Chapter 4
Plant Growth and Vitality

4.1 Introduction

4.1.1 The Vitality of Plants

Many different ways to define plant vitality or vigour have been suggested. Although definitions differ in details, they generally refer to the capacities to live or grow, as well as to resist stress (reviewed by Dobbertin 2005). Importantly, the hypothetical 'optimal' plant vitality remains a theoretical concept: it can neither be measured directly nor predicted on the basis of other measurements. However, it is generally accepted that plants experiencing environmental stress differ in some characteristics from plants growing under optimal conditions, and these characteristics can therefore be considered as indices of vitality.

Plants' responses to environmental changes, including pollution, have been explored from the molecular to the community levels (Kozlowski 1980; Treshow & Anderson 1989; Sandermann 2004; Dobbertin 2005; DalCorso et al. 2008). Consequently, a number of vitality indices have been suggested (Waring 1987; Stolte et al. 1992; Schulz & Härtling 2003; Dobbertin 2005; Polak et al. 2006). Although molecular indicators may appear most suitable to detect plant responses to experimental manipulations (DalCorso et al. 2008; Nesatyy & Suter 2008), they are difficult to use for predicting responses of plant organisms to chronic pollution impacts. Moreover, the use of molecular and biochemical methods in field assessment programs is limited by a shortage of qualified workers and generally high costs (Dobbertin 2005). Therefore, we restricted our study to several cost-effective methods that allow for evaluation of processes reflecting the accumulation of plant biomass, i.e., plant growth.

Changes in primary productivity are seen as one of the very basic responses of ecosystems to various disturbances (Odum 1985; Rapport et al. 1985; Sigal & Suter 1987). Since growth and biomass accumulation critically depend on photosynthesis, we have chosen the efficiency of photosynthetic system II as the first index of plant vitality. Further on, we measured the size of the photosynthetic organs (leaves in deciduous plants and needle in conifers) and plant growth in terms of shoot length and radial increment. Finally, we assessed needle longevity in conifers, since premature

shedding of foliage may have adverse affects on both forest products and forest services (Smith 1992). The selected characteristics reflect different aspects of biomass accumulation, and their combination is indicative of plant productivity (Sigal & Suter 1987).

4.1.2   Indices of Plant Vitality Used in Our Study

4.1.2.1   Chlorophyll Fluorescence

Although the processes resulting in chlorophyll fluorescence are complicated, the principle underlying fluorescence analysis is relatively straightforward. Light energy absorbed by chlorophyll molecules can be used for photosynthesis, dissipated as heat, or re-emitted as light; the latter process is called chlorophyll fluorescence. Since fluorescence reflects the primary processes of photosynthesis, it can be used to obtain information on changes in the efficiency of the photochemical reaction in photosystem II (Krause & Weis 1988; Maxwell & Johnson 2000).

Many environmental stressors directly or indirectly affect the function of photosystem II (Öquist 1987). Therefore, chlorophyll fluorescence is a frequently used index in the assessment of plant stress (Daley 1995; Nesterenko et al. 2007), including stress imposed by pollution (Adams et al. 1989; Snel et al. 1991; Saarinen 1993; Kitao et al. 1997; Odasz-Albrigtsen et al. 2000; Zvereva & Kozlov 2005). However, chlorophyll fluorescence is influenced by numerous factors in a complex manner, and therefore, an exact interpretation of the observed phenomena is often difficult (Krause & Weis 1988; Snel et al. 1991; Maxwell & Johnson 2000).

4.1.2.2   Leaf/Needle Size and Shoot Length

Retarded growth and decreased leaf area are commonly considered as general and well-known plant responses to industrial emissions, including sulphur dioxide, fluorine and heavy metals (National Research Council of Canada 1939; Scurfield 1960a, b; Odum 1985; Treshow & Anderson 1989; Armentano & Bennett 1992; Dobbertin 2005). Although 'positive' effects of these pollutants have also been documented (Bennett et al. 1974; Lechowicz 1987; Zvereva et al. 1997a; Zvereva & Kozlov 2001; Kozlov & Zvereva 2007b), a meta-analysis of published data demonstrated significant decreases in leaf/needle size and weight, shoot length, root growth and radial increment with pollution, while leaf number and shoot weight were not affected (Roitto & Kozlov 2007; Roitto et al. 2009). At the same time, another data set on herbaceous plants revealed a decrease in plant size near industrial polluters, but detected no effects on aboveground biomass due to an increase in the number of leaves and flowers/inflorescences (Kozlov & Zvereva 2007b). The diversity of responses, as well as discrepancies

between outcomes of the meta-analyses of published and original data, give special importance to further investigation of plant growth responses to industrial pollution, and especially to identification of the factors affecting the direction and magnitude of the effects.

4.1.2.3 Radial Increment

Adverse effects of pollution on the radial growth of trees were documented long ago (National Research Council of Canada 1939), and in the middle of the twentieth century, measurements of tree rings were routinely used to estimate economic losses of foresters due to pollution (Treshow 1984). Therefore, we did not intend to measure radial increments of woody plants when designing our project. However, evaluation of the published data demonstrated that the results of many dendrochronological studies are not suitable for meta-analysis. Although the published evidence, such as the abrupt decline in the width of annual rings during the first years of a polluter's operation (Bunce 1979; Fox et al. 1986; Nöjd & Reams 1996; Kobayashi et al. 1997; Long & Davis 1999), is quite impressive, the data generally do not allow for calculation of ESs in the same manner as for other variables used in our analyses. This is mostly due to reporting of plot-specific means only (usually in a graphical form) and frequent use of temporal control, i.e., growth of the same stand(s) prior to the beginning of pollution impact, instead of spatial control, i.e., growth of another stand(s) outside the polluted area. As the result, by the beginning of 2007, we had identified only 28 published data sets that were suitable for meta-analysis (Roitto & Kozlov 2007). This unexpected shortage of information forced us to measure the radial increment of Scots pine around some of our polluters.

4.1.2.4 Needle Longevity in Conifers

Most conifers are typical evergreens with long-living foliage. Every year about one class of the oldest needles shed at the end of the growing season is replaced by new needles in the spring of the following year. Longevity of needles is generally defined by the number of age classes simultaneously occurring on a plant, but sometimes it is corrected for the proportion of needle survival in different age classes (Lamppu 2002). The accumulated needle mass contains a considerable reserve of mobile nutrients, and prolonged needle longevity in conditions of low nutrient availability maximises nutrient use efficiency (Lamppu & Huttunen 2003, and references therein). Thus, needle longevity is often considered as an important ecophysiological trait related to both carbon and nutrient balances (Aerts 1995).

The effects of pollution on needle longevity have been known for decades (Treshow 1984; Kryuchkov & Makarova 1989), and a decrease in the number of needle age classes has often been suggested as one of the vitality indices for

bioindication of pollution impact on forests (Dässler 1976; Schubert 1985). However, since reductions in needle longevity can be caused by other stressors (including diseases, climate, and soil nutritional quality), this measure can serve an indicator of air pollution stress only when other factors leading to accelerated needle abscission are taken into account. The feasibility of the needle age structure as an objective and reliable vitality indicator for Scots pine was recently confirmed by Lamppu and Huttunen (2001). However, national and international monitoring programs addressing the health conditions of forest ecosystems in Europe and North America do not use this index, but instead visually estimate crown defoliation and discoloration (UN-ECE 2006).

4.1.3 Carbon Allocation and Allometric Relationships

Pollution may not only reduce carbon assimilation, but also alter carbon allocation within a plant (Waring 1987; Kozlowski & Pallardy 1996). Thus, the outcome of vitality analysis may change with the measured characteristic, and obtaining an adequate estimate of plant response to pollution requires simultaneous investigation of different vitality indices.

Waring (1987) ranked growth processes in the order of their decreasing importance for a tree as follows: foliage, root, bud, storage tissue, stem, defensive compounds, and reproductive growth. Although comparing responses of different growth processes to pollution seems a relatively easy task, to our knowledge this has not yet been performed except for our meta-analysis of published data (Roitto et al. 2009). Therefore, we specifically aimed to address resource partitioning effects by comparing pollution-induced changes in different vitality indices measured from the same individuals of woody plants.

4.2 Materials and Methods

4.2.1 Selection of Study Objects and Plant Individuals

To avoid object selection bias, we have chosen plant species for our measurements without *a priori* knowledge on their responses to pollution. The first criterion was plant abundance in the study area: we selected the most common species, including forest-forming trees and shrubs dominating field layer vegetation. The second criterion was the balance between plant taxa and life forms: whenever possible, we preferred to measure one coniferous and one deciduous tree species, instead of measuring two conifers or two deciduous plants. Similarly, we attempted to keep a balance between top-canopy plants (trees and large shrubs) and field layer vegetation

(dwarf shrubs), and to measure both evergreen and deciduous species. Third, to allow for comparisons among polluters, we preferred species that were studied around other polluters. As a result, our samples included four species of Gymnosperms and 39 species of Angiosperms, among which were 17 species of deciduous trees and large shrubs, six species of dwarf shrubs, and 16 species of herbs. The largest numbers of measurements were obtained from Scots pine, cowberry (*Vaccinium vitis-idaea*) and white/mountain birch (around 12, 11 and 10 of 18 polluters, respectively).

The five sampled trees or shrubs were the first mature individuals with accessible foliage found at the study site. In practice, we chose trees that were closest to the centres of the selected study sites. For small (dwarf) shrubs,[1] we selected ramets growing at least 5 m apart (usually 10–15 m apart) to minimise the probability that two or more of the sampled ramets belonged to the same plant individual. For abundant herbs, we sampled ten individuals that were growing nearest to points located 2 m apart along a line crossing the study site. For all plants, we disregarded individuals bearing signs of severe damage not attributable to pollution impact (broken main stem, intensive browsing, etc.).

From plant individuals selected for chlorophyll fluorescence measurements, we always collected information on growth (both leaf/needle size and shoot length) and needle longevity (from Scots pine only), as well as samples for measurements of fluctuating asymmetry (see below, Chapter 5). All measurements performed in woody plants refer to vegetative shoots. Radial increment was explored in other individuals of Scots pines than were used for measurements of chlorophyll fluorescence, needle size and shoot growth.

4.2.2   Chlorophyll Fluorescence

In each impact zone, we measured chlorophyll fluorescence in two or three species of woody plants. All measurements were conducted during the second half of the growth season, when growth of shoots and leaves had already terminated. As a rule, all measurements around the polluter were performed on the same day; the order of plots was randomised whenever possible.

Prior to the beginning of the project, we demonstrated that measurements conducted with freshly detached leaves (not later than 20 min after sampling) yield the same results as measurements conducted on intact leaves. Therefore, all measurements were conducted by using detached leaves/needles, three leaves (or

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[1] Dwarf shrubs, or chamaephytes in the Raunkiaer's classification of life forms, are woody plants with perennating buds borne close to the ground, no more than 25 cm above soil surface. Within this book, dwarf shrubs are restricted to *Vaccinium* and *Empetrum* species, which form substantial part of field layer vegetation in boreal forests.

groups of needle fascicles) per individual. For trees and large shrubs, we took leaves/needles from different sides of the crown at a height of 1–3 m. In small shrubs, we sampled leaves from shoots located at approximately one half of the ramet's height.

In birches, which possess two distinct types of vegetative shoots (Fig. 5.1), we sampled short-shoot leaves; in other deciduous trees shoot length varied continuously, and therefore leaves were selected from a random sample of shoots irrespective of shoot length. We always collected the largest leaf from the selected shoot. In Scots pine, we collected current-year needles from the terminal shoot of the first-order branches (Fig. 5.3).

A lightweight leaf cuvette assuring dark adaptation was placed on the collected leaves/needles at the time of sampling, and samples were placed into a plastic box to minimise desiccation. Within 15–20 min after sampling (an amount of time sufficient for dark adaptation), chlorophyll fluorescence was measured using a portable fluorometer (Biomonitor S.C.I. AB, Umeå, Sweden) with a light level of 200 μmol photons/m²×s. The indices measured were the ratio of variable to maximum fluorescence yielded under the artificial light treatment (F_v/F_m) and the time needed for the leaf to reach half of its F_m ($T_{1/2}$). In total, we obtained approximately 5,700 measurements of each of two indices from 13 plant species in impact zones of 16 polluters.

4.2.3   Leaf/Needle Size and Shoot Length

Sampling of needles and leaves of woody plants followed the same protocol as described for measurements of chlorophyll fluorescence (Section 4.2.1). Leaf and needle size of woody plants were measured in the laboratory from dried and mounted samples prepared for fluctuating asymmetry analysis (Section 5.2.1). We measured (with a ruler, to the nearest 1 mm) the length of the leaf lamina (i.e., excluding petiole) of large-leaved plants and the length of the longest needle in each pair of Scots pine needles. In small-leaved plants (leaf length generally less than 10 mm), the length of the leaf lamina was measured using a dissecting micro-scope with an ocular scale (to the nearest 0.1 mm). Most samples were measured twice to minimise the probability of occasional errors. As a rule, we measured ten leaves and 20 needles from one individual of woody plants.

Shoot length of Norway spruce was also measured in the laboratory from dried and mounted samples of annual whorls prepared for fluctuating asymmetry analysis (Section 5.2.1). In these samples, we measured (with a ruler, to the nearest 1 mm) the length of an apical shoot (Fig. 5.2a), i.e., the annual increment of the first-order branch. Shoot length of other trees and dwarf shrubs (long shoots in birches, Fig. 5.1) was measured either in the field or in the laboratory from field-collected branches. As a rule, we measured ten shoots from one individual of woody plants.

In contrast to woody plants, herbaceous plants were sampled only from the two most and two least polluted sites. The samples were transported to the laboratory,

where we measured (with a ruler) the length of the longest leaf (except for grasses) and plant height, which was presumed to be equivalent to the length of the annual shoot in woody plants. Accuracy of measurements was 1 mm for values not exceeding 100 mm and 5 mm for larger values.

4.2.4 Radial Increment

Radial increment was measured at the two most and two least polluted sites, in contrast to all other measurements of woody plants that were performed at ten study sites. At each site we selected five Scots pine trees of the dominant size class, avoiding trees that were too close to their neighbours (less than half of the stand-specific value), and cored these at a height of 1.3 m by using a standard increment borer. An approximate tree age was estimated immediately after coring. This information allowed us to modify the sampling scheme whenever necessary in order to sample trees of about the same age from both polluted and unpolluted sites.

In the laboratory, annual rings were counted under a dissecting microscope, and the total width of rings formed during the past 10 years (excluding the year of sampling) was measured to the nearest 0.2 mm. Analysis was always based on three trees per study site, selected on the basis of their age in such a way that between-site variation in age was kept to a minimum. ANCOVA with tree age as a covariate was used to distinguish between-site variation from age effects. However, none of the analyses detected a significant effect of tree age (data not shown), and therefore ANOVA was used in the final analyses. Hedge's d was calculated on the basis of site-specific means.

4.2.5 Needle Longevity in Conifers

Foliage longevity in many conifer species can be measured by counting nodes on branches back from the branch tip to the oldest whorl, with each node separating an annual whorl of needles or needle fascicles corresponding to 1 year of growth. Several methods have been developed, accounting in particular for needle loss in each age class; needle losses were either reported by age class (Choi et al. 2006) or combined into a composite index called mean longevity (Lamppu 2002). However, accurate estimation of mean longevity is laborious and may appear somewhat subjective due to visual estimation of the proportion of needle loss. Therefore, we used the maximum longevity, i.e., the age (in years) of the oldest green needle recorded in a sampling branch.

Estimations of the maximum needle age within each pollution gradient were performed by the same observer (either V.E.Z. or M.V.K.). They were conducted

in mature (aged 20 years or more) trees, on two first-order branches selected from opposite sides of the crown of each tree at a height of 0.5–2.5 m. We surveyed ten trees per site; tree-specific values (averaged from measurements of two branches) were used to explore between-plot variation, while correlation analysis was based on plot-specific means. Lower needle longevity was considered a sign of decreased vitality.

4.2.6   Identification of Traits Associated with Sensitivity

We compared individual ESs between species, and compared species-specific mean ESs between Raunkiaer life forms (classification follows Hill et al. 2004). We also correlated species-specific mean ESs with axis scores for the 'competitor', 'stress tolerator' and 'ruderal' components for each species according to Grime's CSR strategy (Grime 1979; data extracted from the Modular Analysis of Vegetation Information System 'MAVIS' package http://www.ceh.ac.uk/products/software/CEHSoftware-MAVIS.htm) and with Ellenberg's scores for habitat requirements (light, temperature, continentality, humidity, pH and nitrogen; data extracted from Ellenberg et al. 1992).

4.3   Results

4.3.1   Chlorophyll Fluorescence

Two indices reflecting chlorophyll fluorescence, F_v/F_m and $T_{1/2}$, responded differently to pollution (correlation between ESs calculated for these indices: $r = 0.09$, $N = 39$ data sets, $P = 0.61$), confirming that their separate analysis was not redundant.

Variation in both indices between study sites was generally significant (32 of 39 tests for F_v/F_m and 31 of 39 tests for $T_{1/2}$); however, only 22 of 156 correlation coefficients (with both distance and pollution load) were significant (Tables 4.1–4.17).

To explore the repeatability of the results, we conducted measurements on the same set of individuals of mountain birch in the impact zone of the Monchegorsk smelter over a period of 4 years (Table 4.1). Repeated measures ANOVA demonstrated a large ($P < 0.0001$) interaction for both F_v/F_m and $T_{1/2}$ between study sites and study years, indicating that the relationship between chlorophyll fluorescence parameters and pollution varied between study years. The latter result was also evident from correlation analysis: even the signs of correlations between chlorophyll fluorescence parameters and distance from the smelter (or pollution load) changed with the study year (Table 4.1). Consequently, the average correlation

Table 4.1 Repeated chlorophyll fluorescence measurements of the same set of mountain birch (*Betula pubescens*) individuals in the impact zone of the nickel-copper smelter at Monchegorsk, Russia

Site	F_v/F_m				$T_{1/2}$, ms			
	2002	2005	2006	2007	2002	2005	2006	2007
1–1	0.410	0.702	0.706	0.745	262	383	506	475
1–2	0.504	0.640	0.486	0.732	351	574	382	418
1–4	0.520	0.713	0.450	0.722	431	499	468	418
1–5	0.523	0.712	0.604	0.590	270	449	412	541
2–2	0.480	0.697	0.455	0.687	285	446	451	495
2–4	0.533	0.673	0.583	0.741	338	551	492	483
2–6	0.572	0.606	0.748	0.691	399	460	500	489
2–8	0.576	0.758	0.773	0.682	356	466	377	420
2–9	0.657	0.767	0.672	0.644	307	316	369	418
2–10	0.629	0.714	0.742	0.690	366	419	339	383
ANOVA: *F*/*P*	4.46/0.0005	5.27/<0.0001	16.1/<0.0001	2.75/0.01	2.54/0.02	4.58/0.0003	2.86/0.01	3.93/0.0012
Dist.: *r*/*P*	0.94/<0.0001	0.38/0.28	0.44/0.21	−0.55/0.10	0.41/0.23	−0.24/0.50	−0.64/0.04	−0.41/0.24
Poll.: *r*/*P*	−0.63/0.05	−0.42/0.23	−0.34/0.34	0.54/0.10	−0.34/0.34	0.31/0.38	0.63/0.05	0.45/0.19

Decreases in F_v/F_m and increases in $T_{1/2}$ indicate lower vitality of plants. ANOVA: test for significance of variation between study sites. Dist.: Pearson linear correlation between site-specific means and log-transformed distance from polluter. Poll.: Pearson linear correlation between site-specific means and concentration of the selected pollutant. Long dash indicates: for woody plants - species not found in study site; for herbaceous plants - site not included in the sampling scheme.

Table 4.2 Chlorophyll fluorescence measurements in the impact zone of the power plant at Apatity, Russia

Site	*Alnus incana*		*Betula pubescens*	
	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.661	317	0.687	345
1–2	0.581	345	0.658	290
1–3	0.676	347	0.637	315
1–4	0.634	310	0.602	308
1–5	0.674	323	0.550	311
2–1	0.678	303	0.642	249
2–2	0.641	324	0.647	287
2–3	0.654	363	0.686	231
2–4	0.644	274	0.657	309
2–5	0.713	278	0.611	402
ANOVA: *F/P*	1.95/0.07	1.27/0.28	1.77/0.11	2.43/0.03
Dist.: *r/P*	0.19/0.60	−0.16/0.67	−0.70/0.02	0.20/0.58
Poll.: *r/P*	−0.55/0.10	0.58/0.07	0.67/0.03	−0.37/0.29

Measurements conducted on 30.7.2006. For other explanations, consult Table 4.1.

Table 4.3 Chlorophyll fluorescence measurements in the impact zone of aluminium smelter at Bratsk, Russia

Site	*Betula pubescens*		*Larix sibirica*		*Pinus sylvestris*	
	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.742	306	0.754	118	0.673	181
1–2	0.742	286	0.757	101	0.727	180
1–3	0.698	345	0.736	99	0.676	155
1–4	0.679	245	0.655	111	0.492	133
1–5	0.609	246	0.649	98	0.472	163
2–1	0.671	337	0.642	91	0.612	181
2–2	0.700	272	0.698	94	0.545	129
2–3	0.654	288	0.687	90	0.589	137
2–4	0.701	250	0.730	90	0.642	137
2–5	0.553	240	0.730	221	0.580	145
ANOVA: *F/P*	4.47/0.0004	2.16/0.05	11.6/<0.0001	1.13/0.37	25.7/<0.0001	9.97/<0.0001
Dist.: *r/P*	−0.72/0.02	−0.66/0.04	−0.17/0.63	0.40/0.25	−0.49/0.15	−0.51/0.13
Poll.: *r/P*	0.21/0.55	0.63/0.05	−0.30/0.40	−0.21/0.56	0.23/0.52	0.62/0.05

Measurements conducted on 2–4.8.2002. For other explanations, consult Table 4.1.

between plot-specific values obtained in different years did not differ from zero for either F_v/F_m (for methods of calculation, consult Section 2.5.2.4; $z_r = 0.10$, CI = −0.19…0.39, $N = 6$) or $T_{1/2}$ ($z_r = 0.13$, CI = −0.21…0.42, $N = 6$).

Table 4.4 Chlorophyll fluorescence measurements in the impact zone of the nickel-copper smelter at Harjavalta, Finland

Site	Betula pubescens		Pinus sylvestris		Salix caprea	
	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.710	342	0.479	142	0.742	224
1–2	0.636	484	0.489	157	0.647	255
1–3	0.666	326	–	–	0.674	317
1–4	0.643	192	0.527	253	0.647	254
1–5	0.704	289	0.524	245	0.748	217
2–1	0.756	213	0.594	123	0.774	186
2–2	0.701	339	0.537	108	0.674	173
2–3	0.782	236	0.518	95	0.694	211
2–4	0.742	241	0.609	129	0.663	265
2–5	0.684	210	0.516	143	0.694	227
ANOVA: *F/P*	5.60/<0.0001	5.75/<0.0001	2.56/0.03	5.07/0.0004	1.79/0.10	7.15/<0.0001
Dist.: *r/P*	−0.17/0.65	−0.41/0.24	0.03/0.94	0.57/0.11	−0.08/0.84	0.28/0.43
Poll.: *r/P*	−0.35/0.32	0.83/0.0029	−0.45/0.23	−0.18/0.65	−0.23/0.52	−0.02/0.95

Measurements conducted on 25.8.2002. Missing values resulted from absence of the selected plant species in some of study sites. For other explanations, consult Table 4.1.

Table 4.5 Chlorophyll fluorescence measurements in the impact zone of the fertiliser factory at Jonava, Lithuania

Site	Betula pendula		Pinus sylvestris	
	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.620	334	0.558	262
1–2	0.739	348	0.706	179
1–3	0.686	295	0.660	178
1–4	0.761	261	0.571	164
1–5	0.712	306	0.630	205
2–1	0.710	369	0.647	169
2–2	0.723	330	0.635	182
2–3	0.771	240	0.688	168
2–4	0.715	328	0.737	193
2–5	0.777	274	0.740	195
ANOVA: *F/P*	4.45/0.0004	3.18/0.0055	7.73/<0.0001	6.11/<0.0001
Dist.: *r/P*	0.50/0.14	−0.68/0.03	0.32/0.37	−0.18/0.63
Poll.: *r/P*	−0.47/0.17	0.34/0.33	−0.06/0.87	0.41/0.24

Measurements conducted on 3–5.9.2008. For other explanations, consult Table 4.1.

Pollution had no overall effect on F_v/F_m (Fig. 4.1) but caused a small increase in $T_{1/2}$ which is indicative of decreased efficiency of the photosynthetic system (Fig. 4.4). This result did not depend on the method used to calculate ES (F_v/F_m: $Q_B = 0.23$,

Table 4.6 Chlorophyll fluorescence measurements in the impact zone of the aluminium smelter at Kandalaksha, Russia

Site	Betula pubescens		Pinus sylvestris		Salix caprea	
	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.775	302	0.658	153	0.757	287
1–2	0.717	255	0.567	128	0.597	286
1–3	0.768	321	0.739	269	0.739	373
1–4	0.727	267	0.633	149	0.632	287
1–5	0.663	306	0.674	168	0.764	362
2–1	0.734	354	0.643	176	0.658	374
2–2	0.722	400	0.626	157	0.711	400
2–3	0.742	271	0.672	141	0.785	275
2–4	0.803	262	0.739	161	0.735	409
2–5	0.784	273	0.746	169	0.748	331
ANOVA: *F/P*	3.61/0.0023	2.63/0.02	11.3/<0.0001	2.37/0.03	8.54/<0.0001	7.21/<0.0001
Dist.: *r/P*	0.00/0.99	−0.50/0.14	0.52/0.13	0.06/0.86	0.33/0.35	−0.01/0.98
Poll.: *r/P*	−0.20/0.59	0.43/0.22	−0.70/0.03	−0.12/0.75	−0.57/0.09	−0.08/0.83

Measurements conducted on 16−17.7.2002. For other explanations, consult Table 4.1.

Table 4.7 Chlorophyll fluorescence measurements in the impact zone of the copper smelter at Karabash, Russia

Site	Betula pendula		Pinus sylvestris	
	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.580	382	–	–
1–2	0.628	378	0.697	187
1–3	0.705	303	0.720	193
1–4	0.742	231	0.669	179
1–5	0.624	292	0.432	315
2–1	0.695	373	–	–
2–2	0.610	458	0.616	229
2–3	0.651	377	0.708	188
2–4	0.737	372	0.714	184
2–5	0.784	237	0.786	194
ANOVA: *F/P*	6.83/<0.0001	4.54/0.0004	21.7/<0.0001	2.12/0.07
Dist.: *r/P*	0.61/0.06	−0.72/0.02	−0.04/0.92	0.18/0.67
Poll.: *r/P*	−0.42/0.23	0.57/0.08	−0.09/0.84	0.04/0.92

Measurements conducted on 23−25.7.2003. Missing values resulted from absence of the selected plant species in some of study sites. For other explanations, consult Table 4.1.

df = 2, $P = 0.89$; $T_{1/2}$: $Q_B = 0.58$, df = 2, $P = 0.75$). Individual polluters did not differ in their effects on $T_{1/2}$ (Fig. 4.5; $Q_B = 16.7$, df = 15, $P = 0.43$). However, variation in F_v/F_m response was significant (Fig. 4.2; $Q_B = 33.4$, df = 15, $P = 0.04$). The latter

Table 4.8 Chlorophyll fluorescence measurements in the impact zone of the iron pellet plant at Kostomuksha, Russia

Site	Betula pubescens		Pinus sylvestris		Salix caprea	
	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.649	184	0.583	115	0.718	259
1–2	0.725	265	0.726	175	0.721	291
1–3	0.743	285	0.648	150	0.683	328
1–4	0.749	313	0.687	190	0.719	304
1–5	0.764	291	0.743	173	0.726	345
2–1	0.751	284	0.745	163	0.713	307
2–2	0.698	254	0.485	130	0.560	241
2–3	0.723	244	0.500	138	0.586	346
2–4	0.647	265	0.548	127	0.634	252
2–5	0.656	334	0.528	124	0.651	295
ANOVA: *F/P*	3.77/0.0017	4.09/0.0009	8.94/<0.0001	7.34/<0.0001	2.43/0.03	2.06/0.06
Dist.: *r/P*	0.02/0.95	0.61/0.06	−0.07/0.85	0.18/0.63	−0.04/0.91	0.32/0.36
Poll.: *r/P*	0.27/0.44	−0.13/0.72	0.37/0.29	0.15/0.68	0.22/0.53	−0.09/0.80

Measurements conducted on 18.7.2002. For other explanations, consult Table 4.1.

Table 4.9 Chlorophyll fluorescence measurements in the impact zone of the copper smelter at Krompachy, Slovakia

Site	Fagus sylvatica		Pinus sylvestris	
	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.682	306	0.668	229
1–2	0.718	273	0.530	194
1–3	0.784	226	0.597	169
1–4	0.749	272	0.556	171
1–5	0.797	191	0.716	206
2–1	0.683	388	0.500	228
2–2	0.771	265	0.567	175
2–3	0.778	276	0.628	191
2–4	0.751	254	0.742	174
2–5	0.720	185	0.512	150
ANOVA: *F/P*	3.31/0.0042	4.50/0.0004	13.4/<0.0001	4.65/0.0003
Dist.: *r/P*	0.50/0.14	−0.78/0.0080	0.03/0.94	−0.66/0.04
Poll.: *r/P*	−0.49/0.15	0.69/0.03	−0.29/0.42	0.77/0.01

Measurements conducted on 2–4.9.2002. For other explanations, consult Table 4.1.

index decreased near six polluters, increased near five polluters, and showed no change around five polluters (Fig. 4.2).

The effect of pollution on chlorophyll fluorescence did not depend on either the type of the polluter (F_v/F_m: Fig. 4.1; $Q_B = 2.99$, df = 4, $P = 0.56$; $T_{1/2}$: Fig. 4.4;

Table 4.10 Chlorophyll fluorescence measurements in the impact zone of the nickel-copper smelter at Monchegorsk, Russia

	Pinus sylvestris		*Salix caprea*	
Site	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.484	163	0.574	435
1–2	0.476	182	0.522	441
1–4	0.529	177	0.521	388
1–5	0.591	179	0.577	356
2–2	0.474	182	0.511	431
2–4	0.532	185	0.588	431
2–6	0.597	180	0.579	375
2–8	0.663	245	0.575	333
2–9	0.588	158	0.521	423
2–10	0.499	202	0.498	452
ANOVA: *F/P*	5.56/<0.0001	3.55/0.0027	1.29/0.27	1.94/0.07
Dist.: *r/P*	0.63/0.05	0.42/0.23	−0.19/0.60	−0.35/0.32
Poll.: *r/P*	−0.51/0.13	−0.21/0.56	0.23/0.51	0.42/0.23

Measurements conducted on 14.8.2002. For data on *Betula pubescens* consult Table 4.1. For other explanations, consult Table 4.1.

Table 4.11 Chlorophyll fluorescence measurements in the impact zone of the aluminium smelter at Nadvoitsy, Russia

	Betula pubescens		*Pinus sylvestris*	
Site	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.716	293	0.641	158
1–2	0.738	290	0.735	184
1–3	0.690	368	0.632	177
1–4	0.786	207	0.726	178
1–5	0.773	357	0.721	163
2–1	0.675	368	0.572	161
2–2	0.739	207	0.532	184
2–3	0.694	322	0.523	152
2–4	0.716	285	0.594	167
2–5	0.748	280	0.638	164
ANOVA: *F/P*	2.69/0.02	7.78/<0.0001	24.3/<0.0001	0.66/0.74
Dist.: *r/P*	0.61/0.06	−0.04/0.92	0.40/0.25	−0.01/0.97
Poll.: *r/P*	−0.42/0.23	0.05/0.92	−0.23/0.53	0.18/0.62

Measurements conducted on 25−27.7.2004. For other explanations, consult Table 4.1.

$Q_B = 1.08$, df = 4, $P = 0.90$) or it's impact on soil pH (F_v/F_m: Fig. 4.1; $Q_B = 2.70$, df = 2, $P = 0.26$; $T_{1/2}$: Fig. 4.4; $Q_B = 1.91$, df = 2, $P = 0.38$). The only source of variation identified in this database was the geographical position of polluters that affected the $T_{1/2}$ response to pollution (Fig. 4.4; $Q_B = 5.37$, df = 1, $P = 0.02$):

Table 4.12 Chlorophyll fluorescence measurements in the impact zone of the nickel-copper smelter at Nikel and ore-roasting plant at Zapolyarnyy, Russia

Site	Betula pubescens		Salix glauca	
	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.694	579	0.654	593
1–2	0.766	499	0.609	632
1–3	0.666	510	0.638	558
1–4	0.647	619	0.634	559
1–5	0.597	581	0.602	603
2–1	0.733	503	0.657	602
2–2	0.685	455	–	–
2–3	0.758	606	0.681	686
2–4	0.778	566	0.736	570
2–5	0.655	775	0.619	542
ANOVA: F/P	5.92/<0.0001	8.24/<0.0001	2.50/0.03	2.33/0.04
Dist.: r/P	−0.42/0.23	0.53/0.12	−0.15/0.71	−0.29/0.46
Poll.: r/P	0.19/0.59	−0.24/0.51	0.10/0.79	0.10/0.79

Measurements conducted on 17−18.7.2001. Missing values resulted from absence of the selected plant species in some of study sites. For other explanations, consult Table 4.1.

Table 4.13 Chlorophyll fluorescence measurements in the impact zone of the nickel-copper smelters at Norilsk, Russia

Site	Larix sibirica		Betula nana		Vaccinium uliginosum	
	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.582	160	0.635	275	0.646	363
1–2	0.536	122	0.607	349	0.600	405
1–3	0.509	130	0.493	335	0.620	398
1–4	0.551	128	0.659	299	0.599	443
1–5	0.631	172	0.688	312	0.634	411
2–1	0.355	46	0.568	243	0.596	235
2–2	0.687	139	0.687	176	0.597	315
2–3	0.573	73	0.635	230	0.623	283
2–4	0.588	154	0.581	300	0.556	339
2–5	0.713	189	0.695	272	0.673	265
ANOVA: F/P	16.5/<0.0001	8.36/<0.0001	6.60/<0.0001	7.06/<0.0001	1.09/0.39	10.4/<0.0001
Dist.: r/P	0.48/0.16	0.47/0.17	0.27/0.45	0.35/0.32	0.17/0.64	0.25/0.48
Poll.: r/P	−0.30/0.41	−0.25/0.49	−0.06/0.87	−0.39/0.27	0.10/0.78	−0.29/0.42

Measurements conducted on 23−28.8.2002. For other explanations, consult Table 4.1.

adverse effects (increase in the time needed for the leaf to reach half of its F_m) were significant only near the southern polluters. The pattern of F_v/F_m changes did not differ between the northern and southern polluters (Fig. 4.1; $Q_B = 2.76$, df = 1, $P = 0.10$).

Table 4.14 Chlorophyll fluorescence measurements in the impact zone of the copper smelter at Revda, Russia

	Betula pubescens		*Pinus sylvestris*	
Site	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.726	321	0.732	237
1–2	0.713	395	0.708	225
1–3	0.668	387	0.634	183
1–4	0.561	377	0.481	171
1–5	0.724	403	0.624	184
2–1	0.692	376	0.705	235
2–2	0.766	319	0.760	277
2–3	0.728	285	0.657	197
2–4	0.689	266	0.691	222
2–5	0.583	309	0.590	271
ANOVA: *F/P*	5.53/<0.0001	2.90/0.01	15.0/<0.0001	11.6/<0.0001
Dist.: *r/P*	−0.59/0.07	0.03/0.94	−0.75/0.01	−0.34/0.34
Poll.: *r/P*	0.54/0.11	−0.24/0.51	0.67/0.04	0.43/0.21

Measurements conducted on 19−21.7.2003. For other explanations, consult Table 4.1.

Table 4.15 Chlorophyll fluorescence measurements in the impact zone of the aluminium smelter at Straumsvík, Iceland

	Salix herbacea		*Vaccinium uliginosum*	
Site	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.660	296	0.639	423
1–2	0.651	319	0.620	379
1–3	0.612	352	0.577	430
1–4	0.584	329	0.587	373
1–5	0.664	281	0.666	320
2–1	0.663	312	0.607	398
2–2	0.620	383	0.646	391
2–3	0.626	323	0.653	354
2–4	0.638	350	0.599	337
2–5	0.670	338	0.710	282
ANOVA: *F/P*	1.40/0.22	1.07/0.40	3.71/0.0019	3.49/0.0029
Dist.: *r/P*	0.09/0.81	−0.09/0.81	0.45/0.19	−0.83/0.0030
Poll.: *r/P*	0.25/0.49	−0.31/0.38	0.01/0.98	0.52/0.13

Measurements conducted on 11−13.7.2002. For other explanations, consult Table 4.1.

We have not discovered any variation in the responses of photosystem II among plant species (F_v/F_m: Fig. 4.3; $Q_B = 3.79$, df = 6, $P = 0.71$; $T_{1/2}$: Fig. 4.6; $Q_B = 2.99$, df = 6, $P = 0.81$). Similarly, we found no differences between Gymnosperms and Angiosperms (F_v/F_m: $Q_B = 0.03$, df = 1, $P = 0.87$; $T_{1/2}$: $Q_B = 1.79$, df = 1, $P = 0.21$),

Table 4.16 Chlorophyll fluorescence measurements in the impact zone of the aluminium smelter at Volkhov, Russia

	Betula pubescens		*Salix caprea*	
Site	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.738	310	0.636	384
1–2	0.652	278	0.518	476
1–3	0.684	255	0.624	314
1–4	0.667	260	0.613	366
1–5	0.662	302	0.573	326
2–1	0.739	286	0.588	413
2–2	0.751	337	0.620	417
2–3	0.695	303	0.637	357
2–4	0.662	246	0.673	313
2–5	0.680	300	0.592	368
ANOVA: *F/P*	1.80/0.10	1.32/0.26	2.18/0.04	3.23/0.0050
Dist.: *r/P*	−0.70/0.02	−0.24/0.51	0.18/0.61	−0.59/0.07
Poll.: *r/P*	0.71/0.02	0.24/0.50	−0.10/0.77	0.42/0.22

Measurements conducted on 8−9.8.2002. For other explanations, consult Table 4.1.

Table 4.17 Chlorophyll fluorescence measurements in the impact zone of the aluminium smelter at Žiar nad Hronom, Slovakia

	Fagus sylvatica		*Carpinus betulus*		*Quercus petraea*	
Site	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms	F_v/F_m	$T_{1/2}$, ms
1–1	0.831	133	0.821	179	0.717	370
1–2	0.827	114	0.835	133	0.783	209
1–3	0.791	170	0.796	143	–	–
1–4	0.801	152	0.830	151	0.807	151
1–5	0.819	121	0.806	197	–	–
2–1	0.804	127	0.810	155	0.679	341
2–2	0.800	165	0.830	136	0.655	379
2–3	0.826	130	0.818	119	–	–
2–4	0.765	150	0.799	131	–	–
2–5	0.798	169	0.794	189	0.767	261
ANOVA: *F/P*	4.60/0.0003	7.07/<0.0001	5.81/<0.0001	3.42/0.0033	2.73/0.05	6.81/0.0007
Dist.: *r/P*	−0.48/0.16	0.42/0.22	−0.45/0.19	0.16/0.67	0.28/0.59	−0.38/0.46
Poll.: *r/P*	0.57/0.08	−0.41/0.24	0.40/0.25	0.16/0.66	0.06/0.91	0.21/0.69

Measurements conducted on 29.8−1.9.2003. Missing values resulted from absence of the selected plant species in some of study sites. For other explanations, consult Table 4.1.

as well as between deciduous and evergreen species (F_v/F_m: $Q_B = 0.05$, df = 1, $P = 0.80$; $T_{1/2}$: $Q_B = 0.13$, df = 1, $P = 0.73$).

We have detected significant non-linear responses in five of 78 data sets (four U-shaped and one dome-shaped, all for F_v/F_m).
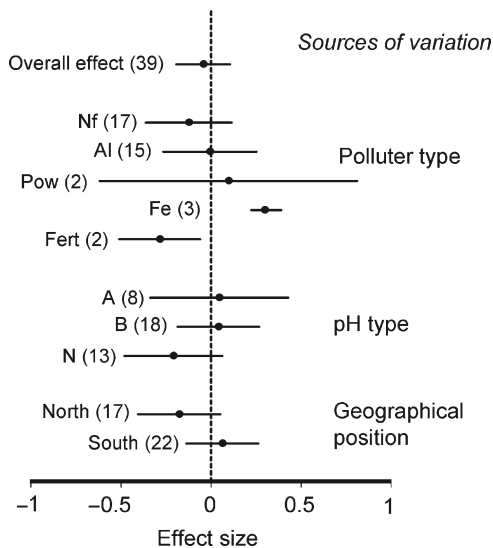
Fig. 4.1 Overall effect and sources of variation in the responses of the ratio of variable to maximum fluorescence yielded under the artificial light treatment (F_v/F_m). Decreases in F_v/F_m indicate lower plant vitality. Horizontal lines denote 95% confidence intervals; sample sizes are shown in brackets; an asterisk denotes significant ($P < 0.05$) between-class heterogeneity. For classifications of polluters and abbreviations, consult Table 2.1
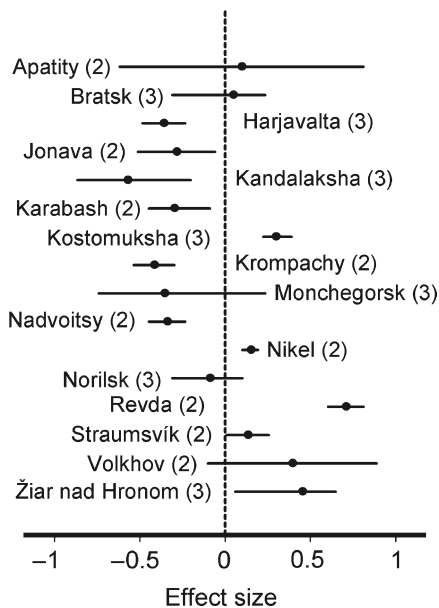

Fig. 4.2 Effects of individual polluters on the ratio of variable to maximum fluorescence yielded under the artificial light treatment (F_v/F_m). For explanations, consult Fig. 4.1
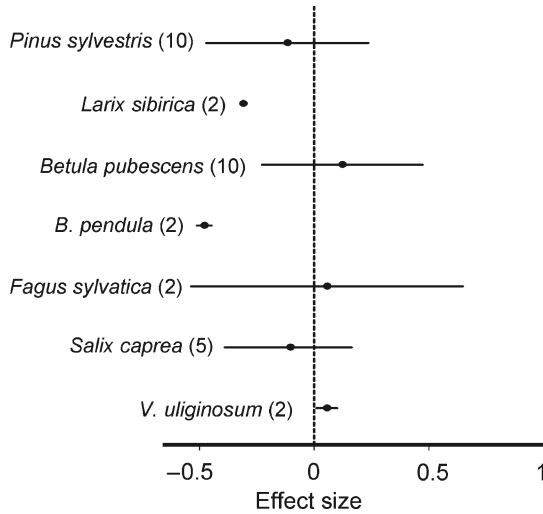
Fig. 4.3 Effects of point polluters on the ratio of variable to maximum fluorescence yielded under the artificial light treatment (F_v/F_m) in woody plant species. For explanations, consult Fig. 4.1
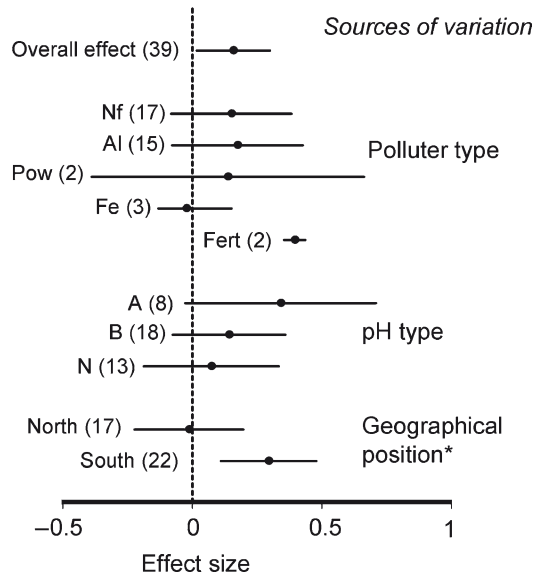

Fig. 4.4 Overall effect and sources of variation in the responses of the time needed for the leaf to reach half of its F_m ($T_{1/2}$). Increases in $T_{1/2}$ indicate lower plant vitality. For explanations, consult Fig. 4.1
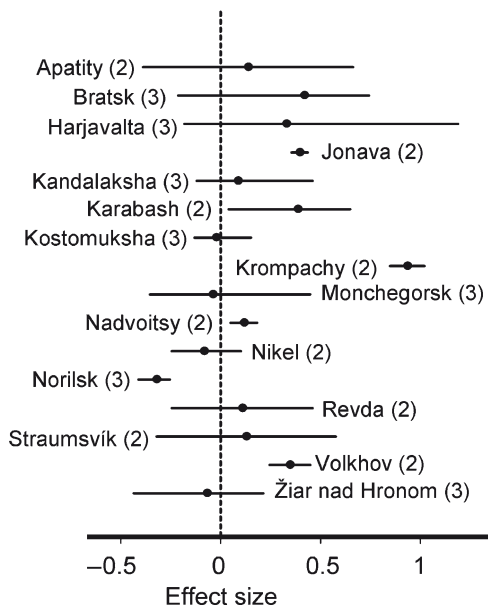
Fig. 4.5 Effects of individual polluters on the time needed for the leaf to reach half of its F_m ($T_{1/2}$). For explanations, consult Fig. 4.1
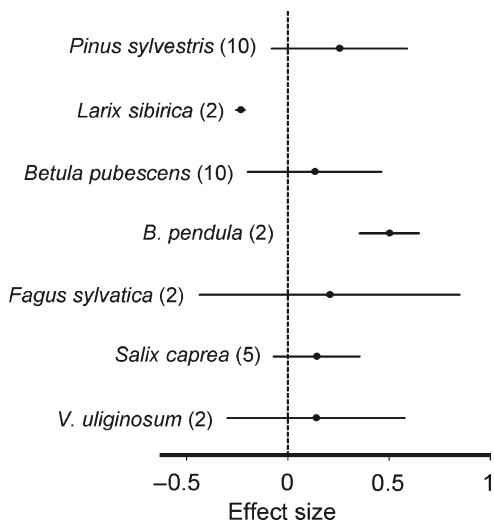

Fig. 4.6 Effects of point polluters on the time needed for the leaf of woody plant species to reach half of its F_m ($T_{1/2}$). For explanations, consult Fig. 4.1

4.3.2 Leaf/Needle Size

Variation in leaf/needle size between study sites was generally significant (60 of 90 data sets); however, only 23 of 146 correlation coefficients (with both distance and pollution load; calculated only for woody plants) were significant (Tables 4.18–4.35).

The magnitude of the pollution effect on the leaf size of woody plants did not depend on the method used to calculate ES ($Q_B = 0.50$, df = 2, $P = 0.78$). Therefore, the analyses of herbaceous plants, as well as of pooled data, are based on Hedge's d values because data on herbs were collected only from the most and least polluted study sites. However, in the analysis of woody plants we employed ESs based on correlations with pollution, in line with all other characteristics analysed in this book.

An overall pollution effect on the leaf/needle size did not differ from zero (Fig. 4.7). However, leaf size in Angiosperms significantly decreased with pollution (Fig. 4.7), although the difference between Angiosperms and Gymnosperms was not significant ($Q_B = 1.87$, df = 1, $P = 0.17$). Trees, dwarf shrubs, and herbs ($Q_B = 1.48$, df = 2, $P = 0.48$) as well as evergreen and deciduous woody plants ($Q_B = 0.50$, df = 1, $P = 0.48$) responded similarly to pollution (Fig. 4.7). We found no differences among plants belonging to four Raunkiaer life forms (phanerophytes, chamaephytes, non-bulbous geophytes and hemicriptophytes) ($Q_B = 2.79$, df = 3, $P = 0.26$).

Effect size (averaged by plant species) positively correlated with the Ellenberg's indicator value for light ($r_S = 0.36$, $N = 28$ species, $P = 0.06$), but did not correlate with indicator values for temperature, continentality, humidity, pH and nitrogen ($r_S = 0.09…0.33$, $N = 15–24$ species, $P = 0.11…0.74$). Similarly, we found no correlation with axis scores for Grime's CSR strategy ($r_S = −0.28…0.19$, $N = 13$ species, $P = 0.35…0.54$).

Table 4.18 Leaf size (L, mm) and shoot length (S, mm) of woody plants in the impact zone of the power plant at Apatity, Russia

Site	Alnus incana		Betula pubescens		Vaccinium vitis-idaea	
	L (1997)	S (2006)	L (2006)	S (2006)	L (2006)	S (2006)
1–1	62.4	105.1	54.7	99.1	–	–
1–2	64.6	87.6	47.8	84.0	26.0	58.4
1–3	56.5	74.3	45.0	102.3	22.5	43.4
1–4	55.7	86.6	42.0	68.9	23.3	55.8
1–5	58.1	93.7	43.9	70.1	24.5	62.4
2–1	60.0	76.3	52.7	92.9	20.6	48.6
2–2	50.2	118.1	50.6	113.5	25.0	58.2
2–3	61.5	162.3	48.6	106.5	24.8	49.9
2–4	57.2	74.5	41.9	87.6	23.3	53.1
2–5	56.9	78.1	47.8	52.1	24.7	44.1
ANOVA: *F/P*	1.75/0.11	0.98/0.47	2.55/0.02	2.30/0.03	3.87/0.0022	6.55/<0.0001
Dist.: *r/P*	−0.41/0.24	−0.12/0.73	−0.85/0.0018	−0.56/0.09	0.30/0.43	0.10/0.79
Poll.: *r/P*	0.36/0.31	0.30/0.39	0.66/0.04	0.71/0.02	0.18/0.64	0.15/0.69

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Table 4.19 Leaf/needle size (L, mm) and shoot length (S, mm) of woody plants in the impact zone of the aluminium smelter at Bratsk, Russia

Site	Betula pubescens		Larix sibirica	Picea abies	Pinus sylvestris		Vaccinium vitis-idaea	
	L (2002)	S (2002)	S (2002)	S (2004)	L (2002)	S (2002)	L (2002)	S (2002)
1–1	52.4	99.6	50.8	46.2	48.9	36.4	17.3	35.8
1–2	57.2	121.0	68.5	30.7	40.5	23.9	17.7	38.4
1–3	53.4	113.6	56.5	51.8	40.7	29.2	17.4	32.8
1–4	51.3	110.0	64.5	58.5	54.5	26.8	18.4	30.4
1–5	53.6	100.8	67.9	47.9	52.2	38.2	17.9	40.3
2–1	45.1	91.2	47.1	53.0	55.8	58.2	16.5	27.7
2–2	53.4	93.4	53.7	42.1	40.4	23.1	18.3	34.7
2–3	46.0	94.2	60.4	53.2	43.0	36.0	18.2	29.9
2–4	50.4	99.5	54.8	38.0	46.5	38.6	19.5	40.6
2–5	46.4	68.6	53.6	83.8	49.4	27.6	19.5	29.6
ANOVA: *F/P*	1.88/0.08	1.01/0.45	1.84/0.09	3.11/0.0079	3.99/0.0013	4.72/0.0003	0.75/0.66	2.17/0.05
Dist.: *r/P*	−0.16/0.65	−0.24/0.51	0.43/0.22	0.49/0.15	0.18/0.61	−0.21/0.56	0.70/0.03	0.10/0.78
Poll.: *n/P*	−0.36/0.31	−0.09/0.81	−0.57/0.09	−0.07/0.84	0.43/0.22	0.76/0.01	−0.72/0.02	−0.40/0.25

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Table 4.20 Leaf/needle size (L, mm), shoot length (S, mm) of woody plants and height (H, mm) of herbaceous plants in the impact zone of the nickel-copper smelter at Harjavalta, Finland

Site	Achillea millefolium		Betula pubescens		Picea abies	Pinus sylvestris		Salix caprea				Vaccinium vitis-idaea	
	L (2007)	H (2007)	L (2002)	S (2002)	S (2001)	L (2002)	S (2002)	S (1997)	S (1998)	L (2002)	S (2002)	L (2002)	S (2002)
1–1	169	526	44.9	77.7	–	40.8	50.7	144.7	71.9	84.3	86.9	–	–
1–2	237	638	40.7	134.4	–	51.4	65.4	191.7	79.6	77.8	94.6	19.3	30.2
1–3	–	–	40.7	105.1	78.2	–	–	184.5	118.7	73.8	97.9	19.3	32.5
1–4	–	–	46.3	96.8	70.8	61.2	220.2	196.1	81.1	86.1	68.0	21.8	46.8
1–5	125	499	41.4	102.6	55.2	42.7	113.4	72.7	49.3	71.0	61.8	22.8	55.8
2–1	–	–	40.2	110.7	–	49.4	98.6	279.2	125.0	80.3	56.3	–	–
2–2	–	–	36.2	90.4	63.4	42.0	86.1	144.8	126.8	74.3	75.5	–	–
2–3	–	–	43.0	126.2	65.5	52.0	67.8	142.0	76.2	68.6	69.6	20.2	32.6
2–4	102	461	39.9	142.1	70.4	42.1	42.3	146.9	60.1	74.1	48.3	18.9	47.3
2–5	–	–	–	123.4	67.4	34.3	96.9	84.9	58.2	72.3	85.6	–	–
ANOVA: F/P	6.41/0.0014	3.22/0.03	2.00/0.07	1.20/0.32	0.85/0.54	3.43/0.0061	6.84/<0.0001	1.70/0.13	2.24/0.04	1.74/0.11	2.11/0.05	2.37/0.07	8.33/0.0001
Dist.: r/P	–	–	0.23/0.55	0.21/0.57	–0.29/0.53	–0.28/0.46	0.31/0.42	–0.70/0.02	–0.69/0.03	–0.38/0.28	–0.17/0.63	0.70/0.12	0.94/0.0053
Poll.: r/P	–	–	–0.11/0.78	0.17/0.64	–0.12/0.80	0.23/0.56	–0.31/0.41	0.31/0.39	0.11/0.77	0.24/0.50	0.45/0.20	–0.37/0.47	–0.58/0.23

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Table 4.21 Leaf/needle size (L, mm) and shoot length (S, mm) of plants in the impact zone of the fertiliser factory at Jonava, Lithuania

Site	Betula pendula		Fragaria vesca	Frangula alnus		Picea abies	Pinus sylvestris		Quercus robur	
	L (2005)	S (2005)	L (2007)	L (2007)	S (2007)	S (2005)	L (2005)	S (2005)	L (2007)	S (2007)
1–1	49.3	95.0	33.9	–	–	–	55.9	53.1	112.1	25.1
1–2	64.4	121.6	–	74.3	69.1	79.1	61.3	86.1	119.1	36.2
1–3	50.7	93.2	–	72.9	65.9	71.8	59.5	113.5	114.2	28.2
1–4	60.7	115.1	–	71.6	62.4	78.7	62.1	46.1	128.9	28.7
1–5	61.3	138.9	44.0	75.7	62.3	58.2	58.7	42.1	105.6	33.6
2–1	55.4	134.7	46.3	81.2	127.8	–	58.2	139.5	121.7	25.5
2–2	47.1	99.7	–	87.6	81.6	75.1	63.3	47.6	102.8	34.4
2–3	52.5	116.5	–	78.2	38.5	74.1	52.4	97.0	118.9	33.0
2–4	64.6	166.9	–	68.0	97.8	68.1	50.9	58.7	110.6	61.3
2–5	54.8	123.1	39.5	74.8	47.6	51.0	48.2	213.9	110.4	24.7
ANOVA: F/P	3.68/0.002	2.94/0.009	2.86/0.05	1.53/0.19	2.60/0.03	3.48/0.0069	2.03/0.06	6.55/<0.0001	1.18/0.33	1.44/0.21
Dist.: r/P	0.35/0.32	0.31/0.38	–	–0.54/0.13	–0.65/0.06	–0.76/0.03	–0.33/0.36	0.05/0.90	–0.20/0.57	0.26/0.46
Poll.: r/P	–0.14/0.70	0.16/0.66	–	0.10/0.80	0.33/0.38	0.06/0.90	0.02/0.97	–0.57/0.09	–0.65/0.04	0.63/0.05

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Table 4.22 Leaf/needle size (L, mm), shoot length (S, mm) of woody plants and height (H, mm) of herbaceous plants in the impact zone of the aluminium smelter at Kandalaksha, Russia

Site	Betula pubescens		Empetrum nigrum	Epilobium angustifolium		Linnaea borealis		Picea abies	Pinus sylvestris
	L (2002)	S (2002)	S (2002)	L (2006)	H (2006)	L (2006)	H (2006)	S (2001)	L (1998)
1–1	40.8	86.5	25.4	110	590	12.2	91	25.6	28.4
1–2	46.0	91.5	26.6	–	–	–	–	29.0	28.7
1–3	35.2	74.1	25.2	–	–	–	–	28.6	29.0
1–4	53.8	132.3	27.8	–	–	–	–	34.3	37.6
1–5	37.3	95.1	27.6	105	548	12.2	99	24.1	27.2
2–1	33.2	38.7	23.7	106	720	11.6	86	34.1	32.0
2–2	45.1	102.6	20.1	–	–	–	–	31.7	27.6
2–3	36.6	116.6	22.5	–	–	–	–	30.9	30.3
2–4	44.1	98.0	25.2	–	–	–	–	34.4	31.3
2–5	33.1	97.2	13.1	88	485	12.4	100	30.9	29.1
ANOVA: F/P	7.33/<0.0001	4.01/0.0011	2.09/0.05	1.88/0.15	4.98/0.0054	0.42/0.73	2.67/0.06	0.95/0.50	1.81/0.10
Dist.: r/P	0.04/0.91	0.61/0.06	−0.22/0.53	–	–	–	–	−0.11/0.75	0.03/0.94
Poll.: r/P	0.04/0.92	−0.61/0.06	0.27/0.45	–	–	–	–	0.01/0.96	−0.06/0.88

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Table 4.22 (continued)

Site	Salix caprea		Trientalis europaea		Vaccinium myrtillus		Vaccinium uliginosum		Vaccinium vitis-idaea	
	L (2002)	S (2002)	L (2006)	H (2006)	L (2005)	S (2005)	L (2005)	S (2005)	L (2001)	S (2001)
1-1	67.3	34.4	44.2	138	24.8	14.0	28.5	19.9	21.3	32.0
1-2	65.0	56.7	–	–	21.7	15.4	25.5	22.5	15.9	29.5
1-3	67.3	39.3	–	–	25.2	14.9	23.5	20.2	18.7	37.3
1-4	74.9	64.8	–	–	23.9	17.0	21.6	20.1	20.0	36.9
1-5	66.4	30.6	48.5	112	29.5	15.7	30.8	22.4	15.2	31.2
2-1	71.8	110.7	38.6	113	24.8	12.4	33.9	23.4	19.3	34.9
2-2	67.2	29.0	–	–	35.1	16.9	35.0	22.5	19.4	32.5
2-3	63.8	34.0	–	–	27.4	15.5	28.3	22.3	18.3	35.2
2-4	68.0	38.4	–	–	35.5	18.3	36.4	24.5	20.1	37.3
2-5	71.9	34.2	49.5	92	24.2	13.4	28.8	19.8	20.9	37.2
ANOVA: F/P	1.28/0.28	6.63/<0.0001	4.48/0.009	3.84/0.02	2.01/0.06	6.81/<0.0001	1.53/0.17	1.41/0.22	3.83/0.0015	1.07/0.41
Dist.: r/P	0.09/0.80	−0.57/0.08	–	–	0.12/0.74	0.37/0.29	−0.23/0.53	−0.24/0.51	−0.13/0.71	0.34/0.34
Poll.: r/P	−0.06/0.87	0.63/0.05	–	–	−0.31/0.38	−0.42/0.22	0.07/0.84	0.18/0.62	−0.08/0.82	−0.52/0.12

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Table 4.23 Leaf/needle size (L, mm), shoot length (S, mm) of woody plants and height (H, mm) of herbaceous plants in the impact zone of the copper smelter at Karabash, Russia

Site	*Alnus incana*		*Betula pendula*		*Fragaria vesca*	*Orthilia secunda*		*Pinus sylvestris*		*Vaccinium vitis-idaea*	
	L (2007)	S (2007)	L (2003)	S (2003)	L (2007)	L (2007)	H (2007)	L (2003)	S (2003)	L (2003)	S (2003)
1–1	–	–	30.2	58.2	–	–	–	–	–	–	–
1–2	78.4	51.4	39.1	45.8	34.4	20.5	124	47.7	45.4	22.3	33.0
1–3	86.1	95.5	46.3	46.3	–	–	–	45.8	42.5	21.5	36.8
1–4	77.8	55.1	43.9	73.8	–	32.6	138	45.4	42.0	22.2	43.6
1–5	92.7	144.7	48.6	75.9	40.7	–	–	53.6	53.1	23.0	39.4
2–1	77.4	158.6	36.3	46.6	–	24.4	105	–	–	–	–
2–2	60.1	29.3	47.9	60.2	32.1	–	–	36.4	19.3	19.4	30.1
2–3	87.8	65.8	41.1	67.1	–	–	–	39.1	37.5	20.5	41.9
2–4	76.8	105.0	43.7	58.7	–	–	–	52.2	42.5	22.6	39.3
2–5	86.7	76.3	48.1	78.3	40.2	34.9	163	43.5	26.2	20.5	35.8
ANOVA: F/P	2.39/0.04	3.98/0.0018	6.34/<0.0001	1.92/0.08	3.14/0.04	25.3/<0.0001	25.9/<0.0001	1.70/0.014	3.24/0.01	1.36/0.26	1.09/0.39
Dist.: r/P	0.52/0.15	0.02/0.96	0.71/0.02	–0.51/0.13	–	–	–	0.62/0.10	0.32/0.44	0.49/0.21	0.02/0.96
Poll.: r/P	–0.47/0.20	0.30/0.44	–0.65/0.04	–0.10/0.79	–	–	–	–0.73/0.04	–0.63/0.09	–0.72/0.05	0.53/0.17

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Table 4.24 Leaf/needle size (L, mm), shoot length (S, mm) of woody plants and height (H, mm) of herbaceous plants in the impact zone of the iron pellet plant at Kostomuksha, Russia

Site	Betula pubescens		Melampyrum sylvaticum	Picea abies	Pinus sylvestris		Salix caprea		Vaccinium vitis-idaea	
	L (2002)	H (2002)	H (2006)	S (2001)	L (2002)	S (2002)	L (2002)	S (2002)	L (2001)	S (2001)
1–1	44.0	83.4	173	24.6	34.9	60.0	64.2	51.0	20.4	38.7
1–2	40.8	98.8	–	36.1	34.8	93.9	80.9	81.0	19.8	36.0
1–3	36.5	136.5	–	28.5	–	81.6	74.6	52.3	21.2	37.5
1–4	42.9	127.8	–	26.4	36.1	63.0	85.2	60.7	19.9	32.8
1–5	37.7	83.2	202	31.4	37.4	64.1	73.2	59.3	20.9	52.4
2–1	39.6	93.9	205	31.2	40.1	53.7	66.8	55.2	21.0	45.5
2–2	42.1	80.6	–	35.1	30.5	41.4	58.8	53.6	21.3	40.3
2–3	42.6	109.6	–	34.2	30.6	54.7	59.2	59.7	18.0	35.9
2–4	32.6	71.3	–	34.4	34.0	43.4	71.0	66.4	16.6	45.8
2–5	41.1	79.2	236	38.5	36.2	–	74.3	52.9	19.6	43.6
ANOVA: F/P	3.40/0.0035	3.99/0.0011	4.94/0.0061	3.49/0.0030	3.20/0.0076	6.95/<0.0001	4.06/0.0009	1.82/0.09	4.41/0.0005	4.84/0.0002
Dist.: r/P	−0.33/0.35	0.10/0.78	–	0.32/0.37	−0.10/0.81	0.24/0.53	0.53/0.12	0.20/0.58	−0.30/0.40	0.11/0.75
Poll.: r/P	0.20/0.59	−0.10/0.79	–	−0.25/0.48	0.52/0.16	−0.28/0.46	−0.29/0.42	−0.26/0.47	0.43/0.21	0.19/0.61

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Table 4.25 Leaf/needle size (L, mm) and shoot length (S, mm) of woody plants in the impact zone of the copper smelter at Krompachy, Slovakia

Site	Betula pendula		Fagus sylvatica			Picea abies	Pinus sylvestris	
	L (2004)	S (2004)	L (2002)	S (2002)	S (2004)	S (2002)	L (2002)	S (2002)
1–1	63.9	185.4	80.5	77.8	20.6	38.4	47.6	61.4
1–2	71.7	223.7	72.5	75.1	67.8	60.9	41.1	44.9
1–3	48.9	147.8	73.9	35.4	26.6	52.7	50.2	35.2
1–4	91.3	240.2	71.8	71.4	62.5	41.9	47.1	46.0
1–5	71.6	241.6	77.9	56.5	4.5	56.7	56.7	55.6
2–1	67.2	181.9	70.7	77.0	54.6	58.6	48.3	108.8
2–2	82.1	217.1	71.2	75.3	30.2	42.7	45.5	25.9
2–3	66.4	197.5	77.7	71.1	12.8	39.9	47.8	53.0
2–4	62.8	218.1	83.2	83.7	22.7	51.0	43.7	55.3
2–5	72.9	230.5	79.1	72.1	62.1	65.0	50.4	58.3
ANOVA: F/P	9.45/<0.0001	1.29/0.27	2.11/0.05	1.33/0.25	5.37/<0.0001	3.75/0.0017	0.79/0.62	3.13/0.0060
Dist.: r/P	0.18/0.61	0.52/0.12	0.16/0.64	−0.35/0.32	0.13/0.72	0.51/0.13	0.45/0.19	−0.21/0.57
Poll.: r/P	−0.17/0.64	−0.34/0.34	−0.40/0.26	0.07/0.85	0.10/0.78	0.28/0.44	0.16/0.66	0.79/0.0062

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Table 4.26 Leaf/needle size (L, mm), shoot length (S, mm) of woody plants and height (H, mm) of herbaceous plants in the impact zone of the nickel-copper smelter at Monchegorsk, Russia

Site	Betula nana			Betula pubescens		Cornus suecica		Dactylorhiza maculata		Empetrum nigrum
	L (2001)	S (2001)	L (2002)	S (2002)	S (2005)	L (2006)	H (2006)	L (2006)	H (2006)	S (2002)
1–1	11.3	55.6	39.0	75.9	57.8	–	–	–	–	10.8
1–2	11.9	52.0	34.1	62.7	53.1	–	–	–	–	12.0
1–4	12.9	51.4	34.0	64.5	45.5	–	–	–	–	6.3
1–5	12.0	45.2	41.3	86.9	67.4	–	–	–	–	8.2
2–2	10.9	52.5	39.5	92.6	55.5	–	–	53.6	237	9.7
2–3	–	–	–	–	–	26.7	99	45.7	240	–
2–4	12.1	52.0	44.1	67.6	42.4	22.8	91	–	–	7.7
2–5	12.4	–	37.6	91.1	61.5	–	–	–	–	12.0
2–6	–	56.9	–	–	–	–	–	–	–	–
2–8	11.3	40.0	42.4	53.5	35.5	29.5	154	–	–	15.6
2–9	11.7	64.5	45.3	70.0	44.8	32.1	230	68.2	333	21.2
2–10	12.7	62.8	41.8	62.4	57.5	–	–	60.8	294	–
2–12	–	–	–	–	–	–	–	–	–	35.0
ANOVA: F/P	0.81/0.61	1.09/0.39	2.53/0.02	1.15/0.35	1.64/0.14	14.6/<0.0001	45.1/<0.0001	11.1/<0.0001	7.39/0.0004	16.2/<0.0001
Dist.: r/P	0.26/0.50	0.13/0.71	0.47/0.20	–0.34/0.34	–0.24/0.51	–	–	–	–	0.70/0.03
Poll.: r/P	–0.08/0.83	–0.05/0.88	–0.02/0.95	0.40/0.25	0.03/0.93	–	–	–	–	–0.50/0.14

Site	Epilobium angustifolium L (2006)	Epilobium angustifolium H (2006)	Equisetum sylvaticum H (2006)	Picea abies S (2002)	Pinus sylvestris L (2002)	Pinus sylvestris S (2002)	Populus tremula L (2002)	Rubus chamaemorus L (2006)	Salix borealis L (1997)	Salix borealis S (1997)
1–1	99.7	620	331	23.4	31.3	26.9	51.3	–	32.4	32.0
1–2	–	–	-.	24.2	32.5	36.6	–	–	39.2	55.4
1–3	–	–	–	–	–	–	39.8	–	–	–
1–4	–	–	–	20.1	23.1	28.3	–	–	35.9	35.4
1–5	–	–	–	28.1	34.5	15.0	–	–	33.8	30.8
2–1	–	–	–	–	–	–	–	–	34.0	28.0
2–2	–	–	–	23.7	34.1	33.4	38.2	37.9	–	–
2–3	98.7	566	–	–	–	–	–	–	–	–
2–4	–	–	235	20.6	31.8	30.5	40.4	34.8	–	–
2–5	–	–	–	30.0	32.0	47.6	41.5	–	41.6	50.8
2–6	–	–	–	–	–	–	–	–	–	–
2–7	–	–	–	–	–	–	–	–	41.7	49.9
2–8	–	–	–	24.3	34.2	20.6	42.4	–	41.6	33.5
2–9	92.1	551	381	26.2	31.6	32.0	43.5	–	36.1	30.5
2–10	85.4	473	311	–	31.4	36.3	44.4	49.6	37.4	41.7
2–11	–	–	–	–	–	–	46.3	–	–	–
2–12	–	–	–	28.7	–	–	47.1	42.2	–	–
ANOVA: F/P	0.92/0.44	1.53/0.22	11.0/<0.0001	6.22/<0.0001	1.40/0.22	3.86/0.0014	6.61/<0.0001	11.2/<0.0001	4.45/0.0004	1.85/0.09
Dist.: r/P	–	–	–	0.48/0.16	0.09/0.81	–0.02/0.95	–0.16/0.65	–	0.54/0.13	0.18/0.61
Poll.: r/P	–	–	–	–0.41/0.23	–0.28/0.47	0.26/0.48	–0.09/0.80	–	–0.29/0.45	0.25/0.48

(continued)

Table 4.26 (continued)

Site	Salix caprea			Solidago virgaurea		Vaccinium myrtillus	Vaccinium uliginosum		Vaccinium vitis-idaea	
	S (1997)	L (2002)	S (2002)	L (2006)	H (2006)	S (1999)	L (2005)	S (2005)	L (2001)	S (1999)
1–1	45.0	59.6	28.7	–	–	25.3	15.1	20.3	16.3	18.9
1–2	–	56.1	33.5	–	–	26.7	17.5	14.5	17.3	15.6
1–4	34.7	49.2	30.5	–	–	36.0	17.7	23.6	14.2	26.2
1–5	–	56.7	44.7	–	–	36.7	16.5	28.7	16.4	24.7
2–1	48.6	–	–	–	–	–	–	–	–	–
2–2	–	55.8	34.8	84.0	335	51.1	20.3	32.9	19.1	16.0
2–4	–	52.3	34.7	89.0	280	29.7	19.7	28.3	13.5	21.4
2–5	44.8	60.2	44.6	–	–	26.7	21.0	21.6	14.5	22.6
2–8	30.5	59.0	31.3	–	–	38.4	19.9	38.6	18.8	15.2
2–9	–	57.8	59.8	128.2	467	36.6	25.2	29.6	15.9	19.5
2–10	57.9	61.9	50.4	133.1	478	30.0	17.9	46.6	17.6	18.0
ANOVA: F/P	1.44/0.25	2.39/0.03	1.66/0.13	1.71/0.20	3.27/0.05	1.57/0.16	9.41/<0.0001	5.50/<0.0001	4.62/0.0003	4.00/0.0010
Dist.: r/P	−0.10/0.85	0.18/0.65	0.68/0.03	–	–	0.13/0.72	0.48/0.19	0.65/0.04	0.01/0.98	0.09/0.80
Poll.: r/P	0.08/0.88	−0.51/0.16	−0.49/0.15	–	–	0.06/0.86	−0.46/0.21	−0.30/0.39	0.41/0.31	−0.22/0.54

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Table 4.27 Leaf/needle size (L, mm), shoot length (S, mm) of woody plants and height (H, mm) of herbaceous plants in the impact zone of the aluminium smelter at Nadvoitsy, Russia

Site	Betula pubescens		Epilobium angustifolium		Empetrum nigrum	Picea abies	Pinus sylvestris	
	L (2004)	S (2004)	L (2007)	H (2007)	S (2004)	S (2004)	L (2004)	S (2004)
1–1	45.0	91.9	149.3	759	46.7	42.2	30.8	24.2
1–2	44.1	105.7	–	–	34.2	40.1	25.2	19.0
1–3	46.5	95.1	–	–	48.1	45.7	30.0	21.4
1–4	45.5	83.8	–	–	36.7	46.0	30.3	26.2
1–5	49.1	66.5	119.4	538	37.4	49.1	28.6	25.5
2–1	46.7	81.5	117.3	673	39.4	48.0	35.8	26.8
2–2	45.3	93.5	–	–	50.4	45.5	38.6	28.2
2–3	47.0	57.0	–	–	42.6	37.0	31.4	25.7
2–4	48.0	69.5	–	–	45.3	35.4	32.6	19.5
2–5	49.1	69.2	152.7	869	42.9	42.6	28.2	19.7
ANOVA: F/P	0.70/0.71	1.30/0.27	7.42/0.0005	5.94/0.0021	2.54/0.02	1.09/0.40	4.83/0.0002	1.16/0.38
Dist.: r/P	0.69/0.03	−0.55/0.10	–	–	−0.28/0.43	0.00/0.99	−0.45/0.18	−0.27/0.45
Poll.: r/P	−0.63/0.05	0.62/0.05	–	–	0.07/0.84	0.26/0.47	0.44/0.20	0.32/0.36

Table 4.27 (continued)

Site	Vaccinium myrtillus		Vaccinium uliginosum		Vaccinium vitis-idaea	
	L (2005)	S (2005)	L (2005)	S (2005)	L (2004)	S (2004)
1–1	16.3	45.0	22.8	39.4	20.8	45.7
1–2	16.4	38.4	23.7	42.7	27.1	51.8
1–3	15.2	28.1	23.6	23.7	21.5	45.2
1–4	14.4	31.4	19.5	19.3	25.9	71.4
1–5	16.8	33.8	25.6	43.1	23.4	63.2
2–1	15.6	35.3	21.5	32.4	24.4	54.5
2–2	15.8	36.3	20.9	49.7	25.7	46.3
2–3	17.0	38.9	22.1	39.0	24.2	62.8
2–4	16.2	37.8	24.7	38.7	21.0	58.7
2–5	17.4	36.9	26.7	39.0	25.2	63.3
ANOVA: F/P	1.39/0.33	0.84/0.59	2.46/0.03	1.84/0.09	4.05/0.001	5.32/<0.0001
Dist.: r/P	0.21/0.55	−0.44/0.21	0.49/0.15	−0.13/0.71	0.06/0.87	0.71/0.02
Poll.: r/P	−0.22/0.55	0.31/0.39	−0.43/0.21	0.24/0.51	0.17/0.64	−0.65/0.04

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

In woody plants, the effect depended on the polluter type (Q_B = 10.4, df = 4, P = 0.04): effects of power plants were positive, while effects caused by other types of polluters did not differ from zero (Fig. 4.8). Effects of polluters also differed in relation to their impact on soil pH (Q_B = 6.64, df = 2, P = 0.04): only acidifying polluters caused a significant negative effect (Fig. 4.8). The geographical position of polluters did not influence their effect on leaf/needle size (Fig. 4.8; Q_B = 0.55, df = 1, P = 0.46). Individual polluters differed in their effects on leaf/needle length (Q_B = 63.5, df = 17, P < 0.0001); two non-ferrous smelters (Karabash, Revda) and one aluminium smelter (Žiar nad Hronom) caused significant negative effects, while we detected significant increase in leaf/needle size in the vicinity of four polluters (Apatity, Sudbury, Volkhov, Vorkuta) (Fig. 4.9). Woody plant species responded similarly to pollution (Q_B = 7.53, df = 11, P = 0.76); leaf size decreased with pollution only in silver birch, European aspen, and European beech (Fig. 4.10).

In herbaceous plants (Fig. 4.11), the effect did not depend on the polluter type (Q_B = 0.44, df = 1, P = 0.51) or changes in soil pH (Q_B = 2.64, df = 2, P = 0.27), or geographical position of polluters (Q_B = 0.03, df = 1, P = 0.86). Individual polluters did not differ in their effects on leaf length of herbaceous plants (Q_B = 4.58, df = 4, P = 0.33); significant negative effects were recorded only around Karabash and Volkhov (Fig. 4.12).

We have detected significant non-linear responses in six of 73 data sets on woody plants (two dome-shaped and four U-shaped), which is nearly twice as high as the number of dome-shaped patterns that may be expected to occur by chance.

4.3.3 Shoot Growth

Variation in shoot length between study sites was generally significant (77 of 120 data sets); however, only 24 of 200 correlation coefficients (with both distance and pollution load; calculated only for woody plants) were significant (Tables 4.18–4.35).
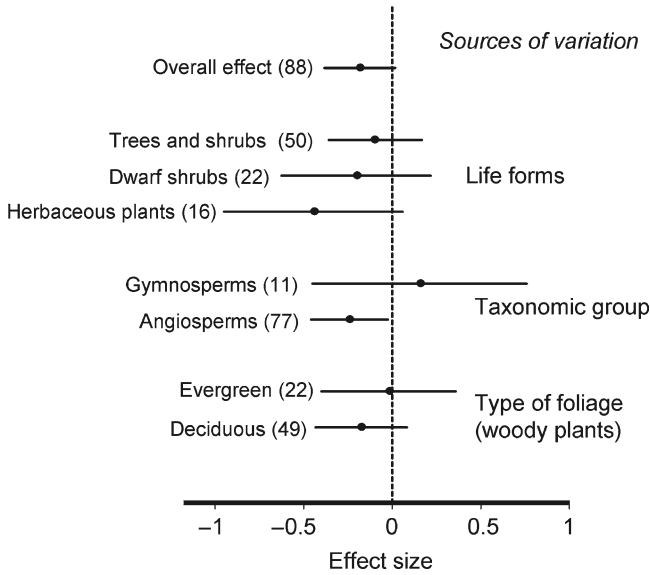
Fig. 4.7 Overall effect and sources of variation in the responses of leaf/needle length of vascular plants. Effect sizes are Hedge's d based on comparison of two most polluted and two control sites. Needle length of Scots pine (*Pinus sylvestris*) measured near aluminium smelter at Volkhov (Table 4.33) is excluded from this figure. For explanations, consult Fig. 4.1
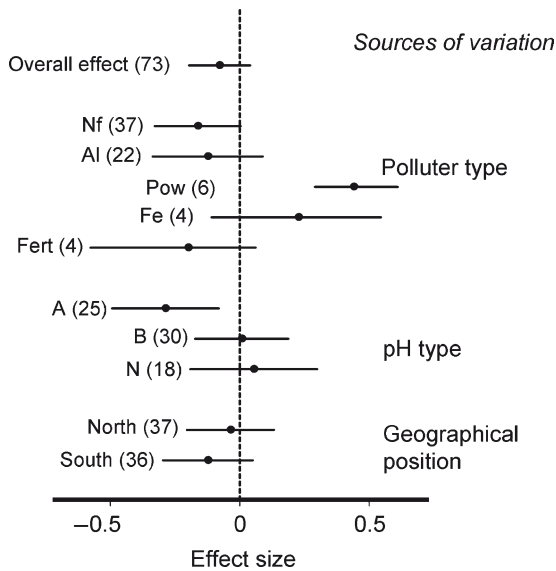
Fig. 4.8 Overall effect and sources of variation in the responses of leaf/needle length of woody plants. For explanations, consult Fig. 4.1
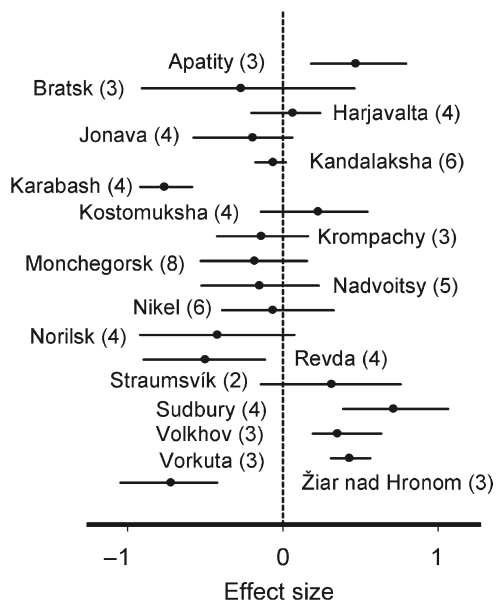
Fig. 4.9 Effects of individual polluters on the leaf/needle length of woody plants. For explanations, consult Fig. 4.1
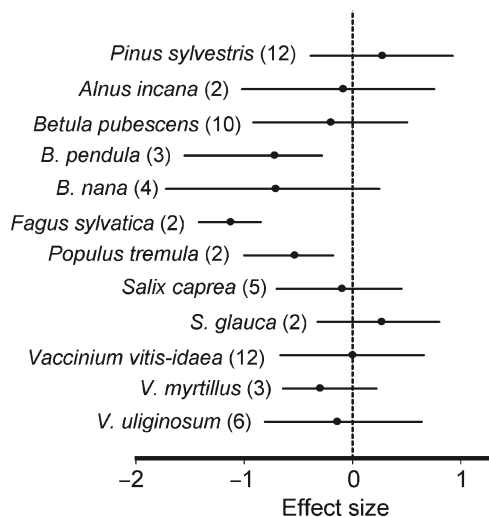
Fig. 4.10 Effects of point polluters on leaf/needle length of woody plant species. For explanations, consult Fig. 4.1

Table 4.28 Leaf size (L, mm), shoot length (S, mm) of woody plants and height (H, mm) of herbaceous plants in the impact zone of the nickel-copper smelter at Nikel and ore-roasting plant at Zapolyarnyy, Russia

Site	Betula nana		Betula pubescens		Empetrum nigrum	Epilobium angustifolium		Equisetum sylvaticum	Eriophorum vaginatum
	L (2001)	S (2001)	L (2001)	S (2001)	S (2003)	L (2006)	H (2006)	H (2006)	H (2006)
1–1	8.4	30.0	33.6	53.3	–	–	–	–	202
1–2	11.6	39.8	32.0	68.3	10.0	–	–	–	–
1–3	11.2	40.7	31.8	64.4	10.6	–	–	–	–
1–4	9.1	32.8	30.9	75.4	22.9	–	–	–	–
1–5	10.0	37.5	28.8	61.6	13.6	–	–	–	–
2–1	10.3	43.4	35.0	60.6	12.3	90.5	431	177	324
2–2	11.6	44.0	39.8	145.0	16.3	111.6	472	197	382
2–3	12.2	43.5	41.2	94.7	8.7	–	–	–	–
2–4	10.8	49.9	36.9	90.8	20.1	124.7	726	225	–
2–5	10.7	39.7	33.3	53.5	11.6	113.0	550	377	464
ANOVA: F/P	2.85/0.01	0.79/0.63	5.88/<0.0001	4.01/0.0010	2.97/0.0084	5.76/0.0025	11.3/<0.0001	23.9/<0.0001	37.0/<0.0001
Dist.: r/P	0.18/0.61	0.17/0.63	−0.28/0.43	−0.03/0.93	0.29/0.45	–	–	–	–
Poll.: r/P	−0.49/0.15	−0.34/0.34	0.11/0.76	−0.23/0.52	−0.21/0.58	–	–	–	–

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

(continued)

Table 4.28 (continued)

Site	Rubus chamaemorus	Salix glauca		Vaccinium myrtillus		Vaccinium uliginosum		Vaccinium vitis-idaea	
	L (2006)	L (2001)	S (2001)	L (2005)	S (2005)	L (2005)	S (2005)	L (2001)	S (2001)
1–1	–	35.1	29.7	–	–	–	–	–	–
1–2	–	34.5	24.1	11.7	19.3	14.8	28.5	12.7	16.0
1–3	–	35.4	22.3	13.6	18.4	18.7	22.9	13.2	33.4
1–4	–	35.5	28.8	12.3	27.1	17.0	35.0	11.9	21.2
1–5	–	34.0	32.3	11.1	26.8	17.8	29.1	12.6	20.0
2–1	38.4	36.0	35.2	13.0	28.3	14.6	28.2	–	33.5
2–2	45.0	–	–	12.0	17.0	15.0	26.9	15.2	27.2
2–3	–	35.5	32.7	11.3	15.5	16.2	19.7	14.6	31.5
2–4	37.6	38.9	32.7	12.3	24.5	14.6	22.9	11.4	17.6
2–5	32.3	38.4	34.5	15.1	24.5	18.0	22.9	13.1	25.8
ANOVA: F/P	3.54/0.02	0.75/0.65	0.98/0.46	3.20/0.0076	1.78/0.11	3.46/0.0046	0.85/0.57	1.87/0.11	4.56/0.0007
Dist.: r/P	–	0.26/0.51	0.11/0.78	0.12/0.76	0.27/0.48	0.69/0.04	0.01/0.98	−0.54/0.17	−0.38/0.31
Poll.: r/P	–	−0.16/0.69	0.16/0.67	0.11/0.78	0.21/0.59	−0.55/0.13	0.09/0.82	0.71/0.05	0.49/0.18

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

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Table 4.29 Leaf size (L, mm), shoot length (S, mm) of woody plants and height (H, mm) of herbaceous plants in the impact zone of the nickel-copper smelters at Norilsk, Russia

Site	Betula nana		Empetrum nigrum	Larix sibirica	Salix lanata		Vaccinium uliginosum		Vaccinium vitis-idaea	
	L (2002)	S (2002)	S (2002)	S (2002)	L (2002)	S (2002)	L (2002)	S (2002)	L (2002)	S (2002)
1–1	9.3	13.4	6.2	51.4	–	23.1	11.7	9.2	12.8	14.2
1–2	12.1	34.1	10.5	57.3	50.2	34.0	11.7	9.8	12.8	11.4
1–3	13.2	43.7	12.5	41.4	54.6	30.9	10.9	10.3	12.4	14.1
1–4	13.6	42.2	18.3	78.9	55.9	37.2	12.2	13.2	12.9	15.5
1–5	14.2	41.9	14.6	75.6	51.2	48.0	12.7	19.4	14.2	17.8
2–1	8.6	12.0	13.0	35.3	45.9	19.9	13.3	5.6	9.7	11.3
2–2	11.9	20.0	20.8	51.1	53.3	27.7	14.6	8.7	12.8	28.8
2–3	15.8	33.8	24.8	90.3	60.5	50.1	12.9	11.1	16.2	23.5
2–4	13.0	40.3	13.5	61.3	45.1	26.6	10.4	14.8	14.5	14.2
2–5	13.6	49.8	18.4	63.2	52.9	33.9	12.3	17.3	16.1	21.9
ANOVA: F/P	7.30/<0.0001	7.51/<0.0001	6.93/<0.0001	9.47/<0.0001	3.35/0.0059	3.91/0.0012	3.15/0.0058	4.54/0.0004	3.63/0.0023	5.01/0.0002
Dist.: r/P	0.81/0.0044	0.96/<0.0001	0.44/0.20	0.57/0.09	0.28/0.46	0.62/0.05	–0.22/0.54	0.85/0.0017	0.64/0.05	0.21/0.55
Poll.: r/P	–0.80/0.006	–0.91/0.0002	–0.46/0.18	–0.45/0.19	–0.28/0.47	–0.57/0.08	0.22/0.54	–0.65/0.04	–0.48/0.16	–0.14/0.71

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

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Table 4.30 Leaf/needle size (L, mm), shoot length (S, mm) of woody plants and height (H, mm) of herbaceous plants in the impact zone of the copper smelter at Revda, Russia

Site	Abies sibirica S (2007)	Betula pubescens L (2003)	Betula pubescens S (2003)	Equisetum silvaticum H (2007)	Linaria vulgaris H (2007)	Picea abies S (2003)	Pinus sylvestris L (2003)	Pinus sylvestris S (2003)	Populus tremula L (2007)	Populus tremula S (2007)	Vaccinium vitis-idaea L (2003)	Vaccinium vitis-idaea S (2003)
1–1	36.9	43.3	59.5	373	444	39.7	34.2	36.5	38.9	35.8	19.7	26.5
1–2	58.3	48.4	40.4	–	–	42.7	39.8	40.2	48.4	59.3	–	–
1–3	55.7	54.2	72.6	–	–	39.1	40.0	79.9	48.4	5.9	–	–
1–4	60.8	53.3	90.2	447	959	60.5	40.6	37.4	44.6	45.1	19.5	41.9
1–5	52.7	47.3	75.2	445	497	49.2	37.5	65.8	43.9	41.5	19.3	50.3
2–1	64.9	42.4	79.8	–	–	45.2	42.9	44.5	43.9	8.7	22.0	39.4
2–2	63.2	47.2	81.1	–	–	50.0	42.0	37.4	47.0	55.2	22.7	49.5
2–3	53.5	50.4	53.6	–	–	42.3	40.9	63.0	43.3	8.8	20.5	30.8
2–4	62.9	52.0	83.4	–	–	39.6	42.4	31.4	43.6	22.9	22.7	52.6
2–5	58.1	53.6	82.6	598	911	41.9	45.0	42.2	43.9	92.4	23.2	36.7
ANOVA:												
F/P	2.66/0.02	2.51/0.02	1.68/0.13	15.6/<0.0001	29.9/<0.0001	1.77/0.10	1.37/0.23	4.37/0.0005	1.23/0.30	3.98/0.0011	2.67/0.03	5.53/0.0003
Dist.: r/P	0.19/0.59	0.73/0.02	0.40/0.25	–	–	0.27/0.44	0.28/0.44	0.19/0.61	0.12/0.75	0.39/0.26	−0.05/0.90	0.40/0.33
Poll.: r/P	−0.33/0.35	−0.80/0.0059	−0.22/0.54	–	–	−0.21/0.57	−0.28/0.43	−0.24/0.50	−0.46/0.18	−0.31/0.39	0.01/0.98	−0.52/0.18

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Table 4.31 Leaf size (L, mm), shoot length (S, mm) of woody plants and height (H, mm) of herbaceous plants in the impact zone of the aluminium smelter at Straumsvík, Iceland

Site	*Empetrum nigrum*		*Juncus trifidus*	*Luzula spicata*	*Salix herbacea*			*Vaccinium uliginosum*	
	S (2002)	S (2007)	H (2007)	H (2007)	L (2002)	S (2002)	S (2007)	L (2002)	S (2002)
1–1	4.6	73.2	153	292	12.7	11.4	6.9	14.8	30.0
1–2	6.3	77.4	–	–	12.8	9.2	8.1	13.1	19.0
1–3	5.1	86.0	–	–	15.0	12.4	10.4	13.3	15.8
1–4	4.8	127.4	–	–	13.0	9.4	6.4	12.3	18.6
1–5	5.2	118.2	183	487	11.9	11.7	18.8	14.1	20.8
2–1	5.3	53.0	158	320	14.1	12.5	4.4	14.3	24.1
2–2	5.4	66.4	–	–	13.6	8.6	5.2	12.3	18.3
2–3	4.4	46.4	–	–	14.1	10.6	4.6	12.1	14.9
2–4	5.4	69.0	–	–	13.6	9.3	–	12.2	22.0
2–5	5.0	91.6	255	375	12.6	9.3	14.1	12.5	15.4
ANOVA: F/P	1.41/0.22	3.22/0.005	10.9/<0.0001	8.73/0.0002	0.88/0.55	0.32/0.96	4.17/0.0013	1.03/0.43	2.34/0.03
Dist.: r/P	−0.07/0.85	0.65/0.04	–	–	−0.47/0.18	−0.21/0.56	0.84/0.005	−0.32/0.36	−0.48/0.16
Poll.: r/P	−0.35/0.32	−0.22/0.54	–	–	−0.14/0.71	0.27/0.45	−0.31/0.42	0.64/0.05	0.83/0.0032

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Table 4.32 Leaf/needle size (L, mm) and shoot length (S, mm) in the impact zone of the nickel-copper smelter at Sudbury, Canada

Site	Betula papyrifera		Pinus resinosa		Populus tremuloides		Vaccinium angustifolium	
	L (2007)	S (2007)	L (2002)	S (2002)	L (2007)	S (2007)	L (2007)	S (2007)
1–1	72.2	207.8	–	–	40.1	41.4	–	–
1–2	48.9	148.7	126.2	126.7	44.7	163.8	22.2	42.5
1–3	78.3	151.5	121.2	43.9	53.8	79.6	16.1	17.2
1–4	49.4	168.9	97.0	58.8	52.7	117.2	20.8	39.7
1–5	77.5	168.1	102.7	27.8	54.9	82.7	21.3	19.3
2–1	78.7	185.6	–	–	57.8	33.7	–	–
2–2	67.4	132.4	118.7	94.6	53.3	16.5	32.9	38.7
2–3	60.7	133.8	110.5	139.7	43.2	64.1	19.0	30.6
2–4	50.7	87.5	96.0	58.6	34.5	24.1	19.1	16.5
2–5	75.5	130.1	79.7	74.5	49.2	67.2	21.0	20.6
ANOVA: F/P	9.79/<0.0001	4.33/0.0005	6.67/<0.0001	6.92/<0.0001	4.57/0.0006	2.85/0.01	6.17/0.0002	11.0/<0.0001
Dist.: r/P	−0.14/0.70	−0.55/0.10	−0.91/0.0018	−0.54/0.17	−0.16/0.66	0.18/0.63	−0.41/0.32	−0.66/0.07
Poll.: r/P	0.27/0.45	0.53/0.11	0.65/0.08	0.41/0.31	0.18/0.61	−0.36/0.30	0.84/0.0086	0.62/0.10

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Table 4.33 Leaf/needle size (L, mm), shoot length (S, mm) of woody plants and height (H, mm) of herbaceous plants in the impact zone of the aluminium smelter at Volkhov, Russia

Site	Achillea millefolium		Betula pubescens		Picea abies	Pinus sylvestris	Salix caprea		Tanacetum vulgare	
	L (2007)	H (2007)	L (2002)	S (2002)	S (2002)	L (1998)	L (2002)	S (2002)	L (2007)	H (2007)
1–1	72.1	168.1	44.5	134.3	34.5	–	63.2	63.4	202.4	1021
1–2	–	–	49.4	109.6	51.0	–	69.2	57.0	–	–
1–3	–	–	56.6	142.4	–	–	79.5	98.4	–	–
1–4	–	–	52.0	128.0	45.2	53.7	71.6	101.0	–	–
1–5	58.9	187.6	48.6	123.7	50.6	42.0	61.8	74.2	188.8	1172
2–1	72.7	172.1	51.2	82.6	59.2	58.3	76.9	69.9	252.3	1024
2–2	–	–	51.4	140.5	41.7	–	75.2	65.7	–	–
2–3	–	–	47.9	142.6	60.2	56.8	80.0	65.0	–	–
2–4	–	–	49.3	149.8	38.9	50.6	66.0	62.7	–	–
2–5	57.7	186.3	32.8	90.7	41.8	51.6	64.0	50.2	205.3	977
ANOVA: F/P	3.37/0.03	0.21/0.89	6.99/<0.0001	2.24/0.04	1.76/0.13	4.59/0.04	2.16/0.05	2.94/0.0093	6.67/0.0011	2.89/0.05
Dist.: r/P	–	–	−0.33/0.35	0.31/0.38	−0.30/0.44	−0.68/0.14	−0.44/0.20	0.04/0.92	–	–
Poll.: r/P	–	–	0.19/0.59	−0.51/0.13	0.38/0.32	0.56/0.25	0.36/0.31	−0.10/0.78	–	–

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Table 4.34 Leaf size (L, mm) and shoot length (S, mm) in the impact zone of the power plant at Vorkuta, Russia

Site	*Betula nana*		*Salix glauca*		*Vaccinium vitis-idaea*	
	L (2001)	S (2001)	L (2001)	S (2001)	L (2001)	S (2001)
1–1	11.7	28.9	32.1	34.8	9.0	13.0
1–2	9.6	16.8	29.6	24.6	10.5	13.3
1–3	10.0	12.7	25.6	31.2	9.1	10.9
1–4	9.6	18.1	31.4	37.2	10.0	15.2
1–5	11.5	23.0	28.9	28.0	10.5	22.8
2–1	12.1	27.0	27.9	19.0	11.4	14.9
2–2	10.2	17.5	33.1	28.2	9.3	12.9
2–3	10.0	18.1	28.1	33.4	9.0	16.4
2–4	8.8	15.5	31.9	30.8	9.6	17.3
2–5	8.9	16.8	31.3	33.0	8.5	13.3
ANOVA: *F/P*	4.51/0.0004	3.64/0.0021	2.26/0.04	2.18/0.04	4.78/0.0002	8.63/<0.0001
Dist.: *r/P*	−0.67/0.03	−0.60/0.07	0.13/0.72	0.54/0.11	−0.41/0.24	0.41/0.24
Poll.: *r/P*	0.30/0.40	0.12/0.75	−0.38/0.28	0.76/0.01	0.51/0.13	−0.24/0.50

Sampling year shown in parentheses. For other explanations, consult Table 4.1.

Site-specific values of shoot length of the same species measured during 2 different years correlated with each other ($z_r = 0.34$, CI = 0.02…0.66, $N = 8$), indicating repeatability of our results.

The magnitude of the pollution effect on the shoot length of woody plants did not depend on the method used to calculate ES ($Q_B = 1.95$, df = 2, $P = 0.38$). Therefore, the analyses of herbaceous plants, as well as of pooled data, are based on Hedge's d values because data on herbs were collected only from the most and least polluted study sites. However, in the analysis of woody plants we employed ESs based on correlations with pollution, in line with all other characteristics analysed in this book.

In general, shoot length (including height of herbaceous plants) decreased with pollution (Fig. 4.13). This effect was pronounced in Angiosperms, while Gymnosperms showed no response to pollution (Fig. 4.13; $Q_B = 0.22$, df = 1, $P = 0.64$). Changes in shoot length did not depend on plant life form ($Q_B = 1.65$, df = 2, $P = 0.44$); evergreen and deciduous woody plants responded similarly to pollution ($Q_B = 0.38$, df = 1, $P = 0.54$) (Fig. 4.13). We found no differences among plants belonging to four Raunkiaer life forms (listed in Section 4.3.2) ($Q_B = 3.17$, df = 3, $P = 0.17$).

Effect sizes (averaged by plant species) did not correlate with any of the six Ellenberg's indicator values listed in Section 4.3.2 ($r_S = 0.10…0.31$, $N = 21–36$ species, $P = 0.14…0.55$). Similarly, we found no correlation with axis scores for Grime's CSR strategy ($r_S = −0.34…0.44$, $N = 14$ species, $P = 0.11…0.97$).

In woody plants (Fig. 4.14), the effect did not depend on polluter type ($Q_B = 2.23$, df = 4, $P = 0.69$), pollution effects on soil pH ($Q_B = 0.42$, df = 2, $P = 0.81$), or geographical position of polluters ($Q_B = 0.001$, df = 1, $P = 0.95$). Individual polluters differed in their effects on shoot length ($Q_B = 45.1$, df = 17, $P = 0.0002$).

Table 4.35 Leaf size (L, mm), shoot length (S, mm) of woody plants in the impact zone of the aluminium smelter at Žiar nad Hronom, Slovakia

Site	Carpinus betulus			Fagus sylvatica				Quercus petraea	
	L (2002)	S (2002)	S (2004)	L (2002)	S (2002)	S (2004)	S (2006)	L (2002)	S (2002)
1–1	42.1	11.6	13.8	65.1	40.0	12.6	43.2	82.1	22.0
1–2	49.1	10.4	34.3	70.9	49.1	42.0	7.8	92.1	23.7
1–3	57.9	13.8	49.4	77.4	61.1	41.0	22.3	–	–
1–4	58.9	26.2	–	75.7	44.1	73.1	40.6	89.8	16.5
1–5	54.8	26.4	50.3	81.0	60.3	40.3	30.8	–	–
2–1	67.1	23.7	33.1	82.4	47.2	54.8	2.2	83.7	42.7
2–2	56.5	12.4	18.0	69.2	40.6	39.2	26.7	95.9	32.1
2–3	52.0	14.7	41.0	72.9	41.4	65.6	27.6	–	–
2–4	56.3	14.8	26.5	70.3	20.8	34.2	8.9	–	–
2–5	60.6	18.3	84.1	77.4	50.1	28.5	26.2	87.0	47.1
ANOVA: F/P	2.98/0.0085	2.06/0.06	4.27/0.0011	3.50/0.0028	1.90/0.08	3.14/0.0059	0.86/0.57	1.03/0.42	1.49/0.24
Dist.: r/P	0.44/0.20	0.51/0.13	0.59/0.09	0.39/0.26	−0.03/0.93	0.30/0.40	0.19/0.60	0.33/0.53	0.31/0.55
Poll.: r/P	−0.78/0.0082	−0.49/0.15	−0.47/0.20	−0.61/0.06	−0.05/0.89	−0.55/0.10	0.22/0.53	−0.40/0.43	−0.50/0.31

Sampling year shown in parentheses. For other explanations, consult Table 4.1.
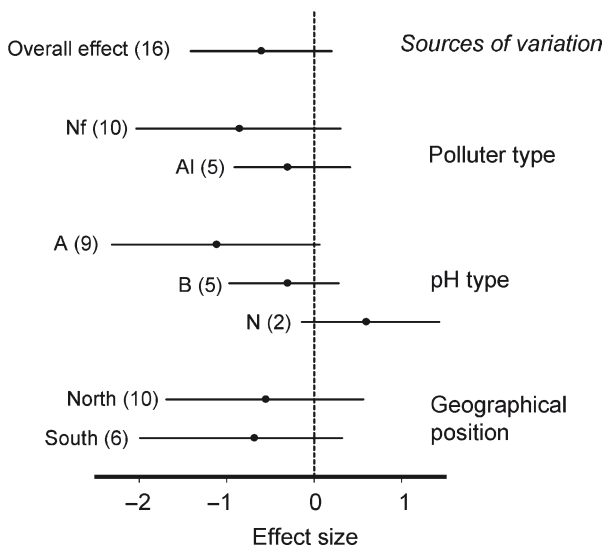
Fig. 4.11 Overall effect and sources of variation in the responses of leaf length of herbaceous plants (including height of herbaceous plants) to pollution. Effect sizes are Hedge's d based on comparison of two most polluted and two control sites. For explanations, consult Fig. 4.1
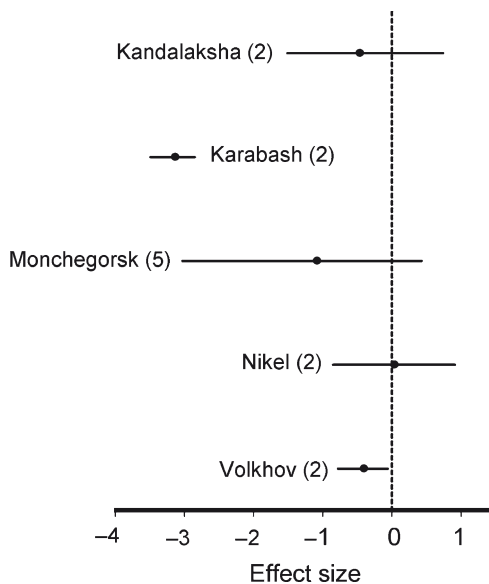
Fig. 4.12 Effects of individual polluters on the leaf length of herbaceous plants. Effect sizes are Hedge's d based on comparison of two most polluted and two control sites. For explanations, consult Fig. 4.1
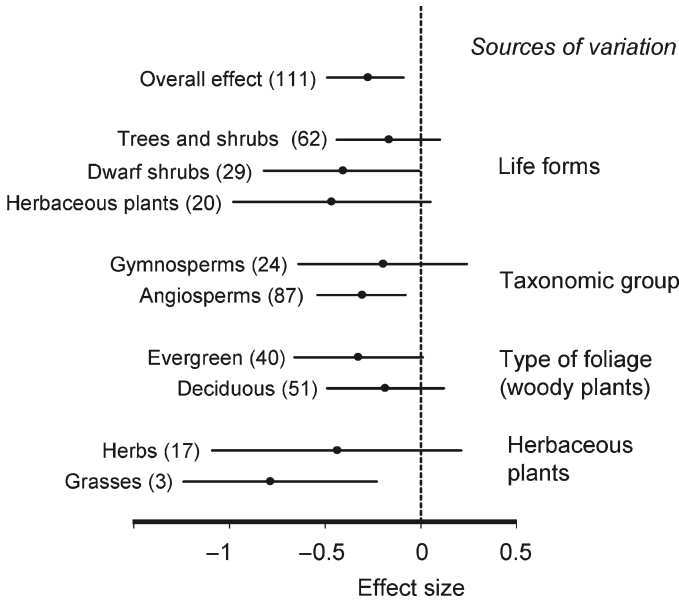
Fig. 4.13 Overall effect and sources of variation in the responses of shoot length of vascular plants (including height of herbaceous plants). Effect sizes are Hedge's d based on comparison of the two most polluted and two control sites. For explanations, consult Fig. 4.1
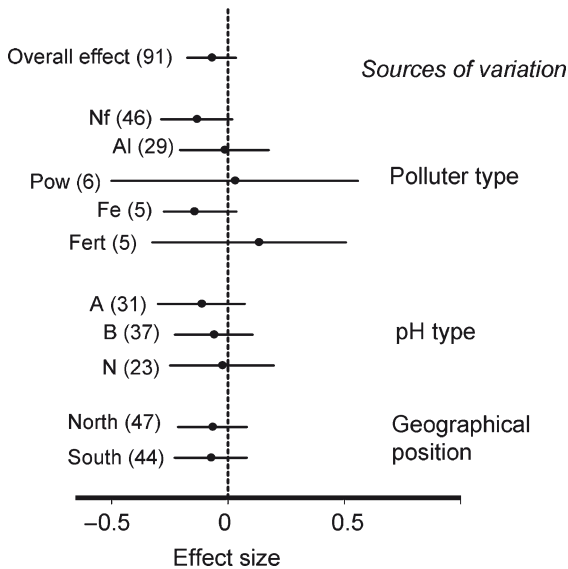
Fig. 4.14 Overall effect and sources of variation in the responses of shoot length of woody plant. For explanations, consult Fig. 4.1
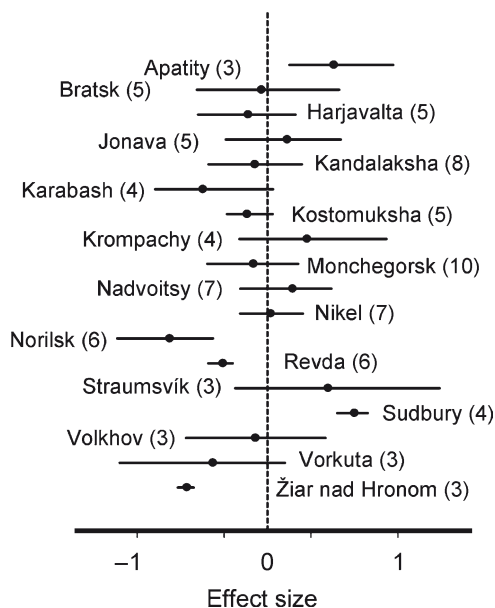
Fig. 4.15 Effects of individual polluters on the shoot length of woody plants. For explanations, consult Fig. 4.1

Three polluters caused significant negative effects (Norilsk, Revda, and Žiar nad Hronom), and two polluters caused positive effects (Apatity and Sudbury); the effects of other polluters were not significant (Fig. 4.15). Individual species of woody plants responded similarly to pollution (Q_B = 12.8, df = 13, P = 0.46); a significant decrease in shoot length was detected only in Siberian larch, *Larix sibirica* (Fig. 4.16).

Only non-ferrous smelters caused a decrease in the height of herbaceous plants (Fig. 4.17), although the difference between non-ferrous and aluminium smelters was not significant (Q_B = 2.66, df = 1, P = 0.10). Correspondingly, the effects depended on the pollution impact on soil pH (Q_B = 5.61, df = 2, P = 0.06): herbs were smaller only around acidifying polluters (Fig. 4.17). Pollution's effects on growth of herbaceous plants were independent of the geographical position of the polluters (Fig. 4.17; Q_B = 0.09, df = 1, P = 0.77). Among individual polluters (Q_B = 6.66, df = 5, P = 0.24), effects of three non-ferrous smelters were negative, while aluminium smelters caused both negative (Straumsvík) and positive (Kandalaksha and Volkhov) effects (Fig. 4.18).

Pollution effects on shoot length and on leaf/needle size did not differ (Q_B = 0.14, df = 1, P = 0.71) when calculated for the same data sets (species by polluter) and positively correlated to each other (r = 0.44, N = 70, P = 0.0001). Individual polluters imposed similar effects on these two vitality indices (r = 0.66, N = 18, P = 0.0027).
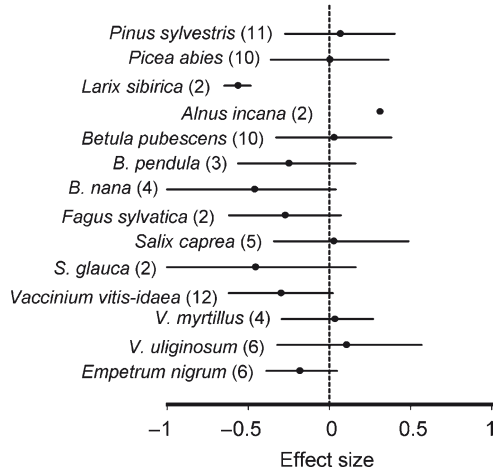
Fig. 4.16 Effects of point polluters on the shoot length of individual species of woody plants. For explanations, consult Fig. 4.1
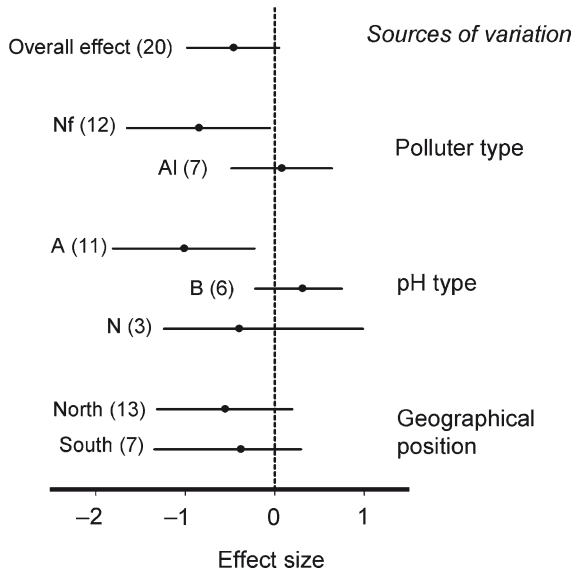
Fig. 4.17 Overall effect and sources of variation in the responses of height (equivalent to shoot length) of herbaceous plants. Effect sizes are Hedge's d based on comparison of two most polluted and two control sites. For explanations, consult Fig. 4.1

We have detected significant non-linear responses in ten of 100 data sets on woody plants (three dome-shaped and seven U-shaped), which is twice as high as the number of dome-shaped patterns that may be expected to occur by chance.
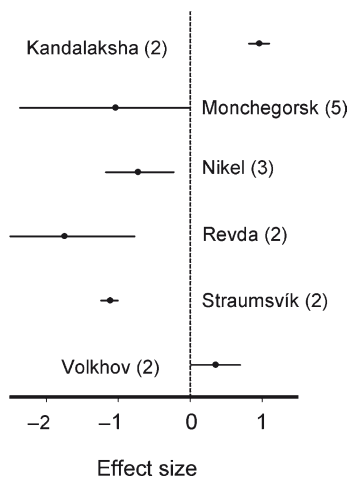
Fig. 4.18 Effects of individual polluters on height (equivalent to shoot length) of herbaceous plants. For explanations, consult Fig. 4.1

4.3.4   Radial Growth

Variation in tree ring width between study sites, in spite of small sample sizes, was significant (or nearly significant: $P = 0.06$) in five of ten data sets (Table 4.36). Radial increment in polluted sites tended to be lower than in clean sites (Fig. 4.19: $d = -0.77$, CI = $-1.55\ldots0.02$, $N = 10$), although the effect did not reach significance. The effect did not depend on the polluter type ($Q_B = 2.50$, df = 1, $P = 0.11$) or its effects on soil pH ($Q_B = 2.51$, df = 2, $P = 0.29$), although significant decreases in radial increment were observed only around acidifying polluters (Fig. 4.19). Similarly, although the differences between Northern and Southern polluters were not significant ($Q_B = 0.49$, df = 1, $P = 0.50$), adverse effects were observed only around the Northern polluters (Fig. 4.19).

Changes in radial growth of Scots pine ($d = -0.72$, CI = $-1.56\ldots0.13$, $N = 9$) tended to be larger than changes in shoot length around the same polluters ($d = -0.24$, CI = $-1.03\ldots0.55$, $N = 9$), but the difference was not significant ($Q_B = 0.91$, df = 1, $P = 0.34$). We found no correlation between polluter-specific effects on radial growth and shoot length ($r = -0.03$, $N = 9$, $P = 0.94$).

4.3.5   Needle Longevity in Conifers

Variation in needle longevity between study sites was significant in all 29 data sets; however, only 28 of 58 correlation coefficients (with both distance and pollution load) appeared significant (Tables 4.37 and 4.38).

Table 4.36 Width (mm) of annual rings of Scots pine (*Pinus sylvestris*), averaged for the past 10 years prior sampling

Sites	Apatity[a]	Harjavalta[b]	Jonava	Kandalaksha	Karabash[c]	Krompachy	Monchegorsk[d]	Nadvoitsy	Nikel[e]	Revda
	2006	2007	2005	2007	2007	2002	2005	2005	2007	2007
1–1	1.63 (60)	0.61 (43)	1.83 (31)	0.59 (49)	0.64 (130)	3.50 (33)	0.42 (47)	1.63 (49)	0.72 (29)	1.47 (59)
1–5	1.83 (49)	2.09 (42)	2.17 (35)	1.57 (52)	0.55 (134)	4.01 (28)	1.06 (38)	1.79 (60)	0.50 (35)	1.44 (65)
2–1	1.22 (59)	1.19 (45)	1.95 (39)	0.68 (54)	1.29 (59)	2.32 (38)	0.62 (32)	1.72 (44)	0.22 (48)	0.98 (63)
2–5	1.88 (56)	1.38 (52)	1.42 (51)	1.75 (48)	1.08 (61)	1.94 (51)	0.90 (44)	1.86 (59)	1.29 (41)	1.55 (63)
ANOVA: *F/P*	2.25/0.16	6.52/0.02	2.47/0.14	10.3/0.0041	3.63/0.06	4.36/0.04	2.17/0.17	0.23/0.87	4.87/0.04	0.62/0.62

Plot-specific means are each based on three tree-specific values; mean age of sampled trees is given in parentheses; sampling year shown under the locality name.

[a] Sampled sites: 1–2, 1–5, 2–1, 2–4.
[b] Sampled sites: 1–1, 1–5, 1–2, 2–4.
[c] Sampled sites: 1–2, 1–5, 2–2, 2–5.
[d] Sampled sites: 1–2, 2–9, 2–4, 2–10.
[e] Sampled sites: 2–1, 2–4, 2–2, 2–5.
For other explanations, consult Table 4.1.
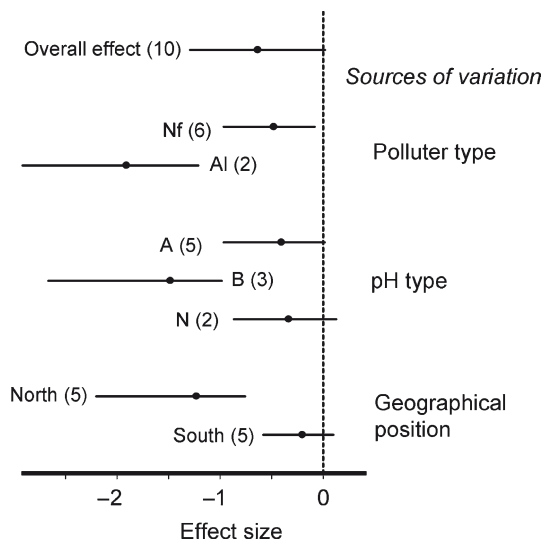
Fig. 4.19 Overall effect and sources of variation in the responses of radial increment of Scots pine (*Pinus sylvestris*). Effect sizes are Hedge's d based on comparison of two most polluted and two control sites. For explanations, consult Fig. 4.1

To explore the repeatability of the results, we estimated the needle longevity of Siberian/Norway spruce needles twice around Harjavalta, Kandalaksha and Monchegorsk, and three times around Krompachy (Table 4.38). Needle longevity of Scots pine was estimated twice around Harjavalta and Monchegorsk (Table 4.37). The measurements conducted in different years strongly correlated with each other ($z_r = 0.95$, CI $= 0.51\ldots1.39$, $N = 7$), demonstrating high repeatability of needle longevity estimates. Repeatability was equally high in both species ($Q_B = 0.09$, df $= 1$, $P = 0.92$).

Pollution generally caused a decrease in needle longevity (Fig. 4.20); this result did not depend on the method used to calculate ES ($Q_B = 1.08$, df $= 2$, $P = 0.58$). Pollution effect on needle longevity did not differ between Siberian/Norway spruce and Scots pine ($Q_B = 0.56$, df $= 1$, $P = 0.45$), allowing us to combine all species in further analyses.

Individual polluters differ in their effects on needle longevity (Fig. 4.21; $Q_B = 18.3$, df $= 8$, $P = 0.02$) from significant decreases (around seven of nine polluters) to significant increases with pollution (near the fertilising factory at Jonava). This variation was not linked with either the type of the polluter (Fig. 4.20; $Q_B = 6.23$, df $= 3$, $P = 0.10$) or with the changes in soil pH (Fig. 4.20; $Q_B = 3.72$, df $= 1$, $P = 0.16$). However, the significant negative effects of acidifying and alkalysing polluters differed (Fig. 4.20; $Q_B = 3.85$, df $= 1$, $P = 0.05$) from non-significant effects of polluters whose impact did not change soil pH. The Northern polluters negatively

Table 4.37 Needle longevity (years) in pines[a]

Site[b]	Bratsk	Harjavalta		Jonava	Kandalaksha	Karabash	Kostomuksha	Krompachy	Monchegorsk		Nadvoitsy	Nikel	Revda	Sudbury
	2002	2001	2007	2004	2001	2003	2002	2002	2001	2008	2004	2003	2003	2002
1–1	5.45	2.40	3.10	3.75	5.80	–	5.25	3.45	3.05	3.55	4.85	–	4.61	–
1–2	6.35	2.65	2.85	3.40	6.40	4.70	5.29	4.00	3.15	3.60	5.65	–	4.50	3.40
1–3	6.15	2.85	2.75	3.55	6.80	5.15	5.00	3.95	4.10	5.80	5.65	–	3.90	4.62
1–4	6.10	3.00	2.60	3.35	7.65	4.10	5.72	3.50	4.75	6.75	5.90	–	4.55	5.45
1–5	6.80	2.85	3.35	3.25	6.85	5.15	4.75	3.15	2.25	3.80	5.70	–	3.95	3.95
2–1	4.05	2.83	3.75	2.67	5.25	–	4.77	4.00	2.40	3.25	5.10	3.85	4.20	–
2–2	6.00	3.65	3.20	3.58	5.60	4.50	5.05	3.30	3.85	5.50	5.05	4.80	4.30	3.40
2–3	6.05	3.95	3.55	3.70	6.95	5.25	5.65	3.92	4.80	6.85	5.20	5.85	3.75	4.05
2–4	6.15	2.65	2.65	3.30	6.50	5.00	4.85	3.30	5.45	6.35	5.65	5.30	5.10	3.90
2–5	6.05	2.90	3.00	3.40	6.70	4.55	4.45	2.90	5.10	6.61	4.20	6.25	4.50	4.10
ANOVA: F/P	6.39/ <0.0001	7.78/ <0.0001	3.42/ 0.0013	6.60/ <0.0001	4.47/ <0.0001	2.50/ 0.02	4.27/ <0.0001	3.57/ 0.0009	21.4/ <0.0001	35.8/ <0.0001	4.35/ <0.0001	12.6/ <0.0001	3.89/ 0.0003	5.20/ 0.0005
Dist.: r/P	0.62/ 0.05	-0.12/ 0.73	-0.30/ 0.40	0.17/ 0.63	0.78/ 0.0072	-0.01/ 0.99	-0.13/ 0.72	-0.47/ 0.17	0.81/ 0.0046	0.85/ 0.0019	0.22/ 0.53	0.92/ 0.02	0.06/ 0.87	0.29/ 0.49
Poll.: r/P	-0.93/ <0.0001	-0.19/ 0.60	-0.04/ 0.91	0.25/ 0.48	-0.71/ 0.02	-0.10/ 0.81	-0.12/ 0.74	0.42/ 0.23	-0.86/ 0.0012	-0.75/ 0.01	-0.17/ 0.64	-0.89/ 0.04	-0.07/ 0.84	-0.53/ 0.17

[a] Scots pine (*Pinus sylvestris*) in all localities except for red pine (*Pinus resinosa*) in Sudbury; sampling year shown under the locality name.
[b] For all polluters except for Monchegorsk, where the sites are ordered as follows: 1–1, 1–2, 1–4, 1–5, 2–3, 2–4, 2–5, 2–8, 2–9, 2–10.
For other explanations, consult Table 4.1.

Table 4.38 Needle longevity (years) in spruces[a]

Site[b]	Bratsk	Harjavalta		Jonava	Kandalaksha		Kostomuksha	Krompachy			Monchegorsk		Nadvoitsy	Revda	Volkhov
	2002	2001	2007	2004	2001	2007	2002	2002	2004	2006	2001	2005	2004	2003	2002
1-1	9.90	–	–	–	10.65	8.75	13.35	5.44	6.25	5.65	4.10	5.80	7.95	8.60	8.75
1-2	10.60	–	6.83	8.75	10.15	10.65	10.55	9.10	8.15	6.60	3.65	7.90	11.15	8.95	5.00
1-3	12.60	7.15	8.35	9.20	14.10	12.45	11.30	8.00	8.16	7.25	8.25	7.65	13.55	10.50	6.17
1-4	12.80	7.56	8.80	7.10	13.95	13.65	11.00	9.05	8.70	8.00	9.40	10.95	13.70	10.30	8.85
1-5	14.00	9.59	8.70	9.55	12.60	13.95	14.55	8.90	9.05	10.10	4.15	6.65	14.95	11.40	9.20
2-1	5.20	–	–	–	7.67	8.00	10.00	6.75	5.45	6.80	6.55	6.35	8.40	6.20	10.00
2-2	9.40	8.83	9.88	8.50	8.62	7.00	12.35	6.50	7.05	6.00	7.50	7.25	9.45	8.20	8.89
2-3	11.00	10.80	10.55	10.60	11.05	11.70	10.65	9.65	9.65	7.45	10.55	8.90	10.60	9.20	8.25
2-4	14.20	11.35	11.35	10.65	13.90	13.05	11.25	7.05	9.90	7.50	9.70	10.95	13.20	11.05	8.75
2-5	13.05	11.65	8.20	7.85	13.10	12.65	14.00	9.10	10.30	7.95	10.80	10.20	14.10	10.35	8.25
ANOVA: F/P	18.2/ <0.0001	9.53/ <0.0001	5.43/ 0.0001	4.37/ <0.0001	8.17/ <0.0001	5.16/ <0.0001	8.38/ <0.0001	7.49/ <0.0001	13.6/ <0.0001	6.72/ <0.0001	27.8/ <0.0001	15.2/ <0.0001	15.2/ <0.0001	9.95/ <0.0001	2.36/ 0.02
Dist.: r/P	0.84/ 0.0022	0.33/ 0.47	-0.02/ 0.97	0.01/ 0.98	0.80/ 0.0054	0.84/ 0.0019	0.39/0.27	0.74/ 0.02	0.79/ 0.0060	0.84/ 0.0023	0.91/ 0.0002	0.80/ 0.0058	0.95/ <0.0001	0.86/ 0.0013	-0.04/ 0.91
Poll.: r/P	-0.89/ 0.0004	-0.15/ 0.74	-0.53/ 0.18	0.42/ 0.31	-0.81/ 0.0050	-0.78/ 0.0071	-0.32/0.37	-0.38/ 0.28	-0.76/ 0.01	-0.14/ 0.69	-0.72/ 0.02	-0.70/ 0.02	-0.85/ 0.0017	-0.83/ 0.0032	0.43/ 0.22

[a] Siberian spruce (*Picea abies* ssp. *obovata*) in all localities except for Norway spruce (*Picea abies* ssp. *abies*) in Jonava and Krompachy; sampling year shown under the locality name.

[b] For all polluters except for Monchegorsk, where the sites are ordered as follows: 1–1, 1–2, 1–4, 1–5, 2–3, 2–4, 2–5, 2–8, 2–9, 2–10. For other explanations, consult Table 4.1.
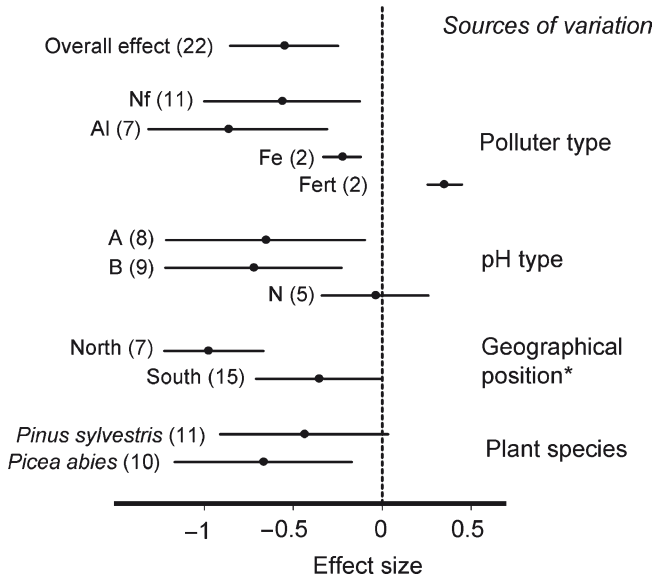
Fig. 4.20 Overall effect and sources of variation in the responses of needle longevity in coniferous plants. For explanations, consult Fig. 4.1
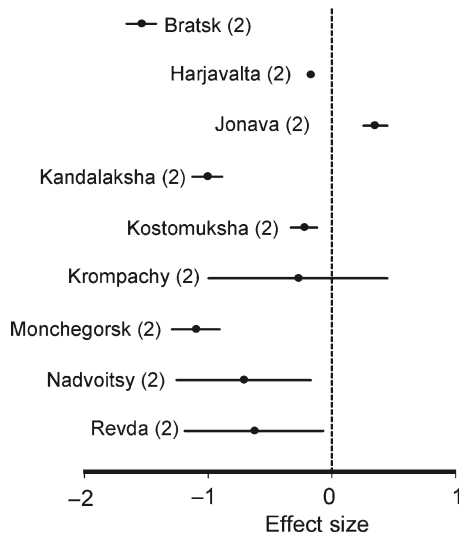

Fig. 4.21 Effects of individual polluters on needle longevity in coniferous plants. For explanations, consult Fig. 4.1

affected needle longevity, whereas southern polluters did not cause any effect (Fig. 4.20; $Q_B = 4.48$, df = 1, $P = 0.03$).

Pollution effects on needle longevity in pines and spruces were larger than the effects on needle size ($Q_B = 4.34$, df = 1, $P = 0.04$) and shoot length ($Q_B = 9.73$, df = 1, $P = 0.002$) when calculated for the same data sets (species by polluter). We found no correlation between polluter-specific effects on needle longevity and either shoot length ($r = -0.14$, $N = 21$, $P = 0.54$) or needle size ($r = -0.11$, $N = 11$, $P = 0.75$).

Only three of 27 data sets were better fitted by the second-order (dome-shaped) function than by the linear model.

4.4   Discussion

4.4.1   Overall Effects of Pollution on Vitality Indices

4.4.1.1   Chlorophyll Fluorescence

Negative effects of different pollutants, like fluorine, sulphur dioxide and heavy metals, on photosynthesis of several species have been detected both in experiments (Snel et al. 1991; Strand 1993; Cook et al. 1997; Łukaszek & Poskuta 1998; Ouzounidou et al. 2006) and in field studies using plants naturally growing in polluted areas (Saarinen 1993; Odasz-Albrigtsen et al. 2000; Andreucci et al. 2006). On the other hand, some researchers did not detect adverse effects of pollution on chlorophyll fluorescence either in experiments (Boese et al. 1995; Sahi et al. 2007) or in field conditions (Lepedus et al. 2005; Zvereva & Kozlov 2005; Divan et al. 2007). The factors contributing to discrepancies between studies have not, to our knowledge, been identified.

The absence of repeatability in multiyear measurements conducted on the same birch trees around Monchegorsk (Table 4.1) is indeed frustrating. This result demonstrated that environmental variables (some of which have not been controlled in the course of our study) can substantially modify responses of the photosynthetic system to pollution. In light of this information, the significant variation between both study sites (Tables 4.1–4.17) and individual polluters (Figs. 4.1 and 4.4) is difficult to interpret. While this variation may reflect more or less stabile differences between study sites (e.g., in soil contamination and nutritional quality, as well as in leaf area index), it may also result from short-term variation (e.g., in temperature, illumination, and soil moisture at the time of sampling). All of these factors are known to influence photosynthesis (Mohammed et al. 1995; Martinez-Carrasco et al. 2005; Qaderi et al. 2006; Kitao et al. 2007), making interpretation of observational data collected at multiple plots a difficult task. Thus, it is not surprising that we failed to confirm the negative effect of pollution on F_v/F_m in the vicinity of Nikel that was detected by Odasz-Albrigtsen et al. (2000). On the other hand, the

absence of a pollution effect on F_v/F_m in Scots pine near Revda is in line with the results of Shavnin et al. (1997).

Meta-analysis revealed no pollution effect on F_v/F_m, suggesting that the significant decline of this index in plants growing in polluted habitats reported in earlier studies (Saarinen 1993; Saarinen & Liski 1993; Odasz-Albrigtsen et al. 2000) can be observed only under specific environmental conditions. The detected absence of F_v/F_m changes around industrial polluters is in line with the conclusion by Bussotti et al. (2008), who found that this index is less sensitive to ozone exposure than other parameters of chlorophyll fluorescence. More generally, F_v/F_m is considered most suitable for evaluation of plant responses to short-term impacts, primarily to temperature extremes (Lichtenthaler & Rinderle 1988; Sayed 2003), while its applicability for exploration of consequences of chronic stress is questioned (Venediktov et al. 1999).

In contrast to F_v/F_m, the time needed for the leaf to reach half of its F_m ($T_{1/2}$) in our data sets increased with an increase in pollution load (Fig. 4.4), indicating a slowing down of the photochemical reaction. Differential responses of two indices of chlorophyll fluorescence to environmental variation have previously been detected in several studies addressing both abiotic and biotic stress on mountain birch (Eränen & Kozlov 2006, 2008). Although in environmental studies $T_{1/2}$ has been used less frequently than F_v/F_m, our results suggest that this parameter may be more informative, or less influenced by factors other than pollution, and therefore deserves more attention from environmental scientists. Other indices reflecting different aspects of the induction and attenuation of chlorophyll fluorescence (reviewed by Van Kooten & Snel 1990; Nesterenko et al. 2007) may also be useful in exploring the consequences of chronic impacts of industrial pollutants.

4.4.1.2 Leaf/Needle Size, Shoot Growth and Radial Increment

Surprisingly, the overall effect of pollution on leaf/needle size appeared non-significant (Fig. 4.7; $d = -0.22$, CI $= -0.46\ldots0.02$, $N = 88$). This result strongly contrasts with a meta-analysis of published data (Roitto et al. 2009), which demonstrated a substantial decrease in leaf/needle size with pollution ($d = -1.08$, CI $= -1.35\ldots-0.80$, $N = 204$). Adverse effects on shoot length detected from our data sets (Fig. 4.13; $d = -0.29$, CI $= -0.49\ldots-0.08$, $N = 111$) better fit both the general theory and meta-analysis of published data, although the magnitude of the effect was about one third of that calculated from published studies ($d = -1.06$, CI $= -1.27\ldots-0.84$, $N = 164$). Similarly, ES based on published data on radial increment (d $= -1.45$, CI $= -2.08 \ldots -0.81$; N $= 40$) was twice as large as ES based on original data (Fig. 4.19: $d = -0.77$, CI $= -1.55\ldots0.02$, $N = 10$).

Of course, the two meta-analyses are based on data of different structure. For example, 50% of the original data on shoot length were collected around non-ferrous polluters, compared with 25% of the published data. Since non-ferrous smelters generally impose stronger effects on biota than other polluters (Kozlov &

Zvereva 2007a; Zvereva et al. 2008), we expected to find a stronger effect relative to the published data. Therefore, as in several other situations (Sections 6.4.3 and 7.4.1), we suggest that the detected differences result from both research and publication biases. The smallest difference between the original and published data was observed for radial increment, further supporting this conclusion since assessment of the width of annual rings (in contrast to leaf size or shoot length) is less susceptible to influence by unintentional non-random selection of study sites.

Since a meta-analysis of published data (Roitto et al. 2009) demonstrated that pollution similarly affected the size and weight of plant metamers (leaves/needles and shoots), the decrease in shoot length with pollution can be interpreted as a decline in biomass production. However, although our results supported the somewhat trivial (Scurfield 1960a, b; Odum 1985; Treshow & Anderson 1989; Armentano & Bennett 1992; Dobbertin 2005; Roitto & Kozlov 2007; Roitto et al. 2009) conclusion on adverse effects of pollution on plant growth, we demonstrated that this effect is usually overestimated.

4.4.1.3   Needle Longevity in Conifers

Our result of a significant decrease in needle longevity near industrial polluters generally agrees with the published data. Substantial decreases in needle longevity were reported for Siberian spruce near the Monchegorsk nickel-copper smelter (Kryuchkov & Makarova 1989; Stjernquist et al. 1998) and Kandalaksha aluminium smelter (Kryuchkov & Makarova 1989); for Scots pine near the Monchegorsk nickel-copper smelter (Yarmishko 1993, 1997; Jalkanen 1996; Lamppu & Huttunen 2003), near the Kostomuksha iron pellet plant (Lamppu & Huttunen 2003), and in industrial regions of Eastern Germany (Schulz et al. 1998); and for both Korean pine (*Pinus koraiensis*) and Pitch pine (*P. rigida*) in the Ansan industrial region of Korea (Choi et al. 2006). An absence of effects was reported only exceptionally: pollution of the oil shale industry in northeast Estonia did not influence needle longevity in Scots pine (Pensa et al. 2000, 2004).

The decrease in needle longevity with pollution is opposite to changes observed along other environmental gradients. Plants growing in less favourable conditions, including lower temperatures during the growth season, tend to compensate for reduced photosynthesis by increased longevity of needles (Ewers & Schmid 1981; Schoettle 1990; Jalkanen 1995; Pensa et al. 2007). Needle longevity is generally higher on less fertile soils (Lamppu & Huttunen 2003; Pensa et al. 2007); fertilisation decreased needle longevity of both Douglas fir (*Pseudotsuga menziesii* var. *glauca*) and grand fir (*Abies grandis*) (Balster & Marshall 2000). Thus, premature shedding of foliage is a specific response to pollution rather than a general response to environmental stress; it may result from acceleration of aging processes due to pollution impact (Wulff et al. 1996). Importantly, shedding of older needle age classes does not necessarily reduce primary production: thinning of the tree crown may increase the levels of photosynthetically active radiation reaching the remaining (younger) needles (Beyschlag et al. 1994).

Although pollution research often focuses on Scots pine, we conclude that needle longevity in Siberian/Norway spruce is a more sensitive indicator of pollution impact. This is particularly due to the generally higher number of age classes (up to 17 in the northernmost regions) retained by spruces in unpolluted regions (Table 4.37), which makes the difference between polluted and control sites larger in absolute value.

Thus, our data support an earlier conclusion (Schubert 1985; Kryuchkov & Makarova 1989) that needle longevity may serve as a handy indicator of pollution impact on the vitality of conifers. However, this indicator is far from being universal: it is applicable only to polluters that change soil pH, and its power decreases from North to South.

4.4.2   Sources of Variation in Pollution Impacts on Vitality Indices

4.4.2.1   Variation Between Study Years

Weather conditions of both previous and current seasons greatly influence plant growth and vitality (Hustich 1978; Junttila & Heide 1981; Valkama & Kozlov 2001; Morison & Morecroft 2006; Jonas et al. 2008) and are likely to modify pollution effects on plant vitality (Armentano & Bennett 1992). However, except for dendrochronological studies, this source of variation remains almost unexplored and is therefore routinely neglected in pollution ecology.

The vitality indices measured in the course of our study demonstrated different levels of annual variation. Needle longevity showed the highest correspondence between measurements conducted in different years (Section 4.3.5). Shoot growth measurements also correlated between study years, although to a lesser extent than needle length (Section 4.3.3). Finally, annual variation in both indices of photosynthetic efficiency was so large that even the sign of the correlation with pollution load changed with study year. These results clearly demonstrate that annual variation in plant responses to pollution is substantial and should therefore be accounted for in environmental monitoring and assessment programs. Long-term monitoring in polluted regions is the only way to obtain the data for parameterisation of phenomenological models accounting for the combined effects of pollution and weather conditions on plant growth.

4.4.2.2   Variation Between Polluters

Individual polluters generally differ in their impacts on woody plants: polluter-specific changes of all vitality indices varied from significantly negative to significantly positive (Figs. 4.2, 4.5, 4.9, 4.15, 4.21). Importantly, vitality indices (except

for leaf/needle size and shoot length) showed individualistic (uncoordinated) responses to the impacts of the investigated polluters.

The detected variation between individual polluters in general was not related to the type of the polluter. This result contrasts with the meta-analyses of published data, which consistently detected significant variation among the classes of polluters (Ruotsalainen & Kozlov 2006; Zvereva et al. 2008; Zvereva & Kozlov 2009, Roitto et al. 2009). The difference most likely resulted from the limited number of polluter types involved in our study. In particular, we did not survey chemical factories, which caused the largest effects on plant growth (Roitto et al. 2009) and significantly altered insect abundance (Zvereva & Kozlov 2009).

Only changes in the leaf/needle size of woody plants and in the height of herbaceous plants depended on pollution effect on soil pH. Adverse effects were stronger around acidifying polluters.

To conclude, our data suggest that only a minor part of the variation in plant vitality changes around industrial polluters can be explained by the type of the polluter or by its impact on soil pH. Thus, other sources of variation need to be explored in greater detail to allow building of phenomenological models.

4.4.2.3   Variation Between Plant Species

Investigated plants similarly responded to pollution: we did not detect differences between species, life forms, or between evergreen and deciduous plants, in any of the vitality indices considered in the present study. We also identified only one marginally significant relationship between the pollution-induced changes in leaf length and ecological habitat requirements, as shown by the Ellenberg's indicator values: species with higher light requirements tended to respond positively to pollution. We think that this regularity reflects plant responses to pollution-induced habitat deterioration, primarily forest decline leading to higher light availability, rather than direct effects of industrial pollutants. Although we did not find significant correlations between the ESs and scores of Grime's CSR strategy, this result should be viewed as tentative, since the scores were available for only 15 of 43 investigated species.

Similarly, Gymnosperms and Angiosperms did not differ in their responses to pollution. This result clearly contrasts with the repeatedly expressed opinion on higher sensitivity of conifers to industrial pollution relative to deciduous plants (Crowther & Steuart 1914; Bohne 1971; Freedman 1989; Vike 1999; Hijano et al. 2005; Ozolincius et al. 2005). Importantly, a meta-analysis of published data (Roitto et al. 2009) yielded stronger adverse effects on Gymnosperms than on Angiosperms in shoot size (d = −1.59 vs. −0.61) but similar changes in leaf/needle size (d = −0.99 vs. −1.12). While original data demonstrated that the decrease in both leaf size and shoot length was significant in Angiosperms, but did not differ from zero in Gymnosperms (Figs. 4.7 and 4.13). These patterns may indicate the existence of both research and publication biases. Damage to conifers (independent of its cause), due to their higher economical importance,

obviously received more attention than damage to other groups of plants, and studies supporting the general paradigm were published more readily.

Last but not least, damage to conifers has sometimes been attributed to pollution erroneously. One of the most recent examples is forest damage observed in Finnish Lapland in the late 1980s. Forest dieback was originally believed to be the result of pollution transfer from the adjacent industrial areas of the Kola Peninsula. However, detailed investigations revealed that the amounts of industrial emissions reaching Finnish Lapland would hardly cause forest damage. The marked premature shedding of needles and other signs of forest damage are now explained by exceptional weather conditions in the previous autumn and winter, when fast freezing of the soil caused root damage, in combination with the extensive epidemy of the scleroderris cancer (Tikkanen & Niemelä 1995).

Thus, although we do not question different pollution sensitivity of plant species, our results suggest that between-species variation in plant responses to pollution does not depend on their taxonomic affinity (in terms of Gymnosperms vs. Angiosperms), growth form or life habit, and is only weakly (if at all) related to their ecological habitat requirements.

4.4.2.4 Geographical Variation

Responses of several vitality indices (such as needle longevity and the rate of photochemical reactions) differ between the northern and southern polluters, while variations in other indices were independent of the location of the polluters.

Significant decreases in both needle longevity and radial increment were observed only around the northern polluters. We suggest that the differential effects on needle longevity were to a certain extent due to well-known geographical variation in this index (Ewers & Schmid 1981; Schoettle 1990; Jalkanen 1995): there are no 'spare' needles in southern regions that can be shed under pollution impact.

Stronger adverse effects of the northern polluters on radial increment of Scots pine may be explained in two ways. First, stand density around the southern polluters is generally higher than around the northern polluters (Tables 6.15–6.26), indicating a greater importance of competition in the southern relative to the northern regions. If plant growth is limited by competition, then we may expect no effects of pollution, or even better growth of the survivors released from competition pressure due to decreased stand density in polluted regions. Second, additional stress from pollution may cause a greater reduction of plant growth in the less favourable northern environment.

In contrast to needle longevity and radial increment, adverse effects of pollution on photosynthesis (in terms of $T_{1/2}$) were significant only near the southern polluters (Fig. 4.4). Although the mechanisms behind this pattern cannot be revealed from our data, we hypothesise that pollution-induced forest deterioration results in more pronounced climatic differences between polluted and unpolluted sites in the harsh climate of the northern taiga and subtundra zone. On sunny days

in particular, polluted (more open) sites are warmer than the surrounding forests (Hursh 1948; Wołk 1977; Kozlov & Haukioja 1997; Winterhalder 2002), and the positive effects of this temperature increase on photosynthesis (Sage & Kubien 2007) can mask or even counterbalance the adverse impacts of toxicants.

4.4.3   Carbon Allocation and Allometric Relationships

Pollution differentially affected growth of plant parts (Kozlov & Zvereva 2007b; Section 4.4.1.2), thus influencing the allometric relationships. However, this research field remains almost unexplored. A notable exception is the shoot/root ratio; however, it was studied almost exclusively in experimental conditions (Rennenberg et al. 1996). Field data exist for tree crown structure, changes of which were documented in several case studies (Sokov & Rozhkov 1975; Yarmishko 1993) but never generalized. We are aware of a single study explicitly addressing the impact of industrial pollution on plant allometry (Elkarmi & Eideh 2006). This acute shortage of information hampers understanding of pollution impact on carbon allocation within the plant.

Stress supposedly alters not only photosynthesis but also subsequent carbon allocation in a tree in such a way that the most important processes are last affected (Waring 1987). A ranking of foliage, shoot and trunk growth responses to pollution in woody plants based on our data (Figs. 4.7, 4.13, 4.19) only partially agrees with the order of their importance for a tree as suggested by Waring (1987). Leaf/needle size, which is considered most important, was not affected by pollution (correlation re-calculated from the ES: $r = -0.08$), and trunk increment, which is least important, showed the largest decrease with pollution ($r = -0.35$). On the other hand, we detected no effect of pollution on shoot growth ($r = -0.09$), which is considered less important for a tree than the growth of foliage (Waring 1987).

Effect sizes calculated for individual vitality indices still show either positive correlations to each other (for leaf/needle size and shoot length) or no correlation. Thus, we did not detect any trade-offs in responses of different growth processes to pollution. However, since these correlations were based on site-specific values, we can only conclude that resource allocation showed no consistent response to pollution, while individualistic responses may well exist. This research field obviously deserves further investigation.

4.5   Summary

Although studies of pollution impact on plant vitality in general and plant growth in particular started more than a century ago, the amount of reliable and comprehensive information remains insufficient to explain variation in plant responses to pollution.

These responses depend more on the individual polluter than on the affected plant species, and vitality indices measured from the same plants often show uncoordinated responses to pollution. In woody plants, we found no effects on the efficiency of photosynthesis (measured by F_v/F_m) or leaf/needle size. Slight adverse effects were detected on the rate of photochemical reaction (measured by $T_{1/2}$) and on shoot length, while radial increment strongly decreased with pollution. Responses of all vitality indices demonstrated annual variation, frequently resulting in inconsistency of results obtained in different years. Still our data confirm that pollution generally decreases plant vitality and productivity, although these effects are much smaller than could have been expected from published studies. Needle longevity is the best operational index of pollution impact on the vitality of conifers.