67**: 345–366.

Ellenberg, H. H. (2009) *Vegetation Ecology of Central Europe, 4th edn*. Cambridge: University Press.

Environmental Board (2016) *Environmental permits*. https://eteenus.keskkonnaamet.ee. Accessed 31 May 2016.

Estonian Acts of Law (2016) *The website of Riigi Teataja*. https://www.riigiteataja.ee/akt/116102013004. Accessed 31 May 2016.

Estonian Environment (1995) *Estonian environment 1994*. Tallinn: Estonian Environmental Information Centre.

Estonian Weather Service (2016) *Estonian Weather Service.* http://www.ilmateenistus.ee/?lang1⁄4en. Accessed 21 June 2016.

Ewald, J. (2003) The calcareous riddle: why are there so many calciphilous species in the Central European flora? *Folia Geobotanica* **38**: 357–366.

Farmer, A. M. (1993) The effects of dust on vegetation − a review. *Environmental Pollution* **79**: 63–75.

Farmer, A. (2002) Effects of particulates. In *Air pollution and plant life, 2nd edition.* (J. N. B. Bell & M. Treshow, eds): 187−199. West Sussex: John Wiley.

Fedorchuk, V. N., Neshatayev, V. Y. & Kuznetsova, M. L. (2005) *Forest Ecosystems of the North-western Regions of Russia: typology, dynamics, forest management features*. St. Petersburg: Forestry Scientific Research Institute.

Forest Public Registry (2012) *Forestry public registry web service*. http://register.metsad.ee/avalik/. Accessed 31 August 2012.

Frankham, R., Ballou, J. D. & Briscoe, D. A. (2010) *Introduction to Conservation Genetics*. Cambridge: Cambridge University Press.

Geoguide Baltoscandia (2012) Mineral resources of Estonia. http:// maavarad.egk.ee. Accessed 31 May 2015.

Gilbert, O. L. (1968) Bryophytes as indicators of air pollution in the Tyne Valley. *New Phytologist* **67**: 15–30.

Gilbert, O. L. (1976) An alkaline dust effect on epiphytic lichens. *Lichenologist* **8**: 173–178.

Gleason, H. A. (1926) The individualistic concept of the plant association. *Bulletin of the Torrey Botanical Club* **53**: 7–26.

Grantz, D. A., Garner, J. H. B. & Johnson, D. W. (2003) Ecological effects of particulate matter. *Environment International* **29**: 213–219.

Guerreiro, C., de Leeuw, F., Foltescu, V., Ortiz, A. G. & Horálek, J. (2015) *Air quality in Europe – 2015 report*. Luxembourg: Publications Office of the European Union.

Haapala, H., Goltsova, N., Pitulko, V. & Lodenius, M. (1996a) The effects of simultaneous large acidic and alkaline airborne pollutants on forest soil. *Environmental Pollution* **94**: 159–168.

Haapala, H., Goltsova, N., Seppälä, R., Huttunen, S., Kouki, J., Lamppu, J. & Popovichev, B. (1996b) Ecological condition of forests around the eastern part of the Gulf of Finland. *Environmental Pollution* **91**: 253–265.

Hawksworth, D. L. & Rose, F. (1970) Qualitative scale for estimating sulphur dioxide air pollution in England and Wales using epiphytic lichens. *Nature* **227**: 145–148.

Helm, A., Oja, T., Saar, L., Takkis, K., Talve, T. & Pärtel, M. (2009) Human influence lowers plant genetic diversity in communities with extinction debt. *Journal of Ecology* **97**: 1329–1336.

Hewitt, G. (2000) The genetic legacy of the Quaternary ice ages. *Nature* **405**: 907–913.

Hill, M. O., Bell, N., Gruggeman-Nannenga, M. A., Brugués, M., Cano, M. J., Enroth, J., Flatberg, K. I., Frahm, J.–P., Gallego, M. T., Garilleti, R., Guerra, J., Hedenäs, L., Holyoak, D. T., Hyvönen, J., Ignatov, M. S., Lara, F., Mazimpaka, V., Muñoz, J. & Söderström, L. (2006) An annotated checklist of the mosses of Europe and Macaronesia. *Journal of Bryology* **28**: 198–267.

Holderegger, R. & Di Giulio, M. (2010) The genetic effects of roads: a review of empirical evidence. *Basic and Applied Ecology* **11**: 522–531.

Holloway, J. W., Savarimuthu Francis, S., Fong, K. M. & Yang, I. A. (2012) Genomics and the respiratory effects of air pollution exposure. *Respirology* **17**: 590–600.

Holt, E. A. & Miller, S. W. (2011) Bioindicators: using organisms to measure environmental impacts. *Nature Education Knowledge* **3**: 8.

Ignatov, M. S. & Ignatova, E. A. (2004) *Moss flora of the Middle European Russia. Vol. 2, Fontinalaceae-Amblystegiaceae*. Moscow: KMK Scientific Press Ltd.

Ingerpuu, N. & Vellak, K. (1998) *Keybook of Estonian bryophytes*. Tartu: Eesti Loodusfoto.

Ingerpuu, N., Vellak, K., Liira, J. & Pärtel, M. (2003) Relationships between species richness patterns in deciduous forests at the north Estonian limestone escarpment. *Journal of Vegetation Science* **14:** 773–780.

Jóźwiak, M. A. & Jóźwiak, M. (2009) Influence of cement industry on accumulation of heavy metals in bioindicators. *Ecological Chemistry and Engineering* **16**: 323–334.

Jüriado, I., Liira, J., Csencsics, D., Widmer, I., Adolf, C., Kohv, K. & Scheidegger, C. (2011) Dispersal ecology of the endangered woodland lichen *Lobaria pulmonaria* in managed hemiboreal forest landscape. *Biodiversity and Conservation* **20**: 1803–1819.

Kairiūkštis, L. A. (1966) Forests of the Lithuanian S.S.R. In *Forests of the S.S.S.R., Vol. 2. The subzone of southern taiga and mixed forests.* (A. B. Žhukov, ed): 93–130. Moscow: Nauka.

Kalinowski, S. T. (2004) Counting alleles with rarefaction: private alleles and hierarchical sampling designs. *Conservation Genetics* **5**: 539–543.

Kannukene, L. (1995) Bryophytes in the forest ecosystem influenced by cement dust. In *Dust pollution and forest ecosystems. A study of conifers in an alkalized environment* (M. Mandre, ed): 141–147. Tallinn: Institute of Ecology.

Kask, R, Ots, K., Mandre, M. & Pikk, J. (2008). Scots pine (*Pinus sylvestris* L.) wood properties in an alkaline air pollution environment. *Trees* **22**: 815–823.

Király, I. & Ódor, P. (2010) The effect of stand structure and tree species composition on epiphytic bryophytes in mixed deciduous–coniferous forests of Western Hungary. *Biological Conservation* **143**: 2063–2069.

Klõšeiko, J. (2005) Concentration of carbohydrates in conifer needles near Kunda cement plant, Estonia, nine years after reduced dust pollution. *Forestry Studies* **42**: 87–94.

Kortesharju, M. & Kortesharju, J. (1989) Studies on epiphytic lichens and pine bark in the vicinity of a cement works in northern Finland. *Silva Fennica* **23**: 301–310.

Kumar, R. K., Shadie, A. M., Bucknall, M. P., Rutlidge, H., Garthwaite, L., Herbert, C., Halliburton, B., Parsons, K. S. & Wark, P. A. (2015) Differential injurious effects of ambient and traffic-derived particulate matter on airway epithelial cells. *Respirology* **20**: 73–79.

Kunda Nordic Tsement (2016) *Kunda Nordic Tsement*. http://www.knc.ee/et/node/4922. Accessed 4 July 2016.

Ksenofontova, T. & Zobel, M. (1987) Kurtna mõhnastiku ja järvede soontaimed. In *Kurtna järvestiku looduslik seisund ja selle areng, I.* (L. Saarse, ed.): 91–103. Tallinn: Valgus.

Kupcinskiene, E., Stikliene, A. & Judzentiene, A. (2008) The essential oil qualitative and quantitative composition in the needles of *Pinus sylvestris* L. growing along industrial transects. *Environmental Pollution* **155**: 481–491.

Laasimer, L. (1958) *Eesti NSV geobotaaniline rajoneerimine*. Tartu: Eesti NSV Teaduste Akadeemia.

Laasimer, L. & Masing, V. (1995) Flora and plant cover. In *Estonian Nature*. (A. Raukas, ed): 364–401. Tallinn: Valgus & Eesti Entsüklopeediakirjastus.

Lacy, R. C. (1997) Importance of genetic variation to the viability of mammalian populations. *Journal of Mammalogy* **78**: 320–335.

Lawesson, J. E. (2003) pH optima for Danish forest species compared with Ellenberg reaction values. *Folia Geobotanica* **38**: 403–418.

Leberg, P. L. (2002) Estimating allelic richness: effects of sample size and bottlenecks. *Molecular Ecology* **11**: 2445–2449.

Lepeduš, H., Cesar, V. & Suver, M. (2003) The annual changes of chloroplast pigments content in current- and previous-year needles of Norway spruce (*Picea abies* L. Karst.) exposed to cement dust pollution. *Acta Botanica Croatica* **62**: 27–35.

Liiv, S. & Kaasik, M. (2004) Trace metals in mosses in the Estonian oil shale processing region. *Journal of Atmospheric Chemistry* **49**: 563–578.

Loppi, S. & Pirintsos, S. (2000) Effect of dust on epiphytic lichen vegetation in the Mediterranean area (Italy and Greece). *Israel Journal of Plant Sciences* **48**: 91–95.

Lovett, G. M., Tear, T. H., Evers, D. C., Findlay, S. E. G., Cosby, B. J., Dunscomb, J. K., Driscoll, C. T. & Weathers, K. C. (2009) Effects of Air Pollution on Ecosystems and Biological Diversity in the Eastern United States. *Annals of the New York Academy of Sciences* **1162**: 99–135.

Luikart, G. & Cornuet, J. M. (1998) Empirical evaluation of a test for identifying recently bottlenecked populations from allele frequency data. *Conservation Biology* **12**: 228–237.

Lukjanova, A., Mandre, M. & Saarman, G. (2013) Impact of alkalisation of the soil on the anatomy of Norway spruce (*Picea abies*) needles. *Water, Air, & Soil Pollution* **224**: 1–12.

Lõhmus, E. (2004) *Eesti metsakasvukohatüübid.* Tartu: EPMÜ Metsanduslik Uurimisinstituut.

Lõhmus, A. & Kull, T. (2011) Orchid abundance in hemiboreal forests: stand-scale effects of clear-cutting, green-tree retention, and artificial drainage. *Canadian Journal of Forest Research* **41**: 1352–1358.

Madl, P., Heinzelmann, E., Hofmann, W. & Türk, R. (2010) Motorway exhaust aerosols and their effects on epiphytic lichen populations. *Gefahrstoffe Reinhaltung der Luft* **70**: 147–153.

Maletsika, P. A., Nanos, G. D. & Stavroulakis, G. G. (2015) Peach leaf responses to soil and cement dust pollution. *Environmental Science and Pollution Research* **22**: 15952–15960.

Mandre, M. (1995) *Dust Pollution and Forest Ecosystems: a study of conifers in an alkalized environment.* Tallinn: Institute of Ecology.

Mandre, M. (2000) Metsaökosüsteemi hälvetest Virumaa tööstuslikust õhusaastest mõjutatud aladel. *Metsanduslikud Uurimused* **33**: 17–36.

Mandre, M., Bogdanov, V. & Rahi, M. (2002) Impact of alkaline air pollution and alkalisation of the environment on the structure and quantity of epicuticular waxes on needles of *Picea abies*. *Forestry Studies* **36**: 107–119.

Mandre, M. & Klõšeiko, J. (2000) Õhusaaste mõju süsivesikute sisaldusele hariliku kuuse okastes. *Metsanduslikud Uurimused* **33**: 129–136.

Mandre, M. & Korsjukov, R. (2007) The quality of stemwood of *Pinus sylvestris* in an alkalised environment. *Water, Air, & Soil Pollution* **182**: 163–172.

Mandre, M., Ots, K., Rauk, J. & Tuulmets, L. (1998) Impact of air pollution emitted from the cement industry on forest bioproduction. *Oil Shale* **15**: 365–373.

Marmor, L. & Randlane, T. (2007) Effects of road traffic on bark pH and epiphytic lichens in Tallinn. *Folia Cryptogamica Estonica* **43**: 23–37.

Marmor, L., Tõrra, T. & Randlane, T. (2010) The vertical gradient of bark pH and epiphytic macrolichen biota in relation to alkaline air pollution. *Ecological Indicators* **10**: 1137–1143.

Martin, L. & Nilson, E. (1992) Impact of the Kunda cement plant (North-East Estonia) emission on the distribution of the epiphytic lichens. *Proceedings of the Estonian Academy of Sciences* **2**: 129–136.

McCune, B. & Mefford, M. J. (1999) *PC-ORD. Multivariate analysis of Ecological Data, Version 4.0 for Windows.* Oregon, Gleneden Beach: MjM Software Design.

Meininger, C. A. & Spatt, P. D. (1988) Variations of tardigrade assemblages in dust-impacted arctic mosses. *Arctic and Alpine Research* **20**: 24–30.

Ministry of the Environment (2011) *Ministry of the Environment of the Republic of Estonia. National development plan for the use of mineral resources 2011–2020.* http://www.envir.ee/et/ehitusmaavarade-kasutamise-riiklik-arengukava-2011-2020. Accessed 01 October 2015.

Nanos, G. D. & Ilias, I. F. (2007) Effects of inert dust on olive (*Olea europaea* L.) leaf physiological parameters. *Environmental Science and Pollution Research-International* **14**: 212–214.

Nash, T. H. III (2008) Lichen sensitivity to air pollution. In *Lichen biology* (T.H. III Nash TH, ed): 299–314. Cambridge: Cambridge University Press.

Nimis, P., Scheidegger, C. & Wolseley, P. (2002) *Monitoring with lichens – monitoring lichens*. Dordrecht: Kluwer Academic Publishers.

Odum, E. P. (1985) Trends expected in stressed ecosystems. *Bioscience* **35**: 419–422.

Ohmura, Y., Masanobu, K., Kasai, F., Watanabe, M. M. & Takeshita, S. (2006) Genetic combinations of symbionts in a vegetatively reproducing lichen, *Parmotrema tinctorum*, based on ITS rDNA sequences. *Bryologist* **109**: 43–59.

Orange, A., James, P. W. & White, F. J. (2001) *Microchemical methods for the identification of lichens*. London: British Lichen Society.

Otalora, M. G., Martinez, I., Belinchon, R., Widmer, I., Aragon, G. & Escudero, A. (2011) Remnants fragments preserve genetic diversity of the old forest lichen *Lobaria pulmonaria* in a fragmented Mediterranean mountain forest. *Biodiversity and Conservation* **20**: 1239–1254.

Ots, K., Mandre, M., Pärn, H., Kask, R. & Pikk, J. (2009) Changes in the allocation of nutrients and biomass in Scots pine (*Pinus Sylvestris* L.) canopy in an area of cement industry in Northeast Estonia. *Baltic Forestry* **15**: 237–247.

Ots, K. & Rauk, J. (2000) Harilik kuusk (*Picea abies* (L.) Karst.) ja tööstusheitmete mõju selle kasvule. *Dendroloogilised Uurimused Eestis* **2**: 124–135.

Ots, K. & Rauk, J. (2001) Defoliation of Scots pine and Norway spruce under alkaline dust impact and its relationship with radial increment. *Oil Shale* **18**: 223–237.

Paal, J. (1999) *Classification of Estonian vegetation site types*. http://www.botany.ut.ee/jaanus.paal/Jaanuse_Artiklite_koopiad/kasvukohatyypide.klassifikatsioon.Paal.pdf. Accessed 12 July 2016.

Paal, J. (2001) The North-Estonian klint: soil and vegetation diversity. *Publicationes Instituti Geographici Universitatis Tartuensis* **92:** 761–764.

Paal, J. & Degtjarenko, P. (2015) Impact of alkaline cement-dust pollution on boreal *Pinus sylvestris* forest communities: a study at the bryophyte synusiae level. *Annales Botanici Fennici* **52**: 120–134.

Paal, J., Vellak, K., Liira, J. & Karofeld, E. (2010) Bog recovery in northeastern Estonia after the reduction of atmospheric pollutant input. *Restoration Ecology* **18**: 387–400.

Pakarinen, P. & Hasanen, E. (1983) Mercury concentrations of bog mosses and lichens. *Suo* **34**: 17–20.

Paoli, L., Guttová, A., Grassi, A., Lackovičová, A., Senko, D. & Loppi, S. (2014) Biological effects of airborne pollutants released during cement production assessed with lichens (SW Slovakia). *Ecological Indicators* **40**: 127–135.

Peakall, R. & Smouse, P. E. (2012) GenAlEx 6.5: genetic analysis in Excel. Population genetic software for teaching and research – an update. *Bioinformatics* **28**: 2537–2539.

Peery, M. Z., Kirby, R., Reid, B. N., Stoelting, R., Doucet-Bëer, E., Robinson, S., Vásquez-Carrillo, C., Pauli, J. N. & Palsbøll, P. J. (2012) Reliability of genetic bottleneck tests for detecting recent population declines. *Molecular Ecology* **21**: 3403–3418.

Piry, S., Luikart, G. & Cornuet, J. M. (1999) BOTTLENECK: a computer program for detecting recent reductions in the effective population size using allele frequency data. *Journal of Heredity* **90**: 502–503.

Pärtel, M. (2002) Local plant diversity patterns and evolutionary history at the regional scale. *Ecology* **83**: 2361–2366.

R Core Team (2013) *R: a language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing.

Rai, P. K. (2016) Impacts of particulate matter pollution on plants: Implications for environmental biomonitoring. *Ecotoxicology and Environmental Safety* **129**: 120–136.

Randlane, T., Saag, A. & Suija, A. (2013) *Lichenized, lichenicolous and allied fungi of Estonia*. http://esamba.bo.bg.ut.ee/checklist/est/home.php. Accessed 31 May 2015.

Reinsalu, E. (2008) *Mining*. Tallinn: Tallinna Tehnikaülikool.

Reintam, L., Rooma, I. & Kull, A. (2001) Map of soil vulnerability and degradation in Estonia. In *Sustaining the global farm. Selected papers from the 10th International Soil Conservation Organization Meeting (24–29 May), Purdue University, the USDA–ARS National Soil Erosion Research Laboratory, West Lafayette*, p. 1068–1074.

Rizvi, R. & Khan, A. (2009) Response of Eggplant (*Solanum melongena* L.) to fly ash and brick kiln dust amended soil. *Biology and Medicine* **1**: 20–24.

Rola, K. & Osyczka, P. (2014) Cryptogamic community structure as a bioindicator of soil condition along a pollution gradient. *Environmental Monitoring and Assessment* **186**: 5897–5910.

Saha, D. C. & Padhy, P. K. (2011) Effects of stone crushing industry on *Shorea robusta* and *Madhuca indica* foliage in Lalpahari forest. *Atmospheric Pollution Research* **2**: 463–476.

Siqueira-Silva, A. I., Pereira, E. G., Modolo, L. V., Lemos-Filho, J. P. & Paiva, E. A. S. (2016) Impact of cement dust pollution on *Cedrela fissilis* Vell. (Meliaceae): A potential bioindicator species. *Chemosphere* **158**: 56–65.

Schmidt, J., Kricke, R. & Feige, G. B. (2001) Measurements of bark pH with a modified flathead electrode. *Lichenologist* **33**: 456–460.

Smith, W. H. (1990) *Air pollution and forests. Interactions between air contaminants and forest ecosystems*. New York: Springer.

Smith, C. W., Aptroot, A., Coppins, B. J., Fletcher, A., Gilbert, O. L., James, P. W. & Wolseley, P. A. (2009) The lichens of Great Britain and Ireland. London: British Lichen Society.

Spagnuolo, V., Muscariello, L., Terracciano, S. & Giordano, S. (2007) Molecular biodiversity in the moss *Leptodon smithii* (Neckeraceae), in relation to habitat disturbance and fragmentation. *Journal of Plant Research* **120**: 595–604.

Spagnuolo, V., Terracciano, S. & Giordano, S. (2009) Trace element content and molecular biodiversity in the epiphytic moss *Leptodon smithii*: two independent tracers of human disturbance. *Chemosphere* **74**: 1158–1164.

StatSoft Inc (2004) *STATISTICA (Data Analysis Software System), Version 7.* http://www.statsoft.com.

Stravinskienė, V. (2011) Pollution of “Akmenės cementas” vicinity: alkalizing microelements in soil, composition of vegetation species and projection coverage. *Journal of environmental engineering and landscape management* **19**: 130–139.

Stravinskienė, V., Sujetovienė, G. & Erlickytė, R. (2004) Miðko augalijos rûðiø ávairovë ir dirvoþemio mikroelementinë sudëtis AB „Akmenës cementas“ aplinkoje. *Ekologija* **1**: 46–53.

Sujetovienė, G. (2008) Undergrowth as a biomonitor for deposition of nitrogen, acidity and dust in pine forest. *Journal of Young Scientists* **19**: 129–135.

Sujetovienė, G (2015) Monitoring lichen as indicators of atmospheric quality. In *Recent advances in lichenology, modern methods and approaches in biomonitoring and bioprospection, vol 1.* (D. K. Upreti, P. K. Divakar & V. Shukla, eds): 87–118. New Delhi: Springer.

Tilman, D. (1988) *Plant strategies and the dynamics and structure of plant communities*. Princeton: Princeton University Press.

Tutin, T. G., Heywood, V. H., Burges, N. A., Moore, D. M., Valentine, D. H., Walters, S. M. & Webb, D. A. 1964–1980. *Flora Europaea. Vols. 1–5.* Cambridge: Cambridge University Press.

Tõrra, T., Cornejo, C., Cheenacharoen, S., Dal Grande, F., Marmor, L. & Scheidegger, C. (2014) Characterization of fungus-specific microsatellite markers in the lichen fungus *Usnea subfloridana* (Parmeliaceae). *Applications in Plant Sciences* **2**: apps.1400034. http://dx.doi.org/10.3732/apps.1400034.

van Haluwyn, C. & van Herk, C. M. (2002) Bioindication: the community approach. In *Monitoring with lichens—monitoring lichens* (P. L. Nimis, C. Scheidegger & P. Wolseley, eds): 39–64. Dordrecht: Kluwer.

van Straalen, N. M. & Timmermans, M. J. T. N. (2002) Genetic variation in toxicant-stressed populations: an evaluation of the “genetic erosion” hypothesis. *Human and Ecological Risk Assessment* **8**: 983–1002.

Vellak, K., Ingerpuu, N., Leis, M. & Ehrlich, L. (2015) Annotated checklist of Estonian bryophytes. *Folia Cryptogamica Estonica* **52**: 109–127.

Vellak, K., Liira, J., Karofeld, E., Galanina, O., Noskova, M. & Paal, J. (2014) Drastic turnover of bryophyte vegetation on bog microforms initiated by air pollution in Northeastern Estonia and Bordering Russia. *Wetlands* **34**: 1097–1108.

Vitousek, P. M., Aber, J. D., Howarth, R. W., Likens, G. E., Matson, P. A., Schindler, D. W., Schlesinger, W. H. & Tilman, D. G. (1997) Human alteration of the global nitrogen cycle: sources and consequences. *Ecological applications* **7**: 737–750.

Werth, S., Wagner, H. H., Holderegger, R., Kalwij, J. M. & Scheidegger, C. (2006) Effect of disturbances on the genetic diversity of an old-growth forest associated lichen. *Molecular Ecology* **15**: 911–921.

World Health Organization (2013) *Health effects of particulate matter. Policy implications for countries in Eastern Europe. Caucasus and central Asia.* Copenhagen: World Health Organization Regional Office for Europe.

Yorifuji, T., Kashima, S. & Doi, H. 2016. Acute exposure to fine and coarse particulate matter and infant mortality in Tokyo, Japan (2002–2013). *Science of The Total Environment* **551**: 66–72.

Zaharopoulou, A., Lanaras, T. & Arianoutsou, M. (1993) Influence of dust from a limestone quarry on chlorophyll degradation of the lichen *Physcia adscendens* (Fr.) Oliv. *Bulletin of environmental contamination and toxicology* **50**: 852–855.

Zobel, M. (1997) The relative role of species pools in determining plant species richness – an alternative explanation for species coexistence? *Trends in Ecology and Evolution* **12**: 266–269.

Zvereva, E. L. & Kozlov, M. V. (2011) Impacts of industrial polluters on bryophytes: a meta-analysis of observational studies. *Water, Air, & Soil Pollution* **218**: 573–586.

Zvereva, E. L., Toivonen, E. & Kozlov, M. V. (2008) Changes in species richness of vascular plants under the impact of air pollution: a global perspective. *Global Ecology and Biogeography* **17**: 305–319.

SUMMARY IN ESTONIAN

Aluselise tolmusaaste mõju taimede ja samblike mitmekesisusele: kooslustest geneetilise mitmekesisuseni

Keskkonnareostus (sh õhusaaste) ohustab märkimisväärselt üldist looduslikku mitmekesisust, avaldades mõju erinevatel bioloogilistel tasemetel – alates rakulisest ja koelisest tasemest kuni ökosüsteemide tasemeni. Näiteks õhusaastest tingitud keskkonnatingimuste muutused muudavad ka koosluste liigilist koosseisu, struktuuri ja funktsiooni, põhjustades tundlike liikide kadu või, vastupidi, saastet taluvate liikide sissetungi. On täheldatud, et keskkonnareostus võib mõjutada ka organismide geneetilist mitmekesisust erinevates liigirühmades. Selleks, et leevendada õhusaastest tekitatud kahju bioloogilisele mitmekesisusele, on vajalik hinnata ja jälgida õhusaaste mõjusid, välja selgitada selle mõju ulatus ja otsida uusi võimalikke bioindikaatoreid täiendamaks õhuseirejaamade andmeid.

Paljude õhusaasteainete (nt SO_2, CO, C_6H_6) emissioon on Euroopas oluliselt vähenenud, kuid tahkete osakeste (*particulate matter*, PM) või tolmu emissioon on endiselt terav probleem, kuna paljudes EL riikides ületatakse jätkuvalt EL-s lubatud PM saasteainete piirkontsentratsioone. Atmosfääriõhku saastavad tahked osakesed või tolmusaaste on kompleksne segu väikestest õhus heljuvatest osakestest, mis on erineva suurusega (ca. 0,1−10 μm), päritoluga (looduslik vs tööstuslik) ja keemilise koostisega. Käesolev töö on keskendunud jämedatele tolmuosakestele, mis vabanevad keskkonda lubjakivi kaevandamise käigus, tsemenditööstusest ja kruusateedelt. Tekkiv tolm sisaldab suures koguses $CaCO_3$, MgO ja K_2O ning saasteainete vesilahus on tugevalt aluseline. Aluseline tolmusaaste on Eestis alati olnud oluline keskkonnaprobleem, kuna paljude aastate vältel moodustasid Eesti tööstusettevõtete poolt õhku paisatud saastest suure osa just tahked aluselised heitmed, mille mõjul tekkinud märkimisväärseid keskkonnamuutuseid Põhja-Eesti piirkonnas täheldati juba möödunud sajandi teisel poolel. Aluseline tolmusaaste võib liike otseselt mõjutada, põhjustades muutusi füsioloogilistes ja biokeemilistes protsessides, kuid võib mõju avaldada ka kasvukeskkonna (muld, puukoor, sademed) kaudu. Lisaks võib tolmusaaste kahjustada inimeste tervist, põhjustades hingamisteede ja südame-veresoonkonna haigusi ning suurendades suremuse riski.

Käesoleva töö peamine eesmärk oli uurida eri päritoluga pikaajalise aluselise tolmusaaste toimet boreaalsetele metsakooslustele (**I**), epifüütsetele sambliku-, sambla- ja vetikakooslustele mändidel (**II**, **III**) ning samblikku moodustava seeneliigi populatsioonide geneetilisele mitmekesisusele (**IV**). Töö detailsemateks eesmärkideks oli (1) välja selgitada tsemenditolmu pikaajaline mõju mustika (*Vaccinium myrtillus*) kasvukohatüübi metsakooslustele Kunda tsemenditehasest väljalastava õhusaaste mõjualas; (2) otsida uusi potentsiaalseid tolmusaaste indikaatoreid (**I**, **II**, **III**) ning hinnata rohevetika *Trentepohlia* *umbrina* kasutamisvõimalusi tolmusaaste indikaatorina (**II**); (3) uurida, kuidas lubjakivikarjääride töötlemisprotsessis tekkiv tolmusaaste muudab epifüütsete sammalde ja samblike liigilist koosseisu ja liigirikkust mändidel (**III**); (4) selgitada välja, kas ja kuidas muutub ühe tavalise, laialt levinud samblikku moodustava seeneliigi, vars-habesambliku (*Usnea subfloridana*) populatsioonide geneetiline varieerivus pikaajalise kruusateedelt lähtuva tolmusaaste mõjul.

Kunda tsemenditehase ümbruses uuriti 20 ringkujulist prooviala suurusega 0,1 ha, kus iseloomustati puurinnet, puistu liituvust, puurinde järelkasvu, põõsarinnet ja alustaimestikku (sh maapinnal kasvavaid samblaid); lisaks koguti kolmest juhuslikust punktist mulla kõduhorisondi proove ning määrati nende pH, tuhasus, N-, P-, Ca-, K- ja Mg-sisaldus (**I**). Lubjakivikarjääride mõjupiirkonnas mõõdeti 32-l proovialal samblike, sammalde ja rohevetika *Trentepohlia umbrina* katvus mändidel kasutades mõõdulindi meetodit, samas registreeriti kõikide männil kasvavate sammalde ja samblike esinemine 0,5 kuni kahe meetri kõrgusel ning koguti männikoort pH määramiseks (**II**, **III**). Vars-habesambliku populatsioonide geneetilise mitmekesisuse uurimuseks valiti kaheksa kuusel kasvavat populatsiooni, millest neli populatsiooni asusid kruusateede vahetus naabruses ning neli – saastamata/häirimata piirkonnas (**IV**). Ka selles uuringus näidati tolmusaaste olemasolu sambliku kasvupinna, kuuse puukoore pH määramise kaudu. Vars-habesamblikku moodustava seene populatsioonide geneetilise varieeruvuse molekulaarseks uurimiseks kasutati üheksat seene-spetsiifilist polümorfset mikrosatelliitmarkerit (**IV**).

Käesolevas töös registreeriti kokku 86 liiki taimi (sh 25 maapinnal kasvavat sammalt) Kunda tsemenditehase mõjualas asuvates mustika kasvukohatüübi metsakooslustes (**I**) ning 34 epifüütset samblaliiki ja 84 samblikku lubjakivikarjääride ümbruskonnas kasvavatel mändidel (**III**).

Töö tulemused kinnitavad, et pikaajaline tolmusaaste on avaldanud neutraliseerivat mõju mulla keemilistele omadustele ning männi ja kuuse koorele; mulla ja puukoore pH on oluliselt tõusnud tolmusaaste mõju piirkondades ja väheneb tolmusaaste allikate kaugenedes (**I**–**IV**). Sarnaselt võib täheldada mulla kõduhorisondi Ca, Mg ja K sisalduse langustendentsi piki tolmu reostusgradienti (**I**). Saadud tulemuste põhjal võib järeldada, et Kunda tsemenditehase ümbruskonnas mulla seisund taastub pärast üle sajandi kestnud aluselist tolmusaastet, kuid osade keemiliste elementide sisaldus mullas ja mulla pH on looduslikust foonist jätkuvalt mitmeid kordi kõrgem (**I**).

Pikaajaline aluseline tolmusaaste on hävitanud looduslikke kooslusi ning põhjustanud uudsete koosluste tekkimist tolmureostuse mõjupiirkondades. Saastatud ala mullastiku omaduste muutused on avaldanud olulist mõju taimestikule Kunda tsemenditehase ümbruses, põhjustades happelembeste/happettaluvate liikide järk-järgulist asendumist neutrofiilsete ja seejärel kaltsifiilsete liikidega (**I**). Sellega koos on toimunud koosluste mitmekesistumine ehk soontaimede, epigeiidsete ja epifüütsete sammalde liigirikkuse tõus tolmusaaste mõjualadel (**I**, **III**). Aluselise tolmusaaste mõjul täheldasime ka epifüütsete koosluste nihkeid mändidel (**III**). Männi puukoore vähenenud happelisus soodustas mändidel tavaliselt mittekasvavate, kõrgemat pH taset eelistavate liikide esinemist

(**III**). Epifüütsete sammalde ja *Trentepohlia umbrina* katvus mändidel oli kõrgem ning vähenes tolmusaaste allikate kaugenedes, samas kui samblike üldkatvus muutus teisiti – suurenes tolmusaaste allikate kaugenedes (**II**, **III**).

Käesoleva töö tulemused kinnitasid mõnede eelnevalt teadaolevate bioindikaatorite kasutatavust. Samas pakkusime välja mitmed uued tolmusaaste indikaatorliigid: näiteks samblikud *Alyxoria varia* (härma-kiiriksamblik) ja *Lecidella elaeochroma* (piir-kärnsamblik), rohevetikas *Trentepohlia umbrina*, samblad *Orthotrichum pallens* (kahkjas tutik)*, Orthotrichum speciosum* (tüvetutik) ja *Schistidium apocarpum* (harilik lõhistanukas) mändidel või *Neottia ovata* (suur käopõll) mustika kasvukohatüübi metsakooslustes (**I**–**III**). Väidame, et liigilise koosseisu, liigirikkuse ja katvuse muutused mõnedes organismirühmades võivad olla abiks tolmusaaste inditseerimisel.

Töös registreeriti esimest korda aluselise tolmusaaste negatiivne mõju samblikku moodustava seeneliigi, vars-habesambliku (*Usnea subfloridana*) populatsioonide geneetilisele mitmekesisusele (**IV**). Kruusateede vahetus läheduses kasvavate vars-habesambliku populatsioonides ilmneb pudelikaela efekt, mille tulemusel on vähenenud alleelide mitmekesisus, kuid mitte veel teised uuritud geneetilise varieeruvuse näitajad (**IV**). Populatsioonide geneetilise varieeruvuse kadu osutab vastupidavuse vähenemisele tolmusaastest põhjustatud keskkonnahäiringute suhtes (**IV**).

Veel ilmnes, et aluseline tolmusaaste mõjub looduslikele kooslustele “parapositiivselt” aidates looduslike koosluste häirimise kõrval kaasa haruldaste ja kaitstavate liikide levikule (**I**, **III**). Sellised häiritud kooslustega saastatud piirkonnad on kui kõrge teadusliku väärtusega pikaajalised ökoloogilised katsealad, samas on tegemist ajutise nähtusega, mis sõltub suurel määral saastuse kestvusest ning see ei ole haruldaste liikide leviku soodustamise soovitatav praktika.

ACKNOWLEDGEMENTS

Well, so many years I dreamed of writing the “acknowledgments” for my PhD thesis, and now, at IAL 8 (International Association for Lichenology) symposium, is best time to express my endless gratitude to such amazing and exceptional people that were around me during my academic years.

First, I would like to thank Jaanus Paal for inspiring, supervising, and scrupulous proof-reading of my language during my bachelor and master studies, and also for valuable remarks on my PhD thesis. My deepest gratitude goes to my PhD supervisor Tiina Randlane for continuous support, constructive guidance, huge patience, perfectionism and all kind of opportunities. I particularly thank Tiina for kindling my interest in lichens. I also highly appreciate her valuable comments, opinions and suggestions that contribute to the improvement of the manuscripts and thesis. I am grateful to my second PhD supervisor Liis Marmor for useful and friendly advices, helpful remarks on manuscripts and thesis, and support at the field works. I am indebted to all my colleagues from lichenological team from University of Tartu who supported and helped me anytime during my studies. I am thankful to Ede Oja for enormous help in identifying lichens, endless support at various questions, practical advices and being always behind me. I would like to thank Ave Suja, Piret Lõhmus, Inga Jüriado, Tiiu Tõrra, and Lauri Saag for giving me words of encouragement and also for sharing inspiration by their interesting works. Lauri and Tiiu are also thanked for introducing me to the universe of lichenological lab in Tartu. I am grateful to Andres Saag for any kind of technical support that I needed during these years. Thank you, Kristiina Mark, for sharing memorable moments and for cheerful and productive discussions at work, at fieldwork, at lunch and coffee time and, particularly, in Switzerland. I wish to say thank to all my colleagues, co-PhD students and secretaries from Department of Botany (UT) – especially to Elle Roosaluste for always encouraging attitude, to Jaan Liira for responding anytime to my occasional questions about statistics, to Nele Ingerpuu, Kai Vellak and Mari Müür for confirming the identification of bryophytes and advising in any questions concerning bryophytes, to Mare Toom for the help in the identification of some vascular plants, to Erich Kukk for confirming the identification of some *Trentepohlia* species, to Ants Kaasik for the help in statistical analyses, and to Katja Aida for “professnl” support. Also, I would like to thank Christoph Scheidegger for wonderful opportunity to work at Biodiversity and Conservation Biology lab at WSL (Switzerland) and for extremely helpful comments on my manuscript. I very much appreciate his endless enthusiasm and amazing ability to create ideas. I am especially grateful to others colleagues from WSL – Olga Nadyeina, Michèle Lerch, Carolina Cornejo, Saran Cheenacharoen, and Maria Tabakova – thank to all for helping, advising and supporting me during my tremendous stay in Birmensdorf. I also thank the Genetic Diversity Centre (ETH Zürich) for technical assistance. I am sincerely appreciative of all my colleagues from other universities and

institutions for sharing their experiences, excellent ideas and opinions: particularly, Malle Mandre (Estonian University of Life Sciences), Julia Gerasimova (Komarov Botanical Institute), Ljudmilla & Jüri Martin (Euroacademy), and Maja Maslać (Oikon Ltd. Institute Of Applied Ecology) with marvelous “Ekenäs Mafia”. I am thankful to all my students from different courses and lectures, but, especially, I am grateful to my ex-master student Tiina Mandel for unforgettable memories during our cooperation and of course for her extreme optimism and incredible support. I am also thankful to Kirill & Alina Ogorodnikovy for providing the accommodation during my fieldworks. In a word, thank you all so much for believing in me during this awesome journey.

Last, but not least, I sincerely thank my beloved family and relatives for their exceptionally wise advices and continuous encouragement during my studies. Huge thanks and giant hug to all my precious and important friends and adored Sisterhood for constant and inexhaustible support. Мои самые любимые и родные, бесконечно благодарю и люблю вас!

* * *

Financial support was provided by the Estonian Science Foundation (grants 8060, 9109, and 7878), the Estonian Research Council (grants ETF9109, PUT1017 and project IUT34-7), the Estonian Ministry of Education and Research (project SF0180012s09), the European Union through the European Regional Development Fund (Centre of Excellence FIBIR), the fellowship (Sciex project 10.005), the grants from the Federal Office for the Environment (FOEN), the European Social Fund’s Doctoral Studies and Internationalisation Programme DoRa, which is carried out by Foundation Archimedes, and national scholarship program Kristjan Jaak, which is funded and managed by Archimedes Foundation in collaboration with the Ministry of Education and Research.

PUBLICATIONS

CURRICULUM VITAE

Name:	Polina Degtjarenko
Date of Birth:	June 22, 1986
Citizenship:	Estonian
Address:	Institute of Ecology and Earth Sciences, University of Tartu, Lai 38, Tartu 51005, Estonia
Phone:	+372 53 420 729
E-mail:	polina.degtjarenko@ut.ee polina.degtjarenko@gmail.com

Current position:	University of Tartu, Institute of Ecology and Earth Sciences, Department of Botany, Junior Research Fellow University of Tartu, Institute of Ecology and Earth Sciences, Department of Botany, PhD student

Education:

2012−	University of Tartu, PhD candidate in Botany and Ecology
2008−2010	University of Tartu, MSc in Environmental Technology
2005−2008	University of Tartu, BSc in Ecology and Biodiversity Conservation
1993−2005	Ahtme Gymnasium

Language skills:	Estonian, English, Russian

Professional employment:

2015−	University of Tartu, Institute of Ecology and Earth Sciences, Department of Botany, Junior Research Fellow
2014	Estonian Fund for Nature, Translator
2011−2012	Estonian Agricultural Board, Main Specialist of Land Reclamation

Research interests:

boreal forest ecosystems in response to long-term dust pollution, bioindication, epiphytic cryptogamic communities, population genetics of lichenized fungi

Publications:

Degtjarenko, P., Marmor, L., Tõrra, T., Lerch, M., Saag, A., Randlane, T. & Scheidegger, C. (2016) Impact of alkaline dust pollution on genetic variation of *Usnea subfloridana* populations. *Fungal Biology* **120**: 1165–1174.

Degtjarenko, P., Marmor, L. & Randlane, T. (2016) Changes in bryophyte and lichen communities on Scots pines along an alkaline dust pollution gradient. *Environmental Science and Pollution Research* **23**: 17413–17425.

Paal, J. & **Degtjarenko, P.** (2015) Impact of alkaline cement-dust pollution on boreal *Pinus sylvestris* forest communities: a study at the bryophyte synusiae level. *Annales Botanici Fennici* **52**: 120–134.

Marmor, L. & **Degtjarenko, P.** (2014) *Trentepohlia umbrina* on Scots pine as a bioindicator of alkaline dust pollution. *Ecological Indicators* **45**: 717–720.

Paal, J., **Degtjarenko, P.**, Suija, A. & Liira, J. (2013) Vegetation responses to long-term alkaline cement dust pollution in *Pinus sylvestris*-dominated boreal forests – niche breadth along the soil pH gradient. *Applied Vegetation Science* **16**: 248–259.

Conference presentations:

Degtjarenko, P., Marmor, L., Tõrra, T., Lerch, M., Saag, A., Randlane, T. & Scheidegger, C. “The genetic diversity of a widespread epiphytic lichen *Usnea subfloridana* (Parmeliaceae, Ascomycota) in response to alkaline dust pollution”. Oral presentation in the 8th International Association for Lichenology Symposium 2016, 1−5 August, Helsinki, Finland.

Degtjarenko, P., Mandel, T., Tõrra, T., Marmor, L., Saag., A. & Randlane, T. “The habitat traits drive genetic diversity of a widespread epyphytic lichen *Usnea subfloridana* in hemiboreal forests”. Poster presentation in the 8th International Association for Lichenology Symposium 2016, 1−5 August, Helsinki, Finland.

Degtjarenko, P., Marmor, L. & Randlane, T. “Changes in lichen and bryophyte communities on Scots pines along an alkaline dust pollution gradient”. Poster presentation in the 8th International Association for Lichenology Symposium 2016, 1−5 August, Helsinki, Finland.

Degtjarenko, P., Marmor, L., Tõrra, T., Lerch, M., Saag, A., Randlane, T., & Scheidegger, C. “Assessing the impact of alkaline dust pollution on the genetic variation of lichen *Usnea subfloridana* (lichenized Ascomycota, Parmeliaceae)”. Oral presentation in the XX Cryptogamic Botany Symposium 2015, 22−25 July, Porto, Portugal.

Degtjarenko, P. & Marmor, L. “*Trentepohlia umbrina* on Scots pine as a bioindicator of alkaline dust pollution”. Poster presentation in the XX Cryptogamic Botany Symposium 2015, 22−25 July, Porto, Portugal.

Degtjarenko, P., Marmor, L. & Randlane, T. “Searching for ecological indicators of alkaline dust pollution”. Oral presentation in the doctoral student conference of Botany Department of UT, 13−14 November, Jäneda, Estonia.

Degtjarenko, P., Marmor, L., Tõrra, T., Randlane, T. & Scheidegger, C. “Genetic diversity of *Usnea subfloridana* (lichenized Ascomycota) populations in conditions of moderate dust pollution”. Oral presentation in the XIX Symposium of the Baltic Mycologists and Lichenologists 2014, 22−26 September, Šķēde, Latvia.

Awards and scholarships:

2015, 2016	Kristjan Jaak Scholarships, Archimedes Foundation
2015	Travel grant from the Doctoral School of Ecology and Earth Sciences
2014	DoRa Activity 6 and 8 scholarships, Archimedes Foundation

Teaching experience at universities:

2015/2016	University of Tartu, LOOM.01.038 Field Course of Taxonomy of Fungi
	University of Tartu, LOOM.01.107 Practical Mycology and Lichenology
	Euroacademy (Tallinn), EM1070 Forest Monitoring
	Euroacademy (Tallinn), GPRU6091 Fundamentals of Research
2014/2015	University of Tartu, LOOM.01.038 Field Course of Taxonomy of Fungi
	University of Tartu, LOOM.01.107 Practical Mycology and Lichenology
2013/2014	University of Tartu, LOOM.01.038 Field Course of Taxonomy of Fungi
	University of Tartu, LOOM.01.107 Practical Mycology and Lichenology
	Euroacademy (Tallinn), EM1070 Forest Monitoring
	Euroacademy (Tallinn), ER1050 General Biology
2012/2013	University of Tartu, LOOM.01.038 Field Course of Taxonomy of Fungi
	University of Tartu, LOOM.01.107 Practical Mycology and Lichenology

Dissertations supervised:

2016	Tiina Mandel, Genetic variability of *Usnea subfloridana* populations in Estonia, MSc thesis (co-supervised with Tiina Randlane)
2014	Kristina Metsanurk, The effect of dust pollution on lichen diversity, BSc thesis

Participation in international courses:

2015	PhD course "Lichen ecology and identification", Swedish University of Agricultural Sciences, Sweden
2014	PhD course "Lichen ecology and biology", Swedish University of Agricultural Sciences, Sweden

Other activities:

- Research stay at Biodiversity and Conservation Biology unit led by Prof. Christoph Scheidegger (Swiss Federal Institute for Forest, Snow and Landscape Research WSL), January–February 2014, Switzerland.

- Lichen inventory in Karula National Park, summer-autumn 2014.
- Reviewer of National Contest of Young Scientists, organized by Estonian Research Council, 2014−2016.
- Different activities in popularization of science and lichenology, 2012−2016.

ELULOOKIRJELDUS

Nimi:	Polina Degtjarenko
Sünniaeg:	22. juuni, 1986
Kodakondsus:	Eesti
Aadress:	Tartu Ülikool, ökoloogia ja maateaduste instituut, botaanika osakond, Lai 38, Tartu 51005, Eesti
Telefon:	+372 53 420 729
E-post:	polina.degtjarenko@ut.ee polina.degtjarenko@gmail.com
Praegune töökoht:	Tartu Ülikool, ökoloogia ja maateaduste instituut, botaanika osakond, nooremteadur Tartu Ülikool, ökoloogia ja maateaduste instituut, botaanika osakond, doktorant

Haridus:

2012−	Tartu Ülikool, doktoriõpe botaanika ja ökoloogia erialal
2008−2010	Tartu Ülikool, magistrikraad keskkonnatehnoloogias
2005−2008	Tartu Ülikool, bakalaureusekraad ökoloogias ning elustiku kaitses
1993−2005	Ahtme Gümnaasium

Keelteoskus: eesti, inglise, vene (emakeel)

Töökogemus:

2015−	Tartu Ülikool, nooremteadur
2014	Eestimaa Looduse Fond, tõlkija
2011−2012	Põllumajandusamet, maaparanduse valdkonna peaspetsialist

Peamised uurimisvaldkonnad:

boreaalsed metsakooslused tolmusaaste mõju piirkondades, epifüütsete krüptogaamide kooslused, bioindikatsioon, samblikke moodustavate seente populatsioonigeneetika

Teaduspublikatsioonide loetelu:

Degtjarenko, P., Marmor, L., Tõrra, T., Lerch, M., Saag, A., Randlane, T. ja Scheidegger, C. (2016) Impact of alkaline dust pollution on genetic variation of *Usnea subfloridana* populations. *Fungal Biology* **120**: 1165–1174.

Degtjarenko, P., Marmor, L. ja Randlane, T. (2016) Changes in bryophyte and lichen communities on Scots pines along an alkaline dust pollution gradient. *Environmental Science and Pollution Research* **23**: 17413–17425.

Paal, J. ja **Degtjarenko, P.** (2015) Impact of alkaline cement-dust pollution on boreal *Pinus sylvestris* forest communities: a study at the bryophyte synusiae level. *Annales Botanici Fennici* **52**: 120–134.

Marmor, L. ja **Degtjarenko, P.** (2014) *Trentepohlia umbrina* on Scots pine as a bioindicator of alkaline dust pollution. *Ecological Indicators* **45**: 717–720.

Paal, J., **Degtjarenko, P.**, Suija, A. ja Liira, J. (2013) Vegetation responses to long-term alkaline cement dust pollution in *Pinus sylvestris*-dominated boreal forests – niche breadth along the soil pH gradient. *Applied Vegetation Science* **16**: 248–259.

Konverentsiettekanded:

Degtjarenko, P., Marmor, L., Tõrra, T., Lerch, M., Saag, A., Randlane, T. ja Scheidegger, C. "The genetic diversity of a widespread epiphytic lichen *Usnea subfloridana* (Parmeliaceae, Ascomycota) in response to alkaline dust pollution". Suuline ettekanne 8. Rahvusvahelisel lihhenoloogide ühingu sümpoosionil, 1−5. august, 2016, Helsingi, Soome.

Degtjarenko, P., Mandel, T., Tõrra, T., Marmor, L., Saag., A.ja Randlane, T. "The habitat traits drive genetic diversity of a widespread epyphytic lichen *Usnea subfloridana* in hemiboreal forests". Posterettekanne 8. Rahvusvahelisel lihhenoloogide ühingu sümpoosionil, 1−5. august, 2016, Helsingi, Soome.

Degtjarenko, P., Marmor, L. ja Randlane, T. "Changes in lichen and bryophyte communities on Scots pines along an alkaline dust pollution gradient". Posterettekanne 8. Rahvusvahelisel lihhenoloogide ühingu sümpoosionil, 1−5. august, 2016, Helsingi, Soome.

Degtjarenko, P., Marmor, L., Tõrra, T., Lerch, M., Saag, A., Randlane, T. ja Scheidegger, C. "Assessing the impact of alkaline dust pollution on the genetic variation of lichen *Usnea subfloridana* (lichenized Ascomycota, Parmeliaceae)". Suuline ettekanne XX Krüptogaamilise botaanika sümpoosionil, 22−25. juuli, 2015, Porto, Portugal.

Degtjarenko, P. ja Marmor, L. "*Trentepohlia umbrina* on Scots pine as a bioindicator of alkaline dust pollution". Posterettekanne XX Krüptogaamilise botaanika sümpoosionil, 22−25. juuli, 2015, Porto, Portugal.

Degtjarenko, P., Marmor, L. ja Randlane, T. "Searching for ecological indicators of alkaline dust pollution". Suuline ettekanne Botaanika osakonna doktorantide konverentsil, 13−14. november, 2014, Jäneda, Eesti.

Degtjarenko, P., Marmor, L., Tõrra, T., Randlane, T. ja Scheidegger, C. "Genetic diversity of *Usnea subfloridana* (lichenized Ascomycota) populations in conditions of moderate dust pollution". Suuline ettekanne XIX Balti mükoloogide ja lihhenoloogide sümpoosionil, 22−26. september, 2014, Šķēde, Läti.

Uurimistoetused ja stipendiumid:

2015, 2016	Kristjan Jaagu välissõidu stipendiumid, SA Archimedes, Euroopa Sotsiaalfond
2015	Välissõidutoetus, maateaduste ja ökoloogia doktorikool
2014	ESF DoRa T8 ja T6 stipendiumid, SA Archimedes, Euroopa Sotsiaalfond

Õppetöö läbiviimise kogemus kõrgkoolis:

2015/2016	Tartu Ülikool, LOOM.01.038 Fungistika välipraktika Tartu Ülikool, LOOM.01.107 Mükoloogia ja lihhenoloogia praktikum Euroakadeemia (Tallinn), EM1070 Metsaseire Euroakadeemia (Tallinn), GPRU6091 Uurimistöö alused
2014/2015	Tartu Ülikool, LOOM.01.038 Fungistika välipraktika Tartu Ülikool, LOOM.01.107 Mükoloogia ja lihhenoloogia praktikum
2013/2014	Tartu Ülikool, LOOM.01.038 Fungistika välipraktika Tartu Ülikool, LOOM.01.107 Mükoloogia ja lihhenoloogia praktikum Euroakadeemia (Tallinn), EM1070 Metsaseire Euroakadeemia (Tallinn), ER1050 Üldine bioloogia
2012/2013	Tartu Ülikool, LOOM.01.038 Fungistika välipraktika Tartu Ülikool, LOOM.01.107 Mükoloogia ja lihhenoloogia praktikum

Juhendatud väitekirjad:

2016	Tiina Mandel, Vars-habesambliku (*Usnea subfloridana*) populatsioonide geneetiline mitmekesisus Eestis, magistritöö (Tiina Randlase kaasjuhendamisel)
2014	Kristina Metsanurk, Tolmusaate mõju samblike mitmekesisusele, bakalaureusetöö

Osalemine kursustel:

2015	Doktorantide kursus "Samblike ökoloogia ja määramine", Uppsala Põllumajandusülikool, Rootsi
2014	Doktorantide kursus "Samblike ökoloogia ja bioloogia", Uppsala Põllumajandusülikool, Rootsi

Muu erialane tegevus:

- Uurimistegevus biodiversiteedi uuringute töörühmas prof. Christoph Scheideggeri juhendamisel Metsa-, Lume- ja Maastiku-uuringute Instituudis (Swiss Federal Institute for Forest, Snow and Landscape Research, WSL), Šveitsis, jaanuar-veebruar 2014.

- Samblike inventeerimine Karula Rahvuspargis, suvi-sügis 2014.
- Õpilaste teadustööde retsenseerimine Eesti Teadusagentuuri poolt korraldatud riikliku konkursi raames, 2014−2016.
- Erinevad teaduse ja lihhenoloogia populariseerimisega seotud tegevused, 2012−2016.

DISSERTATIONES BIOLOGICAE UNIVERSITATIS TARTUENSIS

1. **Toivo Maimets**. Studies of human oncoprotein p53. Tartu, 1991, 96 p.
2. **Enn K. Seppet**. Thyroid state control over energy metabolism, ion transport and contractile functions in rat heart. Tartu, 1991, 135 p.
3. **Kristjan Zobel**. Epifüütsete makrosamblike väärtus õhu saastuse indikaatoritena Hamar-Dobani boreaalsetes mägimetsades. Tartu, 1992, 131 lk.
4. **Andres Mäe**. Conjugal mobilization of catabolic plasmids by transposable elements in helper plasmids. Tartu, 1992, 91 p.
5. **Maia Kivisaar**. Studies on phenol degradation genes of *Pseudomonas* sp. strain EST 1001. Tartu, 1992, 61 p.
6. **Allan Nurk**. Nucleotide sequences of phenol degradative genes from *Pseudomonas sp.* strain EST 1001 and their transcriptional activation in *Pseudomonas putida.* Tartu, 1992, 72 p.
7. **Ülo Tamm**. The genus *Populus* L. in Estonia: variation of the species biology and introduction. Tartu, 1993, 91 p.
8. **Jaanus Remme**. Studies on the peptidyltransferase centre of the *E.coli* ribosome. Tartu, 1993, 68 p.
9. **Ülo Langel**. Galanin and galanin antagonists. Tartu, 1993, 97 p.
10. **Arvo Käärd**. The development of an automatic online dynamic fluorescense-based pH-dependent fiber optic penicillin flowthrought biosensor for the control of the benzylpenicillin hydrolysis. Tartu, 1993, 117 p.
11. **Lilian Järvekülg**. Antigenic analysis and development of sensitive immunoassay for potato viruses. Tartu, 1993, 147 p.
12. **Jaak Palumets**. Analysis of phytomass partition in Norway spruce. Tartu, 1993, 47 p.
13. **Arne Sellin**. Variation in hydraulic architecture of *Picea abies* (L.) Karst. trees grown under different enviromental conditions. Tartu, 1994, 119 p.
13. **Mati Reeben**. Regulation of light neurofilament gene expression. Tartu, 1994, 108 p.
14. **Urmas Tartes**. Respiration rhytms in insects. Tartu, 1995, 109 p.
15. **Ülo Puurand**. The complete nucleotide sequence and infections *in vitro* transcripts from cloned cDNA of a potato A potyvirus. Tartu, 1995, 96 p.
16. **Peeter Hõrak**. Pathways of selection in avian reproduction: a functional framework and its application in the population study of the great tit (*Parus major*). Tartu, 1995, 118 p.
17. **Erkki Truve**. Studies on specific and broad spectrum virus resistance in transgenic plants. Tartu, 1996, 158 p.
18. **Illar Pata**. Cloning and characterization of human and mouse ribosomal protein S6-encoding genes. Tartu, 1996, 60 p.
19. **Ülo Niinemets**. Importance of structural features of leaves and canopy in determining species shade-tolerance in temperature deciduous woody taxa. Tartu, 1996, 150 p.

20. **Ants Kurg**. Bovine leukemia virus: molecular studies on the packaging region and DNA diagnostics in cattle. Tartu, 1996, 104 p.
21. **Ene Ustav**. E2 as the modulator of the BPV1 DNA replication. Tartu, 1996, 100 p.
22. **Aksel Soosaar**. Role of helix-loop-helix and nuclear hormone receptor transcription factors in neurogenesis. Tartu, 1996, 109 p.
23. **Maido Remm**. Human papillomavirus type 18: replication, transformation and gene expression. Tartu, 1997, 117 p.
24. **Tiiu Kull**. Population dynamics in *Cypripedium calceolus* L. Tartu, 1997, 124 p.
25. **Kalle Olli**. Evolutionary life-strategies of autotrophic planktonic microorganisms in the Baltic Sea. Tartu, 1997, 180 p.
26. **Meelis Pärtel**. Species diversity and community dynamics in calcareous grassland communities in Western Estonia. Tartu, 1997, 124 p.
27. **Malle Leht**. The Genus *Potentilla* L. in Estonia, Latvia and Lithuania: distribution, morphology and taxonomy. Tartu, 1997, 186 p.
28. **Tanel Tenson**. Ribosomes, peptides and antibiotic resistance. Tartu, 1997, 80 p.
29. **Arvo Tuvikene**. Assessment of inland water pollution using biomarker responses in fish *in vivo* and *in vitro*. Tartu, 1997, 160 p.
30. **Urmas Saarma**. Tuning ribosomal elongation cycle by mutagenesis of 23S rRNA. Tartu, 1997, 134 p.
31. **Henn Ojaveer**. Composition and dynamics of fish stocks in the gulf of Riga ecosystem. Tartu, 1997, 138 p.
32. **Lembi Lõugas**. Post-glacial development of vertebrate fauna in Estonian water bodies. Tartu, 1997, 138 p.
33. **Margus Pooga**. Cell penetrating peptide, transportan, and its predecessors, galanin-based chimeric peptides. Tartu, 1998, 110 p.
34. **Andres Saag**. Evolutionary relationships in some cetrarioid genera (Lichenized Ascomycota). Tartu, 1998, 196 p.
35. **Aivar Liiv**. Ribosomal large subunit assembly *in vivo*. Tartu, 1998, 158 p.
36. **Tatjana Oja**. Isoenzyme diversity and phylogenetic affinities among the eurasian annual bromes (*Bromus* L., Poaceae). Tartu, 1998, 92 p.
37. **Mari Moora**. The influence of arbuscular mycorrhizal (AM) symbiosis on the competition and coexistence of calcareous grassland plant species. Tartu, 1998, 78 p.
38. **Olavi Kurina**. Fungus gnats in Estonia (*Diptera: Bolitophilidae, Keroplatidae, Macroceridae, Ditomyiidae, Diadocidiidae, Mycetophilidae*). Tartu, 1998, 200 p.
39. **Andrus Tasa**. Biological leaching of shales: black shale and oil shale. Tartu, 1998, 98 p.
40. **Arnold Kristjuhan**. Studies on transcriptional activator properties of tumor suppressor protein p53. Tartu, 1998, 86 p.
41. **Sulev Ingerpuu**. Characterization of some human myeloid cell surface and nuclear differentiation antigens. Tartu, 1998, 163 p.

42. **Veljo Kisand**. Responses of planktonic bacteria to the abiotic and biotic factors in the shallow lake Võrtsjärv. Tartu, 1998, 118 p.
43. **Kadri Põldmaa**. Studies in the systematics of hypomyces and allied genera (Hypocreales, Ascomycota). Tartu, 1998, 178 p.
44. **Markus Vetemaa**. Reproduction parameters of fish as indicators in environmental monitoring. Tartu, 1998, 117 p.
45. **Heli Talvik**. Prepatent periods and species composition of different *Oesophagostomum* spp. populations in Estonia and Denmark. Tartu, 1998, 104 p.
46. **Katrin Heinsoo**. Cuticular and stomatal antechamber conductance to water vapour diffusion in *Picea abies* (L.) karst. Tartu, 1999, 133 p.
47. **Tarmo Annilo**. Studies on mammalian ribosomal protein S7. Tartu, 1998, 77 p.
48. **Indrek Ots**. Health state indicies of reproducing great tits (*Parus major*): sources of variation and connections with life-history traits. Tartu, 1999, 117 p.
49. **Juan Jose Cantero**. Plant community diversity and habitat relationships in central Argentina grasslands. Tartu, 1999, 161 p.
50. **Rein Kalamees**. Seed bank, seed rain and community regeneration in Estonian calcareous grasslands. Tartu, 1999, 107 p.
51. **Sulev Kõks**. Cholecystokinin (CCK) – induced anxiety in rats: influence of environmental stimuli and involvement of endopioid mechanisms and serotonin. Tartu, 1999, 123 p.
52. **Ebe Sild**. Impact of increasing concentrations of O_3 and CO_2 on wheat, clover and pasture. Tartu, 1999, 123 p.
53. **Ljudmilla Timofejeva**. Electron microscopical analysis of the synaptonemal complex formation in cereals. Tartu, 1999, 99 p.
54. **Andres Valkna**. Interactions of galanin receptor with ligands and G-proteins: studies with synthetic peptides. Tartu, 1999, 103 p.
55. **Taavi Virro**. Life cycles of planktonic rotifers in lake Peipsi. Tartu, 1999, 101 p.
56. **Ana Rebane**. Mammalian ribosomal protein S3a genes and intron-encoded small nucleolar RNAs U73 and U82. Tartu, 1999, 85 p.
57. **Tiina Tamm**. Cocksfoot mottle virus: the genome organisation and translational strategies. Tartu, 2000, 101 p.
58. **Reet Kurg**. Structure-function relationship of the bovine papilloma virus E2 protein. Tartu, 2000, 89 p.
59. **Toomas Kivisild**. The origins of Southern and Western Eurasian populations: an mtDNA study. Tartu, 2000, 121 p.
60. **Niilo Kaldalu**. Studies of the TOL plasmid transcription factor XylS. Tartu, 2000, 88 p.
61. **Dina Lepik**. Modulation of viral DNA replication by tumor suppressor protein p53. Tartu, 2000, 106 p.

62. **Kai Vellak**. Influence of different factors on the diversity of the bryophyte vegetation in forest and wooded meadow communities. Tartu, 2000, 122 p.
63. **Jonne Kotta**. Impact of eutrophication and biological invasionas on the structure and functions of benthic macrofauna. Tartu, 2000, 160 p.
64. **Georg Martin**. Phytobenthic communities of the Gulf of Riga and the inner sea the West-Estonian archipelago. Tartu, 2000, 139 p.
65. **Silvia Sepp**. Morphological and genetical variation of *Alchemilla L.* in Estonia. Tartu, 2000. 124 p.
66. **Jaan Liira**. On the determinants of structure and diversity in herbaceous plant communities. Tartu, 2000, 96 p.
67. **Priit Zingel**. The role of planktonic ciliates in lake ecosystems. Tartu, 2001, 111 p.
68. **Tiit Teder**. Direct and indirect effects in Host-parasitoid interactions: ecological and evolutionary consequences. Tartu, 2001, 122 p.
69. **Hannes Kollist**. Leaf apoplastic ascorbate as ozone scavenger and its transport across the plasma membrane. Tartu, 2001, 80 p.
70. **Reet Marits**. Role of two-component regulator system PehR-PehS and extracellular protease PrtW in virulence of *Erwinia Carotovora* subsp. *Carotovora*. Tartu, 2001, 112 p.
71. **Vallo Tilgar**. Effect of calcium supplementation on reproductive performance of the pied flycatcher *Ficedula hypoleuca* and the great tit *Parus major,* breeding in Nothern temperate forests. Tartu, 2002, 126 p.
72. **Rita Hõrak**. Regulation of transposition of transposon Tn*4652* in *Pseudomonas putida*. Tartu, 2002, 108 p.
73. **Liina Eek-Piirsoo**. The effect of fertilization, mowing and additional illumination on the structure of a species-rich grassland community. Tartu, 2002, 74 p.
74. **Krõõt Aasamaa**. Shoot hydraulic conductance and stomatal conductance of six temperate deciduous tree species. Tartu, 2002, 110 p.
75. **Nele Ingerpuu**. Bryophyte diversity and vascular plants. Tartu, 2002, 112 p.
76. **Neeme Tõnisson**. Mutation detection by primer extension on oligonucleotide microarrays. Tartu, 2002, 124 p.
77. **Margus Pensa**. Variation in needle retention of Scots pine in relation to leaf morphology, nitrogen conservation and tree age. Tartu, 2003, 110 p.
78. **Asko Lõhmus**. Habitat preferences and quality for birds of prey: from principles to applications. Tartu, 2003, 168 p.
79. **Viljar Jaks**. p53 – a switch in cellular circuit. Tartu, 2003, 160 p.
80. **Jaana Männik**. Characterization and genetic studies of four ATP-binding cassette (ABC) transporters. Tartu, 2003, 140 p.
81. **Marek Sammul**. Competition and coexistence of clonal plants in relation to productivity. Tartu, 2003, 159 p
82. **Ivar Ilves**. Virus-cell interactions in the replication cycle of bovine papillomavirus type 1. Tartu, 2003, 89 p.

83. **Andres Männik**. Design and characterization of a novel vector system based on the stable replicator of bovine papillomavirus type 1. Tartu, 2003, 109 p.
84. **Ivika Ostonen**. Fine root structure, dynamics and proportion in net primary production of Norway spruce forest ecosystem in relation to site conditions. Tartu, 2003, 158 p.
85. **Gudrun Veldre**. Somatic status of 12–15-year-old Tartu schoolchildren. Tartu, 2003, 199 p.
86. **Ülo Väli**. The greater spotted eagle *Aquila clanga* and the lesser spotted eagle *A. pomarina*: taxonomy, phylogeography and ecology. Tartu, 2004, 159 p.
87. **Aare Abroi**. The determinants for the native activities of the bovine papillomavirus type 1 E2 protein are separable. Tartu, 2004, 135 p.
88. **Tiina Kahre**. Cystic fibrosis in Estonia. Tartu, 2004, 116 p.
89. **Helen Orav-Kotta**. Habitat choice and feeding activity of benthic suspension feeders and mesograzers in the northern Baltic Sea. Tartu, 2004, 117 p.
90. **Maarja Öpik**. Diversity of arbuscular mycorrhizal fungi in the roots of perennial plants and their effect on plant performance. Tartu, 2004, 175 p.
91. **Kadri Tali**. Species structure of *Neotinea ustulata*. Tartu, 2004, 109 p.
92. **Kristiina Tambets**. Towards the understanding of post-glacial spread of human mitochondrial DNA haplogroups in Europe and beyond: a phylogeographic approach. Tartu, 2004, 163 p.
93. **Arvi Jõers**. Regulation of p53-dependent transcription. Tartu, 2004, 103 p.
94. **Lilian Kadaja**. Studies on modulation of the activity of tumor suppressor protein p53. Tartu, 2004, 103 p.
95. **Jaak Truu**. Oil shale industry wastewater: impact on river microbial community and possibilities for bioremediation. Tartu, 2004, 128 p.
96. **Maire Peters**. Natural horizontal transfer of the *pheBA* operon. Tartu, 2004, 105 p.
97. **Ülo Maiväli**. Studies on the structure-function relationship of the bacterial ribosome. Tartu, 2004, 130 p.
98. **Merit Otsus**. Plant community regeneration and species diversity in dry calcareous grasslands. Tartu, 2004, 103 p.
99. **Mikk Heidemaa**. Systematic studies on sawflies of the genera *Dolerus, Empria,* and *Caliroa* (Hymenoptera: Tenthredinidae). Tartu, 2004, 167 p.
100. **Ilmar Tõnno**. The impact of nitrogen and phosphorus concentration and N/P ratio on cyanobacterial dominance and N_2 fixation in some Estonian lakes. Tartu, 2004, 111 p.
101. **Lauri Saks**. Immune function, parasites, and carotenoid-based ornaments in greenfinches. Tartu, 2004, 144 p.
102. **Siiri Rootsi**. Human Y-chromosomal variation in European populations. Tartu, 2004, 142 p.
103. **Eve Vedler**. Structure of the 2,4-dichloro-phenoxyacetic acid-degradative plasmid pEST4011. Tartu, 2005. 106 p.

104. **Andres Tover**. Regulation of transcription of the phenol degradation *pheBA* operon in *Pseudomonas putida*. Tartu, 2005, 126 p.
105. **Helen Udras**. Hexose kinases and glucose transport in the yeast *Hansenula polymorpha*. Tartu, 2005, 100 p.
106. **Ave Suija**. Lichens and lichenicolous fungi in Estonia: diversity, distribution patterns, taxonomy. Tartu, 2005, 162 p.
107. **Piret Lõhmus**. Forest lichens and their substrata in Estonia. Tartu, 2005, 162 p.
108. **Inga Lips**. Abiotic factors controlling the cyanobacterial bloom occurrence in the Gulf of Finland. Tartu, 2005, 156 p.
109. **Kaasik, Krista**. Circadian clock genes in mammalian clockwork, metabolism and behaviour. Tartu, 2005, 121 p.
110. **Juhan Javoiš**. The effects of experience on host acceptance in ovipositing moths. Tartu, 2005, 112 p.
111. **Tiina Sedman**. Characterization of the yeast *Saccharomyces cerevisiae* mitochondrial DNA helicase Hmi1. Tartu, 2005, 103 p.
112. **Ruth Aguraiuja**. Hawaiian endemic fern lineage *Diellia* (Aspleniaceae): distribution, population structure and ecology. Tartu, 2005, 112 p.
113. **Riho Teras**. Regulation of transcription from the fusion promoters generated by transposition of Tn*4652* into the upstream region of *pheBA* operon in *Pseudomonas putida*. Tartu, 2005, 106 p.
114. **Mait Metspalu**. Through the course of prehistory in india: tracing the mtDNA trail. Tartu, 2005, 138 p.
115. **Elin Lõhmussaar**. The comparative patterns of linkage disequilibrium in European populations and its implication for genetic association studies. Tartu, 2006, 124 p.
116. **Priit Kupper**. Hydraulic and environmental limitations to leaf water relations in trees with respect to canopy position. Tartu, 2006, 126 p.
117. **Heili Ilves**. Stress-induced transposition of Tn*4652* in *Pseudomonas Putida.* Tartu, 2006, 120 p.
118. **Silja Kuusk**. Biochemical properties of Hmi1p, a DNA helicase from *Saccharomyces cerevisiae* mitochondria. Tartu, 2006, 126 p.
119. **Kersti Püssa**. Forest edges on medium resolution landsat thematic mapper satellite images. Tartu, 2006, 90 p.
120. **Lea Tummeleht**. Physiological condition and immune function in great tits (*Parus major* l.): Sources of variation and trade-offs in relation to growth. Tartu, 2006, 94 p.
121. **Toomas Esperk**. Larval instar as a key element of insect growth schedules. Tartu, 2006, 186 p.
122. **Harri Valdmann**. Lynx (*Lynx lynx*) and wolf (*Canis lupus*) in the Baltic region: Diets, helminth parasites and genetic variation. Tartu, 2006. 102 p.
123. **Priit Jõers**. Studies of the mitochondrial helicase Hmi1p in *Candida albicans* and *Saccharomyces cerevisia*. Tartu, 2006. 113 p.
124. **Kersti Lilleväli**. Gata3 and Gata2 in inner ear development. Tartu, 2007, 123 p.

125. **Kai Rünk**. Comparative ecology of three fern species: *Dryopteris carthusiana* (Vill.) H.P. Fuchs, *D. expansa* (C. Presl) Fraser-Jenkins & Jermy and *D. dilatata* (Hoffm.) A. Gray (Dryopteridaceae). Tartu, 2007, 143 p.
126. **Aveliina Helm**. Formation and persistence of dry grassland diversity: role of human history and landscape structure. Tartu, 2007, 89 p.
127. **Leho Tedersoo**. Ectomycorrhizal fungi: diversity and community structure in Estonia, Seychelles and Australia. Tartu, 2007, 233 p.
128. **Marko Mägi**. The habitat-related variation of reproductive performance of great tits in a deciduous-coniferous forest mosaic: looking for causes and consequences. Tartu, 2007, 135 p.
129. **Valeria Lulla**. Replication strategies and applications of Semliki Forest virus. Tartu, 2007, 109 p.
130. **Ülle Reier**. Estonian threatened vascular plant species: causes of rarity and conservation. Tartu, 2007, 79 p.
131. **Inga Jüriado**. Diversity of lichen species in Estonia: influence of regional and local factors. Tartu, 2007, 171 p.
132. **Tatjana Krama**. Mobbing behaviour in birds: costs and reciprocity based cooperation. Tartu, 2007, 112 p.
133. **Signe Saumaa**. The role of DNA mismatch repair and oxidative DNA damage defense systems in avoidance of stationary phase mutations in *Pseudomonas putida.* Tartu, 2007, 172 p.
134. **Reedik Mägi**. The linkage disequilibrium and the selection of genetic markers for association studies in european populations. Tartu, 2007, 96 p.
135. **Priit Kilgas**. Blood parameters as indicators of physiological condition and skeletal development in great tits (*Parus major*): natural variation and application in the reproductive ecology of birds. Tartu, 2007, 129 p.
136. **Anu Albert**. The role of water salinity in structuring eastern Baltic coastal fish communities. Tartu, 2007, 95 p.
137. **Kärt Padari**. Protein transduction mechanisms of transportans. Tartu, 2008, 128 p.
138. **Siiri-Lii Sandre**. Selective forces on larval colouration in a moth. Tartu, 2008, 125 p.
139. **Ülle Jõgar**. Conservation and restoration of semi-natural floodplain meadows and their rare plant species. Tartu, 2008, 99 p.
140. **Lauri Laanisto**. Macroecological approach in vegetation science: generality of ecological relationships at the global scale. Tartu, 2008, 133 p.
141. **Reidar Andreson**. Methods and software for predicting PCR failure rate in large genomes. Tartu, 2008, 105 p.
142. **Birgot Paavel**. Bio-optical properties of turbid lakes. Tartu, 2008, 175 p.
143. **Kaire Torn**. Distribution and ecology of charophytes in the Baltic Sea. Tartu, 2008, 98 p.
144. **Vladimir Vimberg**. Peptide mediated macrolide resistance. Tartu, 2008, 190 p.
145. **Daima Örd**. Studies on the stress-inducible pseudokinase TRB3, a novel inhibitor of transcription factor ATF4. Tartu, 2008, 108 p.

146. **Lauri Saag**. Taxonomic and ecologic problems in the genus *Lepraria* (*Stereocaulaceae*, lichenised *Ascomycota*). Tartu, 2008, 175 p.
147. **Ulvi Karu**. Antioxidant protection, carotenoids and coccidians in greenfinches – assessment of the costs of immune activation and mechanisms of parasite resistance in a passerine with carotenoid-based ornaments. Tartu, 2008, 124 p.
148. **Jaanus Remm**. Tree-cavities in forests: density, characteristics and occupancy by animals. Tartu, 2008, 128 p.
149. **Epp Moks**. Tapeworm parasites *Echinococcus multilocularis* and *E. granulosus* in Estonia: phylogenetic relationships and occurrence in wild carnivores and ungulates. Tartu, 2008, 82 p.
150. **Eve Eensalu**. Acclimation of stomatal structure and function in tree canopy: effect of light and CO_2 concentration. Tartu, 2008, 108 p.
151. **Janne Pullat**. Design, functionlization and application of an *in situ* synthesized oligonucleotide microarray. Tartu, 2008, 108 p.
152. **Marta Putrinš**. Responses of *Pseudomonas putida* to phenol-induced metabolic and stress signals. Tartu, 2008, 142 p.
153. **Marina Semtšenko**. Plant root behaviour: responses to neighbours and physical obstructions. Tartu, 2008, 106 p.
154. **Marge Starast**. Influence of cultivation techniques on productivity and fruit quality of some *Vaccinium* and *Rubus* taxa. Tartu, 2008, 154 p.
155. **Age Tats**. Sequence motifs influencing the efficiency of translation. Tartu, 2009, 104 p.
156. **Radi Tegova**. The role of specialized DNA polymerases in mutagenesis in *Pseudomonas putida.* Tartu, 2009, 124 p.
157. **Tsipe Aavik**. Plant species richness, composition and functional trait pattern in agricultural landscapes – the role of land use intensity and landscape structure. Tartu, 2009, 112 p.
158. **Kaja Kiiver**. Semliki forest virus based vectors and cell lines for studying the replication and interactions of alphaviruses and hepaciviruses. Tartu, 2009, 104 p.
159. **Meelis Kadaja**. Papillomavirus Replication Machinery Induces Genomic Instability in its Host Cell. Tartu, 2009, 126 p.
160. **Pille Hallast**. Human and chimpanzee Luteinizing hormone/Chorionic Gonadotropin beta (*LHB/CGB*) gene clusters: diversity and divergence of young duplicated genes. Tartu, 2009, 168 p.
161. **Ain Vellak**. Spatial and temporal aspects of plant species conservation. Tartu, 2009, 86 p.
162. **Triinu Remmel**. Body size evolution in insects with different colouration strategies: the role of predation risk. Tartu, 2009, 168 p.
163. **Jaana Salujõe**. Zooplankton as the indicator of ecological quality and fish predation in lake ecosystems. Tartu, 2009, 129 p.
164. **Ele Vahtmäe**. Mapping benthic habitat with remote sensing in optically complex coastal environments. Tartu, 2009, 109 p.

165. **Liisa Metsamaa**. Model-based assessment to improve the use of remote sensing in recognition and quantitative mapping of cyanobacteria. Tartu, 2009, 114 p.
166. **Pille Säälik**. The role of endocytosis in the protein transduction by cell-penetrating peptides. Tartu, 2009, 155 p.
167. **Lauri Peil**. Ribosome assembly factors in *Escherichia coli.* Tartu, 2009, 147 p.
168. **Lea Hallik**. Generality and specificity in light harvesting, carbon gain capacity and shade tolerance among plant functional groups. Tartu, 2009, 99 p.
169. **Mariliis Tark**. Mutagenic potential of DNA damage repair and tolerance mechanisms under starvation stress. Tartu, 2009, 191 p.
170. **Riinu Rannap**. Impacts of habitat loss and restoration on amphibian populations. Tartu, 2009, 117 p.
171. **Maarja Adojaan**. Molecular variation of HIV-1 and the use of this knowledge in vaccine development. Tartu, 2009, 95 p.
172. **Signe Altmäe**. Genomics and transcriptomics of human induced ovarian folliculogenesis. Tartu, 2010, 179 p.
173. **Triin Suvi**. Mycorrhizal fungi of native and introduced trees in the Seychelles Islands. Tartu, 2010, 107 p.
174. **Velda Lauringson**. Role of suspension feeding in a brackish-water coastal sea. Tartu, 2010, 123 p.
175. **Eero Talts**. Photosynthetic cyclic electron transport – measurement and variably proton-coupled mechanism. Tartu, 2010, 121 p.
176. **Mari Nelis**. Genetic structure of the Estonian population and genetic distance from other populations of European descent. Tartu, 2010, 97 p.
177. **Kaarel Krjutškov**. Arrayed Primer Extension-2 as a multiplex PCR-based method for nucleic acid variation analysis: method and applications. Tartu, 2010, 129 p.
178. **Egle Köster**. Morphological and genetical variation within species complexes: *Anthyllis vulneraria* s. l. and *Alchemilla vulgaris* (coll.). Tartu, 2010, 101 p.
179. **Erki Õunap**. Systematic studies on the subfamily Sterrhinae (Lepidoptera: Geometridae). Tartu, 2010, 111 p.
180. **Merike Jõesaar**. Diversity of key catabolic genes at degradation of phenol and *p*-cresol in pseudomonads. Tartu, 2010, 125 p.
181. **Kristjan Herkül**. Effects of physical disturbance and habitat-modifying species on sediment properties and benthic communities in the northern Baltic Sea. Tartu, 2010, 123 p.
182. **Arto Pulk**. Studies on bacterial ribosomes by chemical modification approaches. Tartu, 2010, 161 p.
183. **Maria Põllupüü**. Ecological relations of cladocerans in a brackish-water ecosystem. Tartu, 2010, 126 p.
184. **Toomas Silla**. Study of the segregation mechanism of the Bovine Papillomavirus Type 1. Tartu, 2010, 188 p.

185. **Gyaneshwer Chaubey**. The demographic history of India: A perspective based on genetic evidence. Tartu, 2010, 184 p.
186. **Katrin Kepp**. Genes involved in cardiovascular traits: detection of genetic variation in Estonian and Czech populations. Tartu, 2010, 164 p.
187. **Virve Sõber**. The role of biotic interactions in plant reproductive performance. Tartu, 2010, 92 p.
188. **Kersti Kangro**. The response of phytoplankton community to the changes in nutrient loading. Tartu, 2010, 144 p.
189. **Joachim M. Gerhold**. Replication and Recombination of mitochondrial DNA in Yeast. Tartu, 2010, 120 p.
190. **Helen Tammert**. Ecological role of physiological and phylogenetic diversity in aquatic bacterial communities. Tartu, 2010, 140 p.
191. **Elle Rajandu**. Factors determining plant and lichen species diversity and composition in Estonian *Calamagrostis* and *Hepatica* site type forests. Tartu, 2010, 123 p.
192. **Paula Ann Kivistik**. ColR-ColS signalling system and transposition of Tn*4652* in the adaptation of *Pseudomonas putida.* Tartu, 2010, 118 p.
193. **Siim Sõber**. Blood pressure genetics: from candidate genes to genome-wide association studies. Tartu, 2011, 120 p.
194. **Kalle Kipper**. Studies on the role of helix 69 of 23S rRNA in the factor-dependent stages of translation initiation, elongation, and termination. Tartu, 2011, 178 p.
195. **Triinu Siibak**. Effect of antibiotics on ribosome assembly is indirect. Tartu, 2011, 134 p.
196. **Tambet Tõnissoo**. Identification and molecular analysis of the role of guanine nucleotide exchange factor RIC-8 in mouse development and neural function. Tartu, 2011, 110 p.
197. **Helin Räägel**. Multiple faces of cell-penetrating peptides – their intracellular trafficking, stability and endosomal escape during protein transduction. Tartu, 2011, 161 p.
198. **Andres Jaanus**. Phytoplankton in Estonian coastal waters – variability, trends and response to environmental pressures. Tartu, 2011, 157 p.
199. **Tiit Nikopensius**. Genetic predisposition to nonsyndromic orofacial clefts. Tartu, 2011, 152 p.
200. **Signe Värv**. Studies on the mechanisms of RNA polymerase II-dependent transcription elongation. Tartu, 2011, 108 p.
201. **Kristjan Välk**. Gene expression profiling and genome-wide association studies of non-small cell lung cancer. Tartu, 2011, 98 p.
202. **Arno Põllumäe**. Spatio-temporal patterns of native and invasive zooplankton species under changing climate and eutrophication conditions. Tartu, 2011, 153 p.
203. **Egle Tammeleht**. Brown bear (*Ursus arctos*) population structure, demographic processes and variations in diet in northern Eurasia. Tartu, 2011, 143 p.

205. **Teele Jairus**. Species composition and host preference among ectomycorrhizal fungi in Australian and African ecosystems. Tartu, 2011, 106 p.
206. **Kessy Abarenkov**. PlutoF – cloud database and computing services supporting biological research. Tartu, 2011, 125 p.
207. **Marina Grigorova**. Fine-scale genetic variation of follicle-stimulating hormone beta-subunit coding gene (*FSHB*) and its association with reproductive health. Tartu, 2011, 184 p.
208. **Anu Tiitsaar**. The effects of predation risk and habitat history on butterfly communities. Tartu, 2011, 97 p.
209. **Elin Sild**. Oxidative defences in immunoecological context: validation and application of assays for nitric oxide production and oxidative burst in a wild passerine. Tartu, 2011, 105 p.
210. **Irja Saar**. The taxonomy and phylogeny of the genera *Cystoderma* and *Cystodermella* (Agaricales, Fungi). Tartu, 2012, 167 p.
211. **Pauli Saag**. Natural variation in plumage bacterial assemblages in two wild breeding passerines. Tartu, 2012, 113 p.
212. **Aleksei Lulla**. Alphaviral nonstructural protease and its polyprotein substrate: arrangements for the perfect marriage. Tartu, 2012, 143 p.
213. **Mari Järve**. Different genetic perspectives on human history in Europe and the Caucasus: the stories told by uniparental and autosomal markers. Tartu, 2012, 119 p.
214. **Ott Scheler**. The application of tmRNA as a marker molecule in bacterial diagnostics using microarray and biosensor technology. Tartu, 2012, 93 p.
215. **Anna Balikova**. Studies on the functions of tumor-associated mucin-like leukosialin (CD43) in human cancer cells. Tartu, 2012, 129 p.
216. **Triinu Kõressaar**. Improvement of PCR primer design for detection of prokaryotic species. Tartu, 2012, 83 p.
217. **Tuul Sepp**. Hematological health state indices of greenfinches: sources of individual variation and responses to immune system manipulation. Tartu, 2012, 117 p.
218. **Rya Ero**. Modifier view of the bacterial ribosome. Tartu, 2012, 146 p.
219. **Mohammad Bahram**. Biogeography of ectomycorrhizal fungi across different spatial scales. Tartu, 2012, 165 p.
220. **Annely Lorents**. Overcoming the plasma membrane barrier: uptake of amphipathic cell-penetrating peptides induces influx of calcium ions and downstream responses. Tartu, 2012, 113 p.
221. **Katrin Männik**. Exploring the genomics of cognitive impairment: whole-genome SNP genotyping experience in Estonian patients and general population. Tartu, 2012, 171 p.
222. **Marko Prous**. Taxonomy and phylogeny of the sawfly genus *Empria* (Hymenoptera, Tenthredinidae). Tartu, 2012, 192 p.
223. **Triinu Visnapuu**. Levansucrases encoded in the genome of *Pseudomonas syringae* pv. tomato DC3000: heterologous expression, biochemical characterization, mutational analysis and spectrum of polymerization products. Tartu, 2012, 160 p.

224. **Nele Tamberg**. Studies on Semliki Forest virus replication and pathogenesis. Tartu, 2012, 109 p.
225. **Tõnu Esko**. Novel applications of SNP array data in the analysis of the genetic structure of Europeans and in genetic association studies. Tartu, 2012, 149 p.
226. **Timo Arula**. Ecology of early life-history stages of herring *Clupea harengus membras* in the northeastern Baltic Sea. Tartu, 2012, 143 p.
227. **Inga Hiiesalu**. Belowground plant diversity and coexistence patterns in grassland ecosystems. Tartu, 2012, 130 p.
228. **Kadri Koorem**. The influence of abiotic and biotic factors on small-scale plant community patterns and regeneration in boreonemoral forest. Tartu, 2012, 114 p.
229. **Liis Andresen**. Regulation of virulence in plant-pathogenic pectobacteria. Tartu, 2012, 122 p.
230. **Kaupo Kohv**. The direct and indirect effects of management on boreal forest structure and field layer vegetation. Tartu, 2012, 124 p.
231. **Mart Jüssi**. Living on an edge: landlocked seals in changing climate. Tartu, 2012, 114 p.
232. **Riina Klais**. Phytoplankton trends in the Baltic Sea. Tartu, 2012, 136 p.
233. **Rauno Veeroja**. Effects of winter weather, population density and timing of reproduction on life-history traits and population dynamics of moose (*Alces alces*) in Estonia. Tartu, 2012, 92 p.
234. **Marju Keis**. Brown bear (*Ursus arctos*) phylogeography in northern Eurasia. Tartu, 2013, 142 p.
235. **Sergei Põlme**. Biogeography and ecology of *alnus*- associated ectomycorrhizal fungi – from regional to global scale. Tartu, 2013, 90 p.
236. **Liis Uusküla**. Placental gene expression in normal and complicated pregnancy. Tartu, 2013, 173 p.
237. **Marko Lõoke**. Studies on DNA replication initiation in *Saccharomyces cerevisiae.* Tartu, 2013, 112 p.
238. **Anne Aan**. Light- and nitrogen-use and biomass allocation along productivity gradients in multilayer plant communities. Tartu, 2013, 127 p.
239. **Heidi Tamm**. Comprehending phylogenetic diversity – case studies in three groups of ascomycetes. Tartu, 2013, 136 p.
240. **Liina Kangur**. High-Pressure Spectroscopy Study of Chromophore-Binding Hydrogen Bonds in Light-Harvesting Complexes of Photosynthetic Bacteria. Tartu, 2013, 150 p.
241. **Margus Leppik**. Substrate specificity of the multisite specific pseudouridine synthase RluD. Tartu, 2013, 111 p.
242. **Lauris Kaplinski**. The application of oligonucleotide hybridization model for PCR and microarray optimization. Tartu, 2013, 103 p.
243. **Merli Pärnoja**. Patterns of macrophyte distribution and productivity in coastal ecosystems: effect of abiotic and biotic forcing. Tartu, 2013, 155 p.
244. **Tõnu Margus**. Distribution and phylogeny of the bacterial translational GTPases and the Mqsr/YgiT regulatory system. Tartu, 2013, 126 p.

245. **Pille Mänd**. Light use capacity and carbon and nitrogen budget of plants: remote assessment and physiological determinants. Tartu, 2013, 128 p.
246. **Mario Plaas**. Animal model of Wolfram Syndrome in mice: behavioural, biochemical and psychopharmacological characterization. Tartu, 2013, 144 p.
247. **Georgi Hudjašov**. Maps of mitochondrial DNA, Y-chromosome and tyrosinase variation in Eurasian and Oceanian populations. Tartu, 2013, 115 p.
248. **Mari Lepik**. Plasticity to light in herbaceous plants and its importance for community structure and diversity. Tartu, 2013, 102 p.
249. **Ede Leppik**. Diversity of lichens in semi-natural habitats of Estonia. Tartu, 2013, 151 p.
250. **Ülle Saks**. Arbuscular mycorrhizal fungal diversity patterns in boreo-nemoral forest ecosystems. Tartu, 2013, 151 p.
251. **Eneli Oitmaa**. Development of arrayed primer extension microarray assays for molecular diagnostic applications. Tartu, 2013, 147 p.
252. **Jekaterina Jutkina**. The horizontal gene pool for aromatics degradation: bacterial catabolic plasmids of the Baltic Sea aquatic system. Tartu, 2013, 121 p.
253. **Helen Vellau**. Reaction norms for size and age at maturity in insects: rules and exceptions. Tartu, 2014, 132 p.
254. **Randel Kreitsberg**. Using biomarkers in assessment of environmental contamination in fish – new perspectives. Tartu, 2014, 107 p.
255. **Krista Takkis**. Changes in plant species richness and population performance in response to habitat loss and fragmentation.Tartu, 2014, 141 p.
256. **Liina Nagirnaja**. Global and fine-scale genetic determinants of recurrent pregnancy loss. Tartu, 2014, 211 p.
257. **Triin Triisberg**. Factors influencing the re-vegetation of abandoned extracted peatlands in Estonia. Tartu, 2014, 133 p.
258. **Villu Soon**. A phylogenetic revision of the *Chrysis ignita* species group (Hymenoptera: Chrysididae) with emphasis on the northern European fauna. Tartu, 2014, 211 p.
259. **Andrei Nikonov**. RNA-Dependent RNA Polymerase Activity as a Basis for the Detection of Positive-Strand RNA Viruses by Vertebrate Host Cells. Tartu, 2014, 207 p.
260. **Eele Õunapuu-Pikas**. Spatio-temporal variability of leaf hydraulic conductance in woody plants: ecophysiological consequences. Tartu, 2014, 135 p.
261. **Marju Männiste**. Physiological ecology of greenfinches: information content of feathers in relation to immune function and behavior. Tartu, 2014, 121 p.
262. **Katre Kets**. Effects of elevated concentrations of CO_2 and O_3 on leaf photosynthetic parameters in *Populus tremuloides*: diurnal, seasonal and interannual patterns. Tartu, 2014, 115 p.

263. **Külli Lokko**. Seasonal and spatial variability of zoopsammon communities in relation to environmental parameters. Tartu, 2014, 129 p.
264. **Olga Žilina**. Chromosomal microarray analysis as diagnostic tool: Estonian experience. Tartu, 2014, 152 p.
265. **Kertu Lõhmus**. Colonisation ecology of forest-dwelling vascular plants and the conservation value of rural manor parks. Tartu, 2014, 111 p.
266. **Anu Aun**. Mitochondria as integral modulators of cellular signaling. Tartu, 2014, 167 p.
267. **Chandana Basu Mallick**. Genetics of adaptive traits and gender-specific demographic processes in South Asian populations. Tartu, 2014, 160 p.
268. **Riin Tamme**. The relationship between small-scale environmental heterogeneity and plant species diversity. Tartu, 2014, 130 p.
269. **Liina Remm**. Impacts of forest drainage on biodiversity and habitat quality: implications for sustainable management and conservation. Tartu, 2015, 126 p.
270. **Tiina Talve**. Genetic diversity and taxonomy within the genus *Rhinanthus.* Tartu, 2015, 106 p.
271. **Mehis Rohtla**. Otolith sclerochronological studies on migrations, spawning habitat preferences and age of freshwater fishes inhabiting the Baltic Sea. Tartu, 2015, 137 p.
272. **Alexey Reshchikov**. The world fauna of the genus *Lathrolestes* (Hymenoptera, Ichneumonidae). Tartu, 2015, 247 p.
273. **Martin Pook**. Studies on artificial and extracellular matrix protein-rich surfaces as regulators of cell growth and differentiation. Tartu, 2015, 142 p.
274. **Mai Kukumägi**. Factors affecting soil respiration and its components in silver birch and Norway spruce stands. Tartu, 2015, 155 p.
275. **Helen Karu**. Development of ecosystems under human activity in the North-East Estonian industrial region: forests on post-mining sites and bogs. Tartu, 2015, 152 p.
276. **Hedi Peterson**. Exploiting high-throughput data for establishing relationships between genes. Tartu, 2015, 186 p.
277. **Priit Adler**. Analysis and visualisation of large scale microarray data, Tartu, 2015, 126 p.
278. **Aigar Niglas**. Effects of environmental factors on gas exchange in deciduous trees: focus on photosynthetic water-use efficiency. Tartu, 2015, 152 p.
279. **Silja Laht**. Classification and identification of conopeptides using profile hidden Markov models and position-specific scoring matrices. Tartu, 2015, 100 p.
280. **Martin Kesler**. Biological characteristics and restoration of Atlantic salmon *Salmo salar* populations in the Rivers of Northern Estonia. Tartu, 2015, 97 p.
281. **Pratyush Kumar Das**. Biochemical perspective on alphaviral nonstructural protein 2: a tale from multiple domains to enzymatic profiling. Tartu, 2015, 205 p

282. **Priit Palta**. Computational methods for DNA copy number detection. Tartu, 2015, 130 p.
283. **Julia Sidorenko**. Combating DNA damage and maintenance of genome integrity in pseudomonads. Tartu, 2015, 174 p.
284. **Anastasiia Kovtun-Kante**. Charophytes of Estonian inland and coastal waters: distribution and environmental preferences. Tartu, 2015, 97 p.
285. **Ly Lindman**. The ecology of protected butterfly species in Estonia. Tartu, 2015, 171 p.
286. **Jaanis Lodjak**. Association of Insulin-like Growth Factor I and Corticosterone with Nestling Growth and Fledging Success in Wild Passerines. Tartu, 2016, 113 p.
287. **Ann Kraut**. Conservation of Wood-Inhabiting Biodiversity – Semi-Natural Forests as an Opportunity. Tartu, 2016, 141 p.
288. **Tiit Örd.** Functions and regulation of the mammalian pseudokinase TRIB3. Tartu, 2016, 182. p.
289. **Kairi Käiro.** Biological Quality According to Macroinvertebrates in Streams of Estonia (Baltic Ecoregion of Europe): Effects of Human-induced Hydromorphological Changes. Tartu, 2016, 126 p.
290. **Leidi Laurimaa**. *Echinococcus multilocularis* and other zoonotic parasites in Estonian canids. Tartu, 2016, 144 p.
291. **Helerin Margus.** Characterization of cell-penetrating peptide/nucleic acid nanocomplexes and their cell-entry mechanisms. Tartu, 2016, 173 p.
292. **Kadri Runnel**. Fungal targets and tools for forest conservation. Tartu, 2016, 157 p.
293. **Urmo Võsa**. MicroRNAs in disease and health: aberrant regulation in lung cancer and association with genomic variation. Tartu, 2016, 163 p.
294. **Kristina Mäemets-Allas**. Studies on cell growth promoting AKT signaling pathway – a promising anti-cancer drug target. Tartu, 2016, 146 p.
295. **Janeli Viil.** Studies on cellular and molecular mechanisms that drive normal and regenerative processes in the liver and pathological processes in Dupuytren's contracture. Tartu, 2016, 175 p.
296. **Ene Kook**. Genetic diversity and evolution of *Pulmonaria angustifolia* L. and *Myosotis laxa sensu lato* (Boraginaceae). Tartu, 2016, 106 p.
297. **Kadri Peil.** RNA polymerase II-dependent transcription elongation in *Saccharomyces cerevisiae*. Tartu, 2016, 113 p.
298. **Katrin Ruisu.** The role of RIC8A in mouse development and its function in cell-matrix adhesion and actin cytoskeletal organisation. Tartu, 2016, 129 p.
299. **Janely Pae**. Translocation of cell-penetrating peptides across biological membranes and interactions with plasma membrane constituents. Tartu, 2016, 126 p.
300. **Argo Ronk.** Plant diversity patterns across Europe: observed and dark diversity. Tartu, 2016, 153 p.

301. **Kristiina Mark.** Diversification and species delimitation of lichenized fungi in selected groups of the family Parmeliaceae (Ascomycota). Tartu, 2016, 181 p.
302. **Jaak-Albert Metsoja**. Vegetation dynamics in floodplain meadows: influence of mowing and sediment application. Tartu, 2016, 140 p.
303. **Hedvig Tamman.** The GraTA toxin-antitoxin system of *Pseudomonas putida*: regulation and role in stress tolerance. Tartu, 2016, 154 p.
304. **Kadri Pärtel**. Application of ultrastructural and molecular data in the taxonomy of helotialean fungi. Tartu, 2016, 183 p.
305. **Maris Hindrikson**. Grey wolf (*Canis lupus*) populations in Estonia and Europe: genetic diversity, population structure and -processes, and hybridization between wolves and dogs. Tartu, 2016, 121 p.