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Artificial drought in Scots pine stands: effects on soil, ground vegetation and tree condition

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A drought simulation (roof experiment) was conducted in a 60-year-old Scots pine (*Pinus sylvestris*) stand in central Lithuania during 2003–2005. The stand represented a typical for Lithuania Scots pine forest of *Pinetum vaccinio-myrtillosum* type, growing on Arenosols. During the simulated-drought experiment, the changes in soil (humidity, pH, chemistry), ground vegetation (species abundant and composition) and tree condition (needle age, litterfall, crown defoliation) were recorded. The drought decreased soil humidity (O horizon and mineral soil down to the 100-cm depth) and increased the concentrations of some N compounds (in mineral topsoil). The cover of ground vegetation was significantly reduced, the needle age decreased, and crown defoliation increased as a result of drought.

Key words: defoliation, drought, ground vegetation, litterfall, Scots pine, soil chemistry

Introduction

Extreme meteorological events (floods, drought, storms, etc.) have direct effects on terrestrial ecosystems (Parmesan *et al*. 2000), among which, boreal forests are considered one of most sensitive ecosystems to warming and other changes in climate conditions. Recently, it has been reported that extreme climate and meteorological events seriously affect forests: e.g. long-term soil drought can damage entire forest ecosystems (Piñol *et al*. 1998). In Lithuania, drought was declared a primary reason for the widespread Norway spruce damage from 1992 to 1994 (Karazija *et al*. 1996).

Prolonged summer drought caused land degradation, lower yields, forest damage (i.e. mortality of trees, premature leaf fall), increased fauna deaths and frequency of fires (IPCC 2007). In addition, increased heat and drought affects the physical, chemical and biological properties of ecosystems, which could lead to a shift in the natural species composition towards more drought tolerant species (Lasch *et al*. 2002, Mueller *et al*. 2005, IPCC 2007).

Drought directly affects the intensity of photosynthesis: photosynthesis decreases when soil moisture decreases. Indirectly, drought may change the efficiency of soil water and nutrient uptake and, therefore, reduce nutrient availability

for trees (Baum *et al*. 2003, Sardans & Peñuelas 2005). Despite the fact that Scots pine is treated as a species relatively resistant to cold and drought, the growth of pine strongly depends on how much water is available in the driest summer months (Piñol *et al*. 1998, Cherubini *et al*. 2003, Bigler *et al*. 2006). Drought weakens tree growth, reduces photosynthesis and intensifies needle fall (Gruber 1988, Bredemeier *et al*. 1998, Lebret *et al*. 2001). According to Ozolincius and Stakenas (2001), tree crown defoliation increased under changed hydrothermal conditions being a result of reduced precipitation. Many authors state that together with declining tree condition, tree increment also decreases. There is, however, no agreement on how the tree growth changes when crown defoliation increases (Ogaya *et al*. 2003). Growth of fine roots depends on tree age, species, available nutrients as well as soil humidity (Persson 1992). Therefore, drought could be affecting fine-root development (growth and death), however, mechanisms of such processes are not clearly known. Some authors state that fine roots die which leads to definitive reduction of their mass and number (Murach 1987, Persson 1992, Palatova 2002), others maintain that root loss due to drought is soon compensated by growth of new fine-roots (Leuschner *et al*. 2001).

Drought experiments and other simulation experiments at the ecosystem scale have already been conducted in Europe: e.g. in Denmark (Klosterhede), The Netherlands (Ysselsteyn, Speuld), Sweden (Skogaby, Gårdsjön), Germany (Solling, Höglewald), Ireland (Ballyhooly), and Norway (Risdalsheia) (Gundersen 1998, Lamersdorf *et al*. 1998). Some of those experimental sites were within the European NITREX project (duration 1996–1999). The joint EXMAN project (in 1987–1995) was conducted in five European countries: Ireland, Denmark, Netherlands and Germany. In most cases, temporary roof covers during the intended drought period were the experimental tool for creating controlled conditions in forest ecosystems.

Data on soil pH and chemistry as well as on ground vegetation and tree condition are quite contradictory. Besides that, most of the abovementioned authors pointed out that reaction patterns during the drought periods may be different within sites.

The artificial drought experiment in Scots pine stands in Lithuania is linked to several other European "roof" experiments, and its aim was to investigate the impact and risk of drought. It was hypothesized that soil drought will increase soil pH and change chemical composition, ground vegetation cover and tree conditions.

Material and methods

Study site

Our drought simulation experiment was conducted in a 60-year-old Scots pine (*Pinus sylvestris*) stand in central Lithuania during 2003–2005. The stand represented a typical Scots pine forest of *Pinetum vaccinio-myrtillosum* type (according to the classification of Lithuanian forest sites types (Ozolincius *et al*. 1999) on Arenosols. Mean pH_{CaCl2} of O + E horizons was 3.9, and pH_{CaCl2} of mineral topsoil was 3.5. The mean annual precipitation was 618 mm and the mean annual temperature was 6.3 °C (data from the Kaunas Meteorological Station). Meteorological conditions of the vegetation period during 2003–2005 were typical for the mean annual conditions, but the amount of precipitation in 2005 was about 20% higher than the average.

The ground vegetation layer in the stand was dominated by mosses *Pleurozium schreberi*, *Hylocomium splendens*, *Ptilium crista-castrensis* and *Dicranum polysetum*. The most common species of vascular plants were *Vaccinium vitis-idea*, *Vaccinium myrtillus* and *Convallaria majalis*.

Differences in the site characteristics between the control and drought plots at the initial stage were not significant.

Artificial drought was simulated by using a transparent roof construction installed below the stand canopy for the duration of the experiment (Fig. 1). The experiment included three randomly selected blocks of two treatments (simulated drought and control). In total, there were six 20 × 25-m plots. The drought plots (simulated drought or control) were situated 30–50 m apart from each other. The spacing of controls was planned randomly. The number of trees per plot varied from 25 to 33; their mean diameter at breast height was 20–21 cm.

Data collection

Soil sampling for soil moisture assessment was carried out in 2004 and 2005. In each plot, soil samples were collected in triplicates from six systematically located profiles from organic layer (O horizon) and seven horizons of mineral soil: 0–5 cm, 5–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm and 80–100 cm. Soil moisture was assessed by using thermostatic weighing method (Vaičys *et al*. 1979).

In 2004, soil samples for chemical analyses were collected from soil organic layer (OL) and upper mineral soil layers — Ap (0–2 cm) and Ap (2–10 cm). Sampling was done in triplicates: in total 54 samples were taken. Chemical soil analyses were performed using the following methods: pH_{CaCl2} potentiometrically in a 0.01 M $CaCl_2$ suspension (ISO 10390); mobile P (P_2O_5) and K (K_2O) using a Egner-Riehm-Domingo (A-L) method; Ca^{2+} and Mg^{2+} using an atomic absorbtion spectrophotometer in 0.1 M $BaCl_2$ extracts; organic C using an Heraeus apparatus (ISO 10694, dry combustion at 900 °C); mineral N using a spectrometric method (ISO 14256-2) in 1 M KCl extraction, NO_3-N using sodium phenolate and sodium hypochlorite, and NH_4-N using sulfanilamide.

Studies of the ground vegetation were commenced before the beginning of the experiment and continued up to two years after the end of the treatment. For ground vegetation assessment, eight 1-m^2 squares were systematically distributed in each experimental plot. In each square, species composition, layer and cover (%) were recorded (as in Tallent-Hansell 1994). Investigations were carried out in July. The Shannon diversity index H' was calculated as follows (Magurran 1987):

$$H' = -\sum(n_i/N) \times \log_2(n_i/N),$$

where n_i = cover of ith species, and N = total cover.

Litterfall was monitored periodically (every 2 months in spring, summer and autumn and once in winter) from September 2003 until the end of 2005. Litterfall was sampled from under the canopy with 4 litter traps (surface area of a trap was 2 m^2) placed in each drought plot at the height of 2–2.5 m above the ground. In the control plots, 6 litter traps per plot (surface area of a trap was 0.25 m^2) were installed at the height of 1-m above the ground. The litter samples from each trap were air-dried and sorted into four fractions: needles, twigs and branches, bark and scales, and cones, then oven-dried at 60 °C for 48 hours and weighed (UN/ECE 2004).

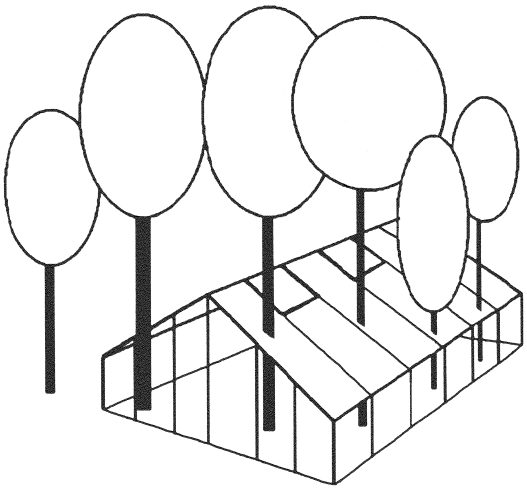

Fig. 1. Scheme the artificial drought experiment.

Defoliation was defined as needle loss from the crown in relation to a reference tree. Defoliation was assessed in 5% steps (UN/ECE 2006).

Statistical procedure

The results on soil chemistry, ground vegetation and defoliation were statistically evaluated using Student's *t*-test. The analyses were performed using Statistica 6.0.

Results

The decrease in soil humidity in the organic and mineral soil horizons down to 1-m depth was determined 1.5–2.5 years after the start of the artificial drought (Table 1). The largest humidity changes were recorded in the organic soil layer — humidity was reduced four times in O horizon. Similarly, humidity of the mineral soil layer in the drought plots was 1.5–2.0 times lower than humidity of the 0–1-m layer in the control.

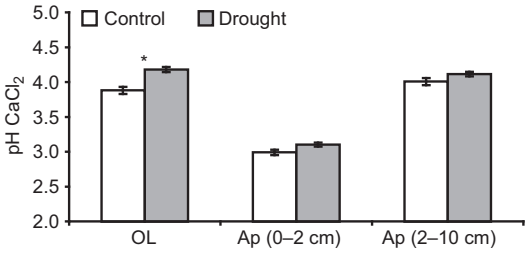

Fig. 2. Effect of drought on soil pH in organic (OL), and mineral — Ap (0–2 cm) and Ap (2–10 cm) — soil layers in Scots pine stand (2004). An asterisk (*) indicates a significant difference at $p < 0.05$ (*t*-test).

In the drought plots, soil humidity decreased with depth (linear regression: R^2 = 0.6–0.8, $p < 0.05$) from 4.0%–4.4% in 0–5 cm topsoil to 2.1%–2.4% in more than 80 cm in soil profile. In the control plots, the differences in soil humidity within the mineral soil layer were smaller: the humidity of the mineral topsoil was 1.8 times higher as compare with that of the soil horizon at 1-m depth. These differences in soil humidity between the drought and control plots remained unchanged for 2.5 years.

Organic soil pH was significantly higher in the drought plots (Fig. 2). No significant soil-pH changes were recorded in the mineral topsoil down to 10-cm depth.

As a result of induced drought, concentrations of mineral N compounds (NO_3-N, NH_4-N and mineral N) in O horizon were 2.3–3.0 times higher as compared with those in the control plots (Fig. 3). Drought had no effect on the content of mineral N in mineral topsoil at 0–2 cm depth.

No significant differences in mobile P (P_2O_5), K (K_2O) and exchangeable Mg^{2+} contents in O horizon and mineral topsoil (down to 10-cm depth) of the control and drought plots were found (Fig. 4). Only the concentration of exchangeable Ca^{2+} was significantly lower (1.3 g kg^{-1}; *t*-test, $p < 0.05$) in Ap horizon (0–2 cm) of the drought plots as compared with that (2 g kg^{-1}) in the control plot. Such changes could occur possibly due to the reduced mineralization rate of the organic matter as there was no litterfall under the roof in drought plots.

Similarly, there was no significant difference in the organic C concentration between control and drought plots (data not shown).

Changes in the ground vegetation cover were recorded one year after the beginning the experiment. Artificial drought significantly decreased the cover of both mosses and vascular plants in the period from 2003 to 2005 (Table 2). The cover of mosses in both treatments (control and drought) was about 90% in 2003. During a two-year period, the drought significantly decreased the cover of mosses to 1% in the drought plots. Similar changes were observed in the cover of vascular plants (Table 3). The Shannon diversity index was 2.5 in the control plots and only 1.8 in the drought plots.

During the first year, litterfall mass in drought-affected plots did not differ from that in the control (Fig. 5). In October–November 2004, litterfall in the drought plots increased by 20% as compared with that in the control due to an intensive autumn needle fall. This continued until the spring of 2005. After the intensive needle fall, total litterfall mass in the drought

Table 1. Mean soil humidity ± SD (%) in experimental plots (2004).

Soil layer	Control				Drought			
	1 (n = 6)	2 (n = 6)	3 (n = 6)	Average	1 (n = 6)	2 (n = 6)	3 (n = 6)	Average
O horizon	130.0 ± 17.9	133.2 ± 28.1	112.7 ± 7.7	125.3 ± 17.9	35.1 ± 2.7	32.7 ± 4.7	31.1 ± 2.0	33.0 ± 3.1
0–5 cm	8.4 ± 0.5	8.0 ± 0.7	6.6 ± 0.3	7.7 ± 0.5	4.2 ± 0.4	4.2 ± 0.3	4.4 ± 0.2	4.3 ± 0.3
5–10 cm	6.1 ± 0.5	7.0 ± 0.6	5.1 ± 0.3	6.1 ± 0.5	4.0 ± 0.4	3.9 ± 0.2	4.2 ± 0.2	4.0 ± 0.3
10–20 cm	4.8 ± 0.2	6.6 ± 0.6	4.9 ± 0.3	5.4 ± 0.4	3.2 ± 0.2	2.9 ± 0.1	3.5 ± 0.2	3.2 ± 0.2
20–40 cm	7.0 ± 0.5	6.8 ± 0.5	7.3 ± 0.7	7.0 ± 0.6	3.5 ± 0.1	3.2 ± 0.3	4.4 ± 0.2	3.7 ± 0.2
40–60 cm	6.3 ± 0.2	6.1 ± 0.4	5.6 ± 0.3	6.0 ± 0.3	3.4 ± 0.1	3.1 ± 0.2	4.2 ± 0.4	3.6 ± 0.2
60–80 cm	5.3 ± 0.5	5.6 ± 0.2	5.0 ± 0.4	5.3 ± 0.4	3.2 ± 0.2	3.3 ± 0.2	3.2 ± 0.2	3.2 ± 0.2
80–100 cm	4.8 ± 0.3	4.9 ± 0.1	3.2 ± 0.5	4.3 ± 0.3	2.5 ± 0.2	2.1 ± 0.1	2.5 ± 0.1	2.4 ± 0.1

plots was smaller as compared with that in the control.

Scots pine crown defoliation increased after the introduction of drought and remained higher than that in the control. Under the drought conditions, mean crown defoliation was 6.3%–7.5% and 17.5% higher in 2004 and 2005, respectively, as compared with that in the control (Table 4). Average crown defoliation in the drought plots was about 40%, and only 25% in the control plots.

Smaller differences were recorded for pine trees belonging to 1–2 Kraft classes. This supports the conclusion that drought first affects trees of lower development classes or damaged trees.

Crown defoliation in the drought plots increased significantly from 2003 to 2005 (Fig. 6).

Mean needle age in the control stand was 2.6–2.7 years (2.8 years of the trees of 1–2 Kraft classes) during 2003–2005. However, as a result of drought mean needle age decreased to 2.3–2.5 years. In 2005, Scots pine mortality was higher in the drought plots (2.8%) than in the control (2.2%).

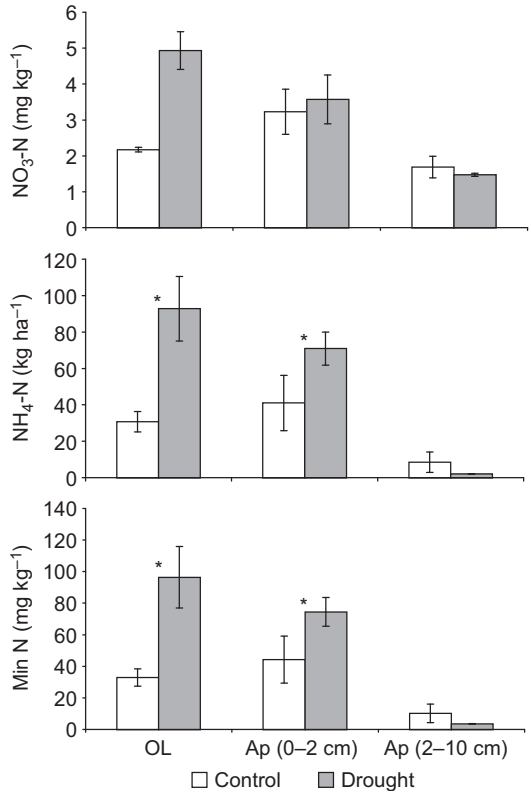

Fig. 3. Effect of drought on concentrations of NO_3-N, NH_4-N and mineral N in organic (OL) and mineral Ap (0–2 cm and 2–10 cm) soil layers. An asterisk (*) indicates a significant difference at $p < 0.05$ (*t*-test).

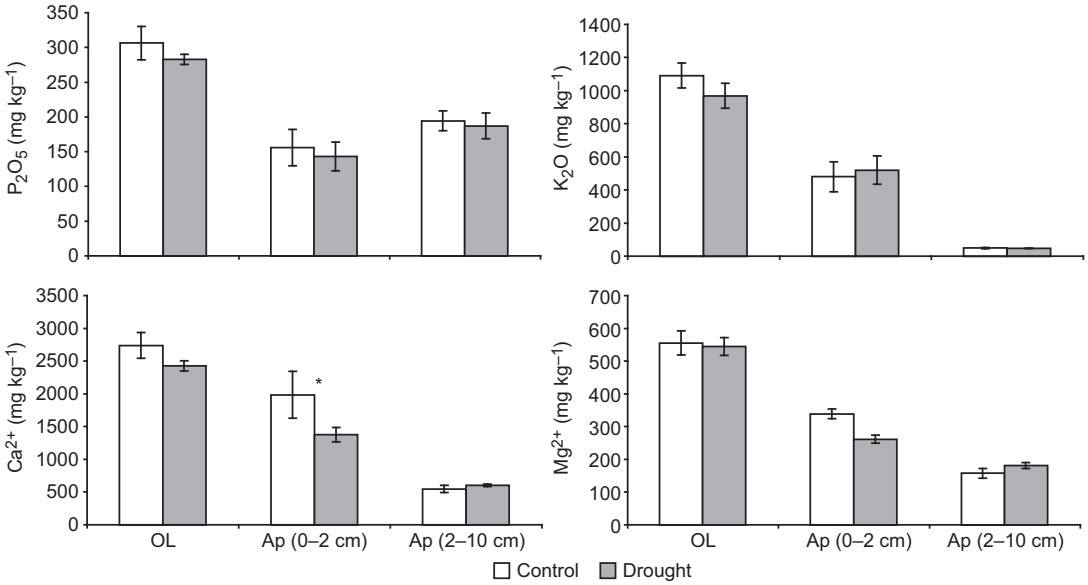

Fig 4. Effect of drought on concentrations of P, K, Ca^{2+} and Mg^{2+} in organic layer (OL) and layers of mineral soil Ap (0–2 cm) and Ap (2–10 cm) in 2004 m. An asterisk (*) indicates a significant difference at $p < 0.05$ (*t*-test).

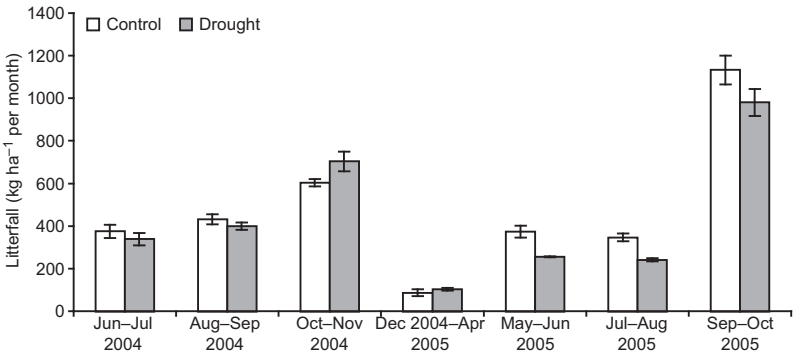

Fig. 5. Seasonal changes of litterfall mass (kg ha^{-1} per month) in Scots pine stand

Discussion

Drought affects mineral nutrient relations in plants in different ways. Disturbed soil nutrient balance under drought conditions may decrease uptake of K, Ca, Mg, P and N by the roots, their transport from the roots to the shoots and, in consequence, reduce plant growth (Hu *et al*. 2008). Restricted transpiration rates also occur due to the drought stress. The results of our experiment show drought intensified accumulation of NO_3-N, NH_4-N and mineral N in organic layer and mineral topsoil, and that drought affected mobility and availability of most of the nutrients in the soil. Similarly to Nilsen's (1995) results, K and P concentrations were affected less than N compounds. Bergholm *et al*. (2001) noticed no changes in soil pH, Ca and Mg concentrations but decrease in N, P and K concentrations. Lamersdorf *et al*. (1998) observed that drought phases can influence element cycling. Similarly, Gundersen *et al*. (1998) found that exclusion of throughfall by the roof, should disturb the internal cycle of nutrients leached from the canopy (Ca, K, Mg) or present in a suspended material (N, P, Mg). Despite contradictory literature data, our results showed the increase of pH in the organic soil layer which partly corroborates the results of Lamersdorf *et al*. (1998), who also found elevated pH values at some drought sites.

Table 2. Mean characteristics ± SD of ground vegetation. *H´* = Shannon diversity index.

Cover (%)	Control			Drought		
	2003 (*n* = 24)	2004 (*n* = 24)	2005 (*n* = 24)	2003 (*n* = 24)	2004 (*n* = 24)	2005 (*n* = 24)
Mosses	89.1±0.6	90.4±1.4	90.5±2.8	88.5±3.8	3.6±2.9	0.5±0.2
Vascular plants	41.5±7.3	35.7±8.8	41.9±11.6	17.5±5.8	2.7±0.6	0.7±0.3
Total	130.6±7.0	126.1±8.5	132.4±10.5	106.0±2.0	6.3±3.5	1.2±0.5
H´	2.4±0.2	2.5±0.1	2.6±0.2	2.2±0.0	2.6±0.0	1.8±0.2

Table 3. The mean cover of main species (%) ± SD.

Species	Control			Drought		
	2003 (*n* = 24)	2004 (*n* = 24)	2005 (*n* = 24)	2003 (*n* = 24)	2004 (*n* = 24)	2005 (*n* = 24)
1. *Vaccinium myrtillus*	12.1 ± 10.8	12.6 ± 11.3	12.8 ± 11.0	2.0 ± 0.8	0.3 ± 0.2	0
2. *Vaccinium vitis-idea*	17.5 ± 2.0	11.7 ± 2.0	13.8 ± 0.5	11.8 ± 4.1	0.9 ± 0.2	0
3. *Hylocomium splendens*	22.5 ± 6.9	24.0 ± 5.4	25.0 ± 4.3	34.4 ± 14.1	1.1 ± 1.0	0
4. *Pleurozium schreberi*	51.9 ± 9.7	50.6 ± 7.3	48.5 ± 8.6	33.4 ± 7.9	1.5 ± 1.1	0.3 ± 0.2
5. *Ptilium crista-castrensis*	13.0 ± 3.6	14.1 ± 3.4	15.4 ± 3.8	20.3 ± 11.0	1.1 ± 0.9	0.1 ± 0.1

Analyzing ground vegetation data, we supposed that the lack of rain water was the initial but not the only factor which affected ground vegetation. According to Gundersen *et al*. (1998), who stated that photosynthetic light could be reduced by 15%–50% below roofs, this factor might also decrease the moss cover of the forest floor. The disturbance of the nutrition cycle could be mentioned as another reason. But, in general, drought has the capacity to cause extreme vegetation changes (Mueller *et al*. 2005). Reduced precipitation may cause shifts in the plant composition, distribution and abundance (Stephenson 1990), and extreme or prolonged drought can result in mortality of plants. Our study shows that despite the morphological differences (root presence) the artificial drought impact was almost lethal for both mosses and vascular plants. However, plant diversity — according to the Shannon diversity index — did not change so drastically: it decreased only by about 20%.

Changes of crown defoliation under drought conditions could be seen in faster old-needle fall and weaker formation of shoots and needles. In comparison, mean crown defoliation of Scots pine in Lithuania during the study period (data from regional forest monitoring) was 2%–4% lower than that in the control plots of our experiment. Excessive needle drop is often an evidence of the drought stress. Loss of needles is a natural reaction of trees to changes in e.g. precipitation, ozone and sulphur deposition, and foliar chemistry (Musio *et al*. 2007). In general, even low levels of water stress could reduce stem and root growth. Tops of trees and branch tips should be damaged first because they are the parts farthest from the water-absorbing roots. Even though the damage may occur in late summer or autumn, the symptoms usually are not visible until the

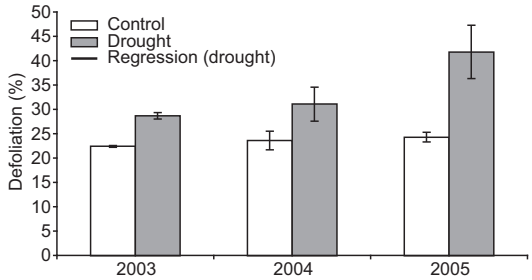

Fig 6. Mean crown defoliation of Scots pine trees. Differences between the control and drought plots are all significant (*t*-test, $p < 0.05$).

Table 4. Mean crown defoliation, needle age and standard errors in Scots pine stands under drought conditions.

Parameter	Assessment year	Control	Drought
Defoliation of the entire crown (%)			
All trees ($n = 80$)	2003	22.4 ± 0.2	28.7 ± 2.4
	2004	23.6 ± 0.7	31.1 ± 3.5
	2005	24.3 ± 1.0	41.8 ± 5.6
1–2 Kraft class trees ($n = 42$)	2003	17.9 ± 0.6	20.7 ± 1.7
	2004	15.3 ± 0.2*	24.4 ± 2.2*
	2005	17.8 ± 1.0	33.9 ± 3.4
Defoliation of upper 1/3 crown part (%)			
All trees ($n = 80$)	2003	20.4 ± 0.3	27.1 ± 2.4
	2004	21.4 ± 0.7	27.8 ± 3.8
	2005	22.7 ± 1.3	37.2 ± 5.3
1–2 Kraft class trees ($n = 42$)	2003	16.6 ± 0.4	17.7 ± 1.2
	2004	12.9 ± 0.5	19.4 ± 2.3
	2005	15.6 ± 1.2	27.7 ± 3.2
Mean needle age, years			
All trees ($n = 80$)	2003	2.6 ± 0.0	2.4 ± 0.1
	2004	2.7 ± 0.0*	2.5 ± 0.0*
	2005	2.6 ± 0.1*	2.3 ± 0.0
1–2 Kraft class trees ($n = 42$)	2003	2.6 ± 0.0	2.5 ± 0.1
	2004	2.8 ± 0.1*	2.6 ± 0.0
	2005	2.8 ± 0.0*	2.4 ± 0.1

* Statistically significant difference at $p < 0.05$ (*t*-test).

following late winter or spring. The obvious statement is that drought often increases litterfall in Europe (Peñuelas *et al*. 2004). In our experiment, increased litterfall due drought was evident in autumn but it was not very much higher as compared with that in the control.

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