# Abundance of day-flying Lepidoptera along an air pollution gradient in the northern boreal forest zone[1]

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Day-active lepidopterans were counted in the summers of 1991–1993 on transects of 5 × 100 m in 12 localities representing five zones of pollution-induced forest deterioration in the Kola Peninsula, northwestern Russia. A total of 671 specimens representing 19 species was observed during 696 counts. Two butterflies (*Clossiana euphrosyne, Vacciniina optilete*) and three day-active moths (*Rheumaptera subhastata, Ematurga atomaria, Sympistis heliophila*) were used in the analysis; the remaining 14 butterfly species were too scarce for the statistical treatment. At early stages of pollution-induced forest damage (mean annual $SO_2$ concentrations 20–40 μg/m$^3$), the densities of the monitored species increased by a factor of 1.5 to 5, but then declined with increase in pollution. Since the host plants of the monitored species, except that of *C. euphrosyne*, were found in all localities surveyed, the decline could be attributed to the $SO_2$ toxicity rather than to the lack of larval food. Although transect counts did produce valuable information about the impact of pollution on subarctic forest ecosystems, the method is poorly suited for routine bioindication of pollution in northern regions.

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## 1. Introduction

Although butterflies are favourite objects of numerous monitoring programs (Pollard *et al.* 1986, 1993, Pollard 1991), they have hardly been used as indicators of pollution impact (but see Barbour 1986). However, the large amount of literature on this group, and the simple methods designed for estimating butterfly abundance (Pollard 1977, Hall 1981) make these insects attractive candidates for monitoring of pollution-induced changes in forest ecosystems. Furthermore, the simultaneous counts of day-active moths which can be distinguished in the field by an experienced ob-

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server (Väisänen 1992) can overcome difficulties connected with the low abundance of butterflies in subarctic regions.

Our study aimed to assess changes in the densities of the most abundant butterflies and day-active moths along an air pollution gradient and to evaluate the suitability of transect counts for a practical monitoring program in the northern boreal forest zone.

## 2. Material and methods

### 2.1. Study area and pollution source

The study was conducted in the largest polluted zone in Northern Europe (about 10 000 $km^2$; Kozlov & Haukioja 1995) around the heavily industrialized city of Monchegorsk (Kola Peninsula, Northwestern Russia; 68°N, 33°E). The region belongs to the northern taiga, 150 km south of the northern tree limit. About 97% of the emissions in the Monchegorsk area are produced by the Severonikel smelter complex, which in 1990 emitted $2.33 \times 10^8$ kg of sulphur dioxide and $1.58 \times 10^7$ kg of dusts containing heavy metals ($2.7 \times 10^6$ kg of nickel, $1.8 \times 10^6$ kg of copper; Berlyand 1991).

### 2.2. Sampling sites

The sampling sites, 23 in total, were chosen at 12 localities (1–13 km N/NE and 1–65 km S/SE of the smelter), representing the mixed spruce–birch forests at different stages of deterioration, as similar in vegetation as possible. Both pre-existing heterogeneity in vegetation structure (Kozlov & Haukioja 1995) and pollution contributed to the variation in habitat characteristics (Table 1). To account for this variation, the localities were classified as follows:

- Zone 0. Healthy spruce forest with an admixture of birches (5–10% of trees); birch seedlings and saplings very sparse; dwarf-shrubs and mosses cover nearly 100% of the ground; the longevity of spruce needles mainly 10 to 12 years.
- Zone 1. Weakened spruce forest with sparsely growing trees, higher proportion of birches (10–20%), and ground cover reduced to 80–90%; the longevity of spruce needles 6 to 9 years; birch leaves without necrotic damage by the end of the growth season.
- Zone 2. Very sparse birch-dominated forest with dense birch growlings and saplings (1 500–6 000 per ha), sometimes with young pine trees; vegetation cover 40–60%; the longevity of spruce needles < 4–5 years, birch leaves with necrotic spots by the end of the growth season.
- Zone 3. Depressed birch woodland, with tree height < 2 m; birch foliage heavily injured already in mid-July; ground vegetation almost vanished (cover 5–15%), soils eroded and bedrock open in large areas.

Table 1. Basic characteristics of the study sites.

| Distance from smelter (km) | Direction from smelter | Annual $SO_2$ level ($\mu g/m^3$)[a] | Plant species per 100 $m^2$ Vascular[b] | Total[b] | Total cover (%)[b] | Zone | Total sampling effort (counts) |
|---|---|---|---|---|---|---|---|
| 13 | North | 20 | 7 | 12 | 40 | 2 | 48 |
| 10 | North | 25 | 6 | 8 | 25 | 2 | 32 |
| 7 | North | 120 | 6 | 7 | 15 | 3 | 28 |
| 1 | North | 1 000 | 5 | 5 | 25 | 4 | 32 |
| 1 | South | 800 | 8 | 8 | 50 | 4 | 40 |
| 5 | South | 450 | 6 | 8 | 30 | 3 | 72 |
| 9 | South | 400 | 6 | 7 | 10 | 3 | 88 |
| 16 | South | 55 | 8 | 10 | 50 | 2 | 80 |
| 23 | South | 40 | 11 | 13 | 80 | 2 | 84 |
| 29 | South | 30 | 7 | 14 | 90 | 1 | 128 |
| 35 | South | 15 | 7 | 14 | 95 | 1 | 24 |
| 65 | South | 5 | 6 | 13 | 95 | 0 | 40 |

[a]After Baklanov and Rodjushkina 1993, Barkan 1993, Kryuchkov 1993.
[b]After Koroleva 1993, M. Kozlov, personal observation.

— Zone 4. Similar to 3, but with large willow bushes (*Salix caprea, S. borealis*) and spots of ruderal vegetation (*Urtica dioica, Epilobium angustifolium*) formed on barrenlands adjacent to the smelter.

### 2.3. Transect counts

Four lines of 100 m, forming a quadrate or circle, were marked at each sampling site. Counts were conducted 1–29 July 1991, 27 June–27 July 1992 and 11–22 July 1993. Limits of weather conditions were followed according to Pollard (1977), with modifications for the northern areas as published by Somerma and Väisänen (1990). Meteorological data were recorded at the beginning of each count. The ambient air temperature was measured by thermometer and wind strength was estimated according to the Beaufort scale. Degree of cloudiness (ranked as 0, 25, 50, 75 or 100%) and the presence of shade were also recorded. These data were used to test the hypothesis that among-site differences were related to variable weather conditions at the time of the counts.

The observer walked along the transect route with an even speed and counted all butterflies and moths sighted within 5 m either side of the 100-m line. Stops were made for identification purposes, but no specimens were collected at the study sites. Each line took < 5 minutes to count. To minimize the error caused by daily rhythms of activity, every second site was visited between 10 a.m. and 2 p.m., other sites between 2 and 6 p.m. The sites visited in the first half of the day were next time counted during the second half of the day.

### 2.4. Treatment of data

The relationship between the site-specific densities of the monitored species and the mean annual $SO_2$ concentrations were investigated by using the Spearman rank correlation coefficient (CORR procedure, SAS Institute 1990). To account for a possible non-linear response, the density variation was tested by SAS NPAR1WAY procedure with vegetation zones as an independent variable. Since sampling design might be unbalanced in respect of observation time and weather conditions, least-square means (LSMs) were computed for each plot and compared with corresponding mean values. LSMs are estimators of the plot marginal means that would be expected had the design been balanced (SAS Institute 1990). Pairwise comparisons between mean values were based on *t*-test with the confidence limit $P = 0.05$.

## 3. Results

### 3.1. Species composition

During the three years of observation, 671 individuals comprising 19 species were observed (Table 2). Five species were commonly encountered, including three day-active moths, *Rheumaptera subhastata, Ematurga atomaria* and *Sympistis heliophila*, and two butterfly species, *Vacciniina optilete* and *Clossiana euphrosyne*. Together, these five species accounted for 93.1% of total observations; *R. subhastata*, the most abundant species, comprised 35.6% of observations.

The maximum number of species was recorded in the vegetation zones 1 and 2 (Table 2). Both mean abundance of Lepidoptera and total number of species counted on transect lines correlated with the total number of plant species (including mosses and lichens) per 100 m² ($r_S = 0.82$ and $r_S = 0.76$, $n = 12$, $P < 0.01$, respectively). The number of vascular plant species and the vegetation cover (Table 1) have lower explanatory values ($r_S = 0.46$–$0.64$).

### 3.2. Population densities

Population densities of the five most abundant species peaked in localities with moderate (15–40 μg/m³) concentrations of sulphur dioxide (Figs. 1–5). The maximum densities were 1.5 to 5 times higher than densities in the site with $SO_2$ concentration close to the background level (5 μg/m³), depending on species. The density variation in respect to both study site (Table 3) and vegetation rank (Figs. 6–10) was highly significant for all species ($F_{4, 723} = 4.7$–$14.5$, $P < 0.001$).

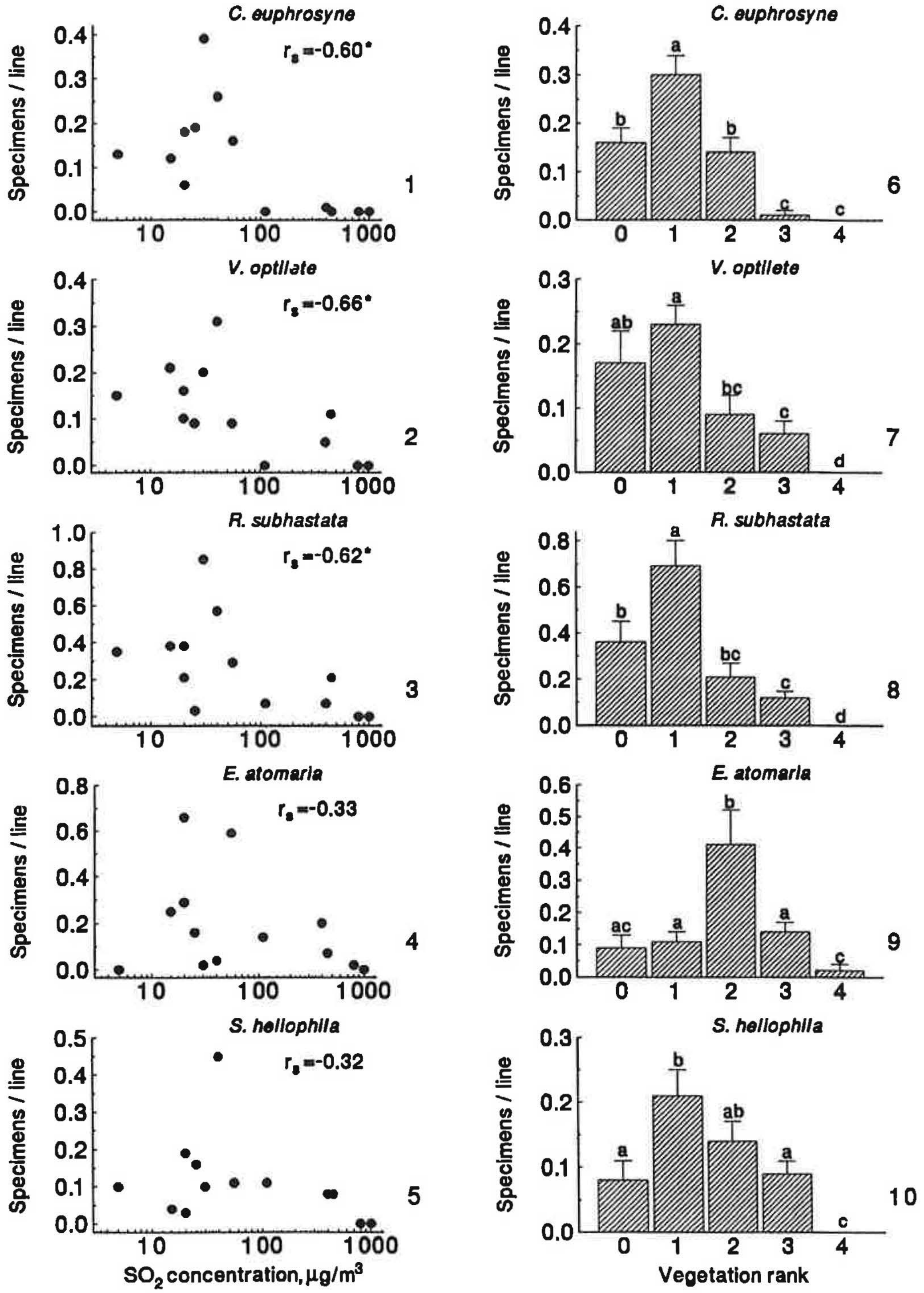
Although individual counts were greatly affected by the observation time and weather conditions (Table 3), the site-specific LSMs (least-square means) of all species except for *R. subhastata* correlated with the corresponding mean values (r = 0.90–0.99, n = 12, P < 0.0001); for *R. subhastata* this correlation was only marginally significant (r = 0.53, n = 12, P < 0.063). The high correlations between means and LSMs indicated that the experimental design has been well balanced, and therefore the differences between study sites could be attributed to the environmental heterogeneity.

Table 2. Species of butterflies and day-active moths observed at different distances from the smelter (cf. Table 1). Data represent the total number of individuals observed at each site.

| | Total no. of specimens | Distance from the smelter (km) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Northwards | | | | Southwards | | | | | | | |
| | | 13 | 10 | 7 | 1 | 1 | 5 | 9 | 16 | 23 | 29 | 35 | 65 |
| **Pieridae** | | | | | | | | | | | | | |
| *Pieris napi* (L.) | 6 | 0 | 0 | 0 | 1 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Colias palaeno* (L.) | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 |
| **Lycaenidae** | | | | | | | | | | | | | |
| *Callophrys rubi* (L.) | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| *Lycaeides idas* (L.) | 14 | 5 | 3 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 3 | 0 | 2 |
| *Vacciniina optilete* (Knoch) | 89 | 5 | 3 | 0 | 0 | 0 | 8 | 4 | 7 | 26 | 25 | 5 | 6 |
| *Polyommatus icarus* (Rott.) | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Nymphalidae** | | | | | | | | | | | | | |
| *Boloria aquilonaris* (Stich.) | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 |
| *Proclossiana eunomia* (Esp.) | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| *Clossiana selene* (D. & S.) | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| *Clossiana freija* (Thunb.) | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 0 | 0 |
| *Clossiana frigga* (Thunb.) | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 |
| *Clossiana euphrosyne* (L.) | 98 | 3 | 6 | 0 | 0 | 0 | 0 | 1 | 13 | 22 | 50 | 3 | 0 |
| **Satyridae** | | | | | | | | | | | | | |
| *Erebia disa* (Thunb.) | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| *Erebia pandrose* (Bkh.) | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 |
| *Oeneis norna* (Thunb.) | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| *Coenonympha tullia* (Müll.) | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| **Geometridae** | | | | | | | | | | | | | |
| *Rheumaptera subhastata* (Nolck.) | 237 | 10 | 1 | 2 | 0 | 0 | 15 | 6 | 23 | 48 | 109 | 9 | 14 |
| *Ematurga atomaria* (L.) | 106 | 14 | 5 | 4 | 0 | 1 | 5 | 12 | 47 | 3 | 3 | 6 | 0 |
| **Noctuidae** | | | | | | | | | | | | | |
| *Sympistis heliophila* (Payk) | 95 | 9 | 5 | 3 | 0 | 0 | 6 | 7 | 9 | 38 | 13 | 1 | 4 |

Table 3. Effects of experimental design and weather conditions (F values and confidence limits) on the abundance of the monitored species. Probability levels: ***P < 0.001, **P < 0.01, *P < 0.05.

| Variation source | *Clossiana euphrosyne* | *Vacciniina optilete* | *Rheumaptera subhastata* | *Ematurga atomaria* | *Sympistis heliophila* |
|---|---|---|---|---|---|
| Locality | 5.75*** | 3.84*** | 4.76*** | 4.34*** | 8.53*** |
| Year | 14.28*** | 0.07 | 74.73*** | 10.93*** | 5.87* |
| Date | 0.01 | 0.09 | 0.34 | 0.03 | 7.27** |
| Time | 0.92 | 0.30 | 26.84*** | 0.18 | 0.22 |
| Temperature | 0.53 | 0.66 | 40.42*** | 7.04** | 1.17 |
| Wind | 0.03 | 6.24* | 21.03*** | 0.00 | 10.09** |
| Shade (yes/no) | 5.61* | 9.24** | 0.37 | 0.22 | 0.20 |
| Cloudiness | 4.48* | 2.17 | 17.73*** | 1.72 | 9.90** |




Figs. 1–10. Densities of the monitored species (specimens per transect line). 1–5: the site-specific means plotted against mean annual concentrations of sulphur dioxide. 6–10: the zone-specific means and standard errors; differences between bars marked with different letters are significant ($P < 0.05$).

*Clossiana euphrosyne* (Fig. 6) was equally abundant in unpolluted (zone 0) and moderately polluted (zone 2) sites, with peak density attained at early stages of pollution-induced forest deterioration (zone 1). In this species, population decline near the smelter was probably related to the decline of host plants (*Viola*) which are strongly associated with forests and were not discovered in birch woodlands and barrenlands.

*Vacciniina optilete* (Fig. 7) showed similar abundance in spruce-dominated forests (zones 0 and 1), while in birch forests and woodlands (zones 2 and 3) the densities were 30 to 50% of the density in the unpolluted site. This species was never recorded in the barrenlands (zone 4) where the host plant (*Vaccinium uliginosum*) was as abundant as in zones 2 and 3 (Koroleva 1993).

*Rheumaptera subhastata* (Fig. 8) showed a density pattern similar to *C. euphrosyne*, with the maximum abundance in the slightly weakened (zone 1) spruce forests. The peak density was twice as high as in the unpolluted plot. But the density of *R. subhastata* in the depressed birch woodlands (zone 3) was about 30% of the background level, while *C. euphrosyne* has practically vanished there. The host plants of *R. subhastata, Vaccinium myrtillus* and *V. uliginosum*, were recorded in all habitats, with maximum density in unpolluted forest (zone 0) (Koroleva 1993).

*Ematurga atomaria* (Fig. 9) was the only species the density of which peaked in the birch transitional community (zone 2). In all other habitats, including barrenlands, this species was almost equally abundant. The density changes matched well with the abundance of the host plant (*Calluna*) which also attained its maximum level in zone 2 (Koroleva 1993).

*Sympistis heliophila* (Fig. 10) peaked in slightly damaged forests (zone 1) and declined toward industrial barrens, although the host plant (*Empetrum nigrum*) was relatively abundant even in the most destroyed habitats (Koroleva 1993).

## 4. Discussion

### 4.1. Spatial trends in population densities

Industrial pollution can radically change densities of insects (for recent reviews, see Riemer & Whittaker 1989, Kozlov 1990a, Heliövaara & Väisänen 1993). Among Lepidoptera, an increase in ecological density (i.e. specimens per food supply) in heavily and/or moderately polluted areas seems to be a typical case (Kozlov 1990b), explained by the beneficial changes in the host plant quality (Koricheva & Haukioja 1992, Kozlov *et al.* 1996b). Our data showed that the abundance of butterflies and day-active moths followed the same pattern, although the peak densities, like in Noctuidae (Kozlov *et al.* 1996a) corresponded to much lower pollution loads than in the birch-feeding microlepidopterans (Kozlov 1985 and personal observations). In contrast to miners and leafrollers, which are more or less protected from acid rains, the direct negative effects of acidification on leaf-chewers may exceed positive changes in the host plant quality (Kozlov *et al.* 1996b).

The autochthonous fauna of butterflies and day-flying moths has almost entirely vanished within a radius of about 10 km from the emission source, where the annual mean concentration of sulphur dioxide exceeds 100 $\mu g/m^3$. Beyond that, there is a zone of decline which (at least for some species) is not caused by the lack of host plants. Most of these plant species occurred even in the immediate vicinity of the smelter, although they generally were less abundant than in undisturbed forests. These results confirm the conclusion by Barbour (1986) who reported a decline of butterfly populations in areas with annual $SO_2$ concentrations around 60 $\mu g/m^3$. Thus, day-active macrolepidopterans seem to be more sensitive to pollution than Noctuidae (cf. Kozlov *et al.* 1996a) and microlepidoptera in general (cf. Kozlov 1995).

The actual reasons for the decline of the monitored species are uncertain, but the effect is most probably connected with $SO_2$ impact either on insects or their habitats or both. However, the level of habitat deterioration is determined by the pollution load, and these two possible causes of decline can not be separated in our study.

We presume that sulphur dioxide rather than heavy metals is the causal factor behind the decline of the moth populations. The foliar concentrations of the main metal pollutants, nickel and copper, recorded for various plants growing near the smelter generally did not exceed 300 mg/kg (Kataev *et al.* 1994, Kozlov *et al.* 1995, Zvereva *et al.* 1995ab) which is below the toxicity limits for terrestrial insects (Butovsky & Roslavtseva 1989, Boyd & Martens 1994). Furthermore, no effects of foliar metals on leaf beetle or leafminer performance was revealed (Zvereva *et al.* 1995ab; Kozlov & Haukioja, personal observations). Correlations between metal concentrations and insect abundance/performance repeatedly reported in field measurements (reviewed by Heliövaara & Väisänen 1993) could not advocate for a causal relationship: distribution patterns of various pollutants are similar, and correlation between the concentrations of metals and $SO_2$ may approach 0.99 (Barkan 1993). In contrast, direct toxicity of $SO_2$ concentrations which mimic the levels observed around the Severonikel smelter (cf. Barkan 1993, Kryuchkov 1993) has been demonstrated by means of fumigation experiments (Whittaker & Warrington 1990, Kozlov *et al.* 1996b).

### 4.2. Environmental assessment using data on Lepidoptera

The practical application of the transect counts to monitor populations of subarctic Lepidoptera seems less profitable than in more southern regions, because the low abundance of butterflies and moths may not provide sufficient data for the analysis. Furthermore, all species are very sensitive to meteorological conditions which creates additional problems in the planning of sampling design and in the treatment of the data. Among the five monitored species, *C. euphrosyne* and *R. subhastata* are most profitable because they demonstrated a relatively low sensitivity to weather conditions and a high density variation in respect to pollution loads.

Although in an earlier study (Kremen 1992) the butterflies were shown to be poor indicators of heterogeneity caused by anthropogenic disturbances, we found that transect counts did produce valuable information about the impact of pollution on subarctic forest ecosystems. The most important conclusion is that all monitored species are highly sensitive to low pollution loads. At early stages of pollution-induced forest damage, which are not easy to monitor, the population densities increased by the factor of 1.5 to 5. At higher pollution loads the numbers of day-active lepidopterans declined.

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