Effect of fertilisation on ^{137}Cs in understory spruces on a dryish pine site

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Abstract. Undergrowth spruces (*Picea abies*) in a pine stand in Finland were studied in 1997, 13 years after refertilisation with NPK. The aim of the study was to quantify the effect of NPK fertilisation on the distribution of radiocaesium (^{137}Cs) and dry mass in the trees. Biomass functions for different tree compartments were derived by means of regression analysis. Radiocaesium contents in the different tree compartments were calculated using plot-specific biomass values and ^{137}Cs concentrations. Fertilisation decreased the ^{137}Cs concentration in each of the compartments by 73-92%. In the control spruces, the ^{137}Cs concentrations were highest in the stem bark, needles and branches of the upper half of the crown (2455-3443 Bq kg^{-1} DW) and in the dead branches (2882-4408 Bq kg^{-1} DW). These concentrations were double those in the lower half of the crown irrespective of the fertiliser treatment. The needles and branches in the lower half of the crown contained 58-62% of the tree biomass and 56-60% of the ^{137}Cs. Changes in the relative vertical distribution of ^{137}Cs in the trees due to fertilisation were small. The total ^{137}Cs content of the trees correlated with the biomass and diameter of the trees.

1. INTRODUCTION

Scots pine (*Pinus sylvestris* L.) is the most common tree species on boreal sub-dry sites in Finland, but Norway spruce (*Picea abies* Karst.) nowadays also occurs in a wider range of biotopes than earlier. Natural regeneration is relatively successful on sub-dry sites, and Norway spruce is becoming more common mainly because of the decrease in forest fires [1]. However, the mean annual stem volume increment in a spruce stand during a rotation of 100 years is only 75% of that produced by Scots pine under similar conditions [2]. Therefore it is not recommended to allow naturally regenerated, understory spruces to grow as the main tree species on sub-dry sites unless they have reached the mean dominant height of 5 metres [2].

Boreal coniferous forests on dryish sites do not usually require applications of mineral nutrient to achieve sufficient tree growth. However, fertilisation with nitrogen and phosphorus may increase tree growth, especially if the organic layer on the site is thin or relatively deficient in nitrogen and phosphorus [3].

The concentrations and dynamics of ^{137}Cs in Norway spruces have been investigated in some studies after the Chernobyl accident [e.g. 4-6]. However, the use of fertilisation or other forest management practices for remediation purposes after an accidental release of radioactive substances into the environment has not been extensively studied experimentally. The aim of the study was to quantify the effect of NPK fertilisation on the vertical distribution of radiocaesium and the above-ground biomass in understory spruces.

2. MATERIAL AND METHODS

2.1 Site

The study was carried out in a fertilisation experiment as part of the LANDSCAPE project during 1997-1999 [7]. The experiment was located in western Finland, where the radioactive fallout resulting from the

Chernobyl accident mostly exceeded 20 kBq m^{-2} during this study [8]. The experiment was originally established in 1980 in order to investigate the effect of nitrogen fertilisation on the growth of a Scots pine stand growing on a sub-dry site. In 1997, the average stem volume of the dominating Scots pine stand on the individual plots varied between 156 and 233 m^3 ha^{-1}, the average dominant height 21.3 m, the stand density in the overstory layer 488 trees ha^{-1}, and the average biological age of the pine trees 61 years. The soil type was ferric podzol and the thickness of the mor humus varied from 2.9 to 5.8 cm.

The experimental design was a completely randomised experiment, with a plot size of 800 m^2. According to the Finnish classification [9], the site is of the Vaccinium forest site type, which is a sub-dry heath forest. A control and two NPK fertilisation plots (N 180, P 80 and K 300 kg ha^{-1}) were used for this study. The experiment was refertilised in 1985 with the same amount of nutrients as in 1980.

2.2 Sampling

The height, crown limit and stem diameter at breast height (DBH, h = 1.3 m) of the undergrowth spruces (height>1.3m) were measured from nine circular subplots (r = 1.5 m) located systematically on each plot in October 1997. DBH of the spruces varied between 4 and 58 mm, and height between 1.4 and 5.4 m. The median tree, based on the diameter distribution, was taken as a sample tree from each subplot (Table 1). However, sample trees were not collected from all the subplots because of the uneven spatial distribution of the spruces on the plots. The crowns of the sample spruces were divided into two parts, and the needles, branches, stem wood and stem bark were separated for biomass (dry mass at 105°C) and ^{137}Cs activity determinations. Bark, wood and dead branches from the portion of the stem below the living crown were also analysed. Phloem was included in the stembark. The upper part of the living crown is referred to as part A, the lower half of the crown as part B, and the compartments below the living crown as part C in the biomass functions, tables and figures.

2.3 Biomass equations

Biomass functions for the different compartments of the understory spruces were calculated for each plot and crown quarter separately by regression analysis in which DBH, height, lower limit of living crown and the crown ratio, with different transformations, were used as the independent variables. If the number of sample trees was not sufficient, the plots were combined until proper functions were found.

Table 1: Characteristics of the sample spruces. DBH = diameter at breast height, h = height, CL = lower limit of living crown, CR = crown ratio, and age was determined from the stumps.

Plot	Fertilisation	DBH, mm	h, cm	CL, cm	CR, %	Age, years
2	NPK+NPK	45	350	40	88.57	39
2	NPK+NPK	22	278	25	91.01	30
2	NPK+NPK	18	213	3	98.59	27
2	NPK+NPK	43	358	34	90.50	29
2	NPK+NPK	17	217	12	94.47	20
2	NPK+NPK	21	242	28	88.43	30
2	NPK+NPK	47	466	35	92.49	43
2	NPK+NPK	6	139	15	89.21	17
8	NPK+NPK	57	437	31	92.91	35
8	NPK+NPK	35	290	2	99.31	29
9	Control	10	165	35	78.79	29
9	Control	6	148	50	66.22	42
9	Control	7	152	35	76.97	47

The functions for the dry mass (g $tree^{-1}$) of the different spruce compartments were as follows (significance levels: $p<0.05$ = *, $p<0.01$ = **, $p<0.001$ = ***; R^2 = degree of determination; n = number of sample trees):

$$\ln(needles\_A) = 3.76133 + 0.0345d \; ; R^2 = 0.752^{***}, n = 13 \quad (1)$$
$$needles\_B = 8902.74 + 14.4713h - 2172.92\ln(h) \; ; R^2 = 0.931^{***}, n = 13 \quad (2)$$
$$\ln(branches\_A) = -0.32375 + 0.4458\ln(d^2CR) \; ; R^2 = 0.779^{***}, n = 13 \quad (3)$$
$$\ln(branches\_B) = -6.33184 + 2.2928\ln(h) \; ; R^2 = 0.885^{***}, n = 13 \quad (4)$$
$$\ln(deadbranches\_A) = -1.799098 + 0.199319(d+CL) - 0.001724(d+CL)^2 \; ; R^2 = 0.904^{*}, n = 4 \quad (5)$$
$$\ln(deadbranches\_B) = 4.53615 - 0.0734CL \; ; R^2 = 0.745, n = 3 \quad (6)$$
$$\ln(deadbranches\_C) = 5.964739 - 0.129131(d+CL) + 0.001183(d+CL)^2 \; ; R^2 = 0.612^{**}, n = 10 \quad (7)$$
$$bark\_A = 10.58949 + 0.0155d^2 \; ; R^2 = 0.930^{***}, n = 10 \quad (8)$$
$$\ln(bark\_B) = -1.01609 + 0.469\ln(d^2h) \; ; R^2 = 0.966^{***}, n = 13 \quad (9)$$
$$\ln(bark\_C) = 1.63547 + 0.0601d \; ; R^2 = 0.867^{***}, n = 10 \quad (10)$$
$$\ln(wood\_A) = -5.63282 + 0.8395\ln(d^2CR) + 7.5407d^{-1} \; ; R^2 = 0.959^{***}, n = 13 \quad (11)$$
$$wood\_B = 3892.7312 + 7.6264h - 981.6149\ln(h) \; ; R^2 = 0.926^{***}, n = 10 \quad (12)$$
$$wood\_C = 1460.57446 + 2.8061h - 373.6191\ln(h) \; ; R^2 = 0.924^{***}, n = 10 \quad (13)$$
$$\ln(bark\_A) = -3.27314 + 0.5894\ln(d^2CR) \; ; R^2 = 0.964, n = 3 \quad (14)$$
$$\ln(bark\_C) = 3.34542 - 0.000006265d^2h \; ; R^2 = 0.806, n = 3 \quad (15)$$
$$\ln(wood\_B) = 4.77043 - 0.017CL \; ; R^2 = 0.987, n = 3 \quad (16)$$
$$\ln(wood\_C) = 5.5595 - 0.000241CR^2 \; ; R^2 = 0.977, n = 3 \quad (17)$$

in which d = DBH, h = height, CL = crown limit, CR = crown ratio (see units in Table 1). Equations 5, 8, 10, 12 and 13 were for fertilised spruces, and equations 14-17 for spruce on the control plot. The other equations were determined for both fertilised and unfertilised spruces. However, biomass functions were determined in order to estimate the dry mass distribution in spruces not taken as sample trees in this study. Because of the limited material, the biomass functions should not be generalised and applied to spruces on different types of site.

2.4 Radiocaesium measurements and statistical analysis

^{137}Cs activity concentration in dried, homogenised samples was determined with a low-background, high-resolution (HPGe) gammaspectrometer at the radioanalytical laboratory of STUK. A calibrated standard geometry was used for each sample type, and the results were corrected for the varying size and density of the samples with the software package developed at STUK [10]. The reference date for the radiocaesium concentrations was 1st of October, 1997. Radiocaesium contents in the different tree compartments were calculated using plot-specific biomass values and ^{137}Cs concentrations.

The effect of fertilisation on dry mass accumulation, ^{137}Cs concentration and ^{137}Cs content in the different tree compartments was tested with ANOVA (The SAS System for Windows, Release 8.01). Correlation analysis was also used.

3. RESULTS

3.1 Biomass distribution

The total above-ground dry mass of the spruces varied from 50 to 1023 g m^{-2}. Refertilisation clearly increased the dry mass of the trees although the growth increment was not statistically significant (control 50 and NPK fertilisation 583 g m^{-2}, P = 0.612). The effect of fertilisation was clear but not significant in all of the compartments and in all parts of the trees (Table 2). The relative vertical distribution of the dry mass was relatively unaffected by fertilisation. However, the proportion of stem wood or bark was 45-48% in the lower half of the crown of the control spruces, and 62-71% in the fertilised spruces. The upper

Table 2. The effect of fertilisation on the biomass distribution (g m^{-2}±SD) in different compartments of undergrowth spruces.

Material	Fertilisation Control part A	part B	part C	NPK part A	part B	part C	P-values part A	part B	part C
Wood	0.71	3.96	4.05	11.52±11.73	105.98±110.04	31.55±32.69	0.589	0.588	0.617
Bark	0.39	1.85	1.65	4.75±4.96	22.47±23.23	8.24±8.75	0.603	0.601	0.649
Branches	1.98	16.35		20.14±20.88	175.95±189.99		0.607	0.617	
Dead branches		0.46	0.92	3.91±4.77	8.66	6.87±8.30			0.663
Needles	3.23	14.36		25.36±28.70	161.57±172.38		0.642	0.612	
Total	6.31	36.97	6.62	65.69±71.04	474.63±501.76	46.66±49.74	0.619	0.609	0.630

part of the crown contained about 10% of the dry masses of stem wood, bark and branches, and 13-18% of the needle dry mass in both the control and fertilised spruces.

3.2 ^{137}Cs distribution

3.2.1 Activity concentrations in the spruces

Fertilisation decreased the ^{137}Cs concentration in each of the compartments by 73-92%. This decrease was statistically significant in most of the compartments (Fig. 1). The ^{137}Cs concentrations were highest in stem bark, needles and branches of the upper half of the crown (2455-3443 Bq kg^{-1} DW) and in the dead branches (2882-4408 Bq kg^{-1} DW) of the control spruces (Fig. 1). The concentrations in the upper half of the crown were double those in the lower half of the crown irrespective of the fertiliser treatment. Also in the stem wood the concentration was highest in the upper half of the crown.

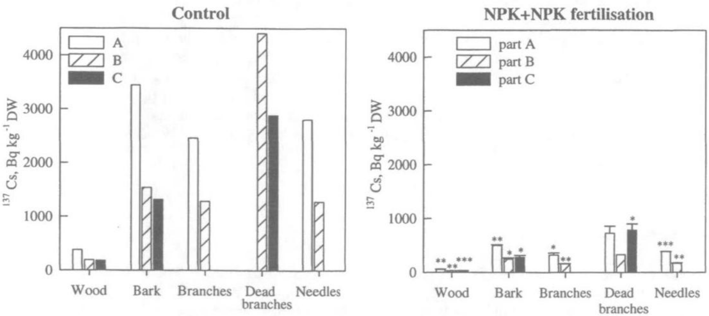

Figure 1. The effect of fertilisation on the radiocaesium concentrations in the different compartments of the undergrowth spruces (significance levels: $p<0.05$ = *, $p<0.01$ = ** and $p<0.001$ = ***).

3.2.2 ^{137}Cs amount in the spruces

The total content of ^{137}Cs in the above-ground compartments of the spruces varied from 22 to 169 Bq m^{-2}, with an average of 66 in the control treatment and 97 Bq m^{-2} in the fertilisation treatment. The effect of fertilisation was not statistically significant (P = 0.856). NPK refertilisation increased the radiocaesium content in each of the compartments, but not statistically significantly (Table 3). The absolute increment due to fertilisation was greatest in the needles and branches of the lower part of the crown, which accounted for 56-66% of the total ^{137}Cs content in the trees (Table 3).

The changes in the relative vertical distribution of the ^{137}Cs content in the different tree compartments due to the fertiliser treatment were small, with the exception of the stem bark and stem wood. In the NPK refertilised trees, 57-66% of the ^{137}Cs content in the bark or wood was in the lower half of the crown, while in the control trees the contribution of bark and wood was 43-45%. The corresponding figures for branches and needles were 19-20% and 25-33%, respectively.

Table 3. The effect of fertilisation on the amount of ^{137}Cs (Bq m^{-2}±SD) in the different compartments of the undergrowth spruces.

Material	Fertilisation Control part A	part B	part C	NPK part A	part B	part C	P-values part A	part B	part C
Wood	0.27	0.75	0.74	0.58±0.57	2.86±2.95	0.91±0.94	0.733	0.664	0.904
Bark	1.35	2.83	2.17	2.40±2.53	5.77±6.20	2.46±2.73	0.791	0.765	0.945
Branches	4.87	20.97		6.87±7.46	27.23±29.05		0.863	0.889	
Dead branches		2.02	2.66	2.56±2.99	2.88	5.86±7.29			0.781
Needles	9.04	18.30		9.81±11.09	26.52±27.79		0.964	0.849	
Total	15.52	44.88	5.56	22.22±24.64	65.26±68.03	9.23±10.96	0.861	0.858	0.830

3.3 Relationships between the radiocaesium content and tree size

The ^{137}Cs content of the spruces on the fertilised plots correlated with the breast height diameter ($y = -70.407 + 23.651x$, $R^2 = 0.888$***, n = 10) and the total above-ground biomass of the trees ($y = 177.79 + 140.88x$, $R^2 = 0.777$***, Fig. 2). The total tree biomass (kg/tree) on the fertilised plots also correlated with tree diameter ($y = 0.1174x$, $R^2 = 0.787$***).

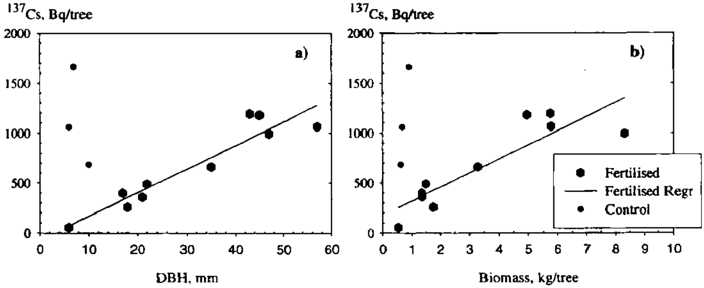

Figure 2. The dependence of the whole tree ^{137}Cs content on the breast height diameter (a) and on the total above-ground biomass (b).

4. DISCUSSION

NPK refertilisation clearly decreased the ^{137}Cs concentration in all the above-ground components of the understory spruces. This is in agreement with the results concerning the effect of fertilisation on radiocaesium uptake by Scots pine trees [7,11]. The application rate of nitrogen used in this study corresponded to the practical forestry guidelines [3]. However, the application rate of potassium, 600 kg ha^{-1} during a 5-year period, was high compared to the potassium status of conifers in these conditions. Furthermore, as regards the timing of the treatments in relation to the Chernobyl fallout, the reduction in the uptake of ^{137}Cs may represent the near to maximum reduction that can be achieved with the doses used in this experiment, because the growth response of the trees to fertilisation is normally observed during the second growing season following fertilisation. Fertilisation seems to have a long-term reducing effect on the ^{137}Cs concentration in the trees, because this study was performed twelve growing seasons after the radioactive fallout incident.

The considerable increment in the dry mass of the spruces was a natural consequence of the amended nutrition of the site. Therefore it is understandable that the total amount of ^{137}Cs also increased in the fertilised spruces, despite the reducing effect of NPK refertilisation. However, the dry mass of the control spruces was only 9% of the dry mass in the trees on the fertilised plots, but the amount of ^{137}Cs was 69% of that on the fertilised ones.

The results indicate the benefits of fertilisation for the remediation of radioactively contaminated forests, although the study material was too limited for in-depth statistical analysis. The results motivate further research on the applicability of forest management methods as counter-measures after radioactive fallout.

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