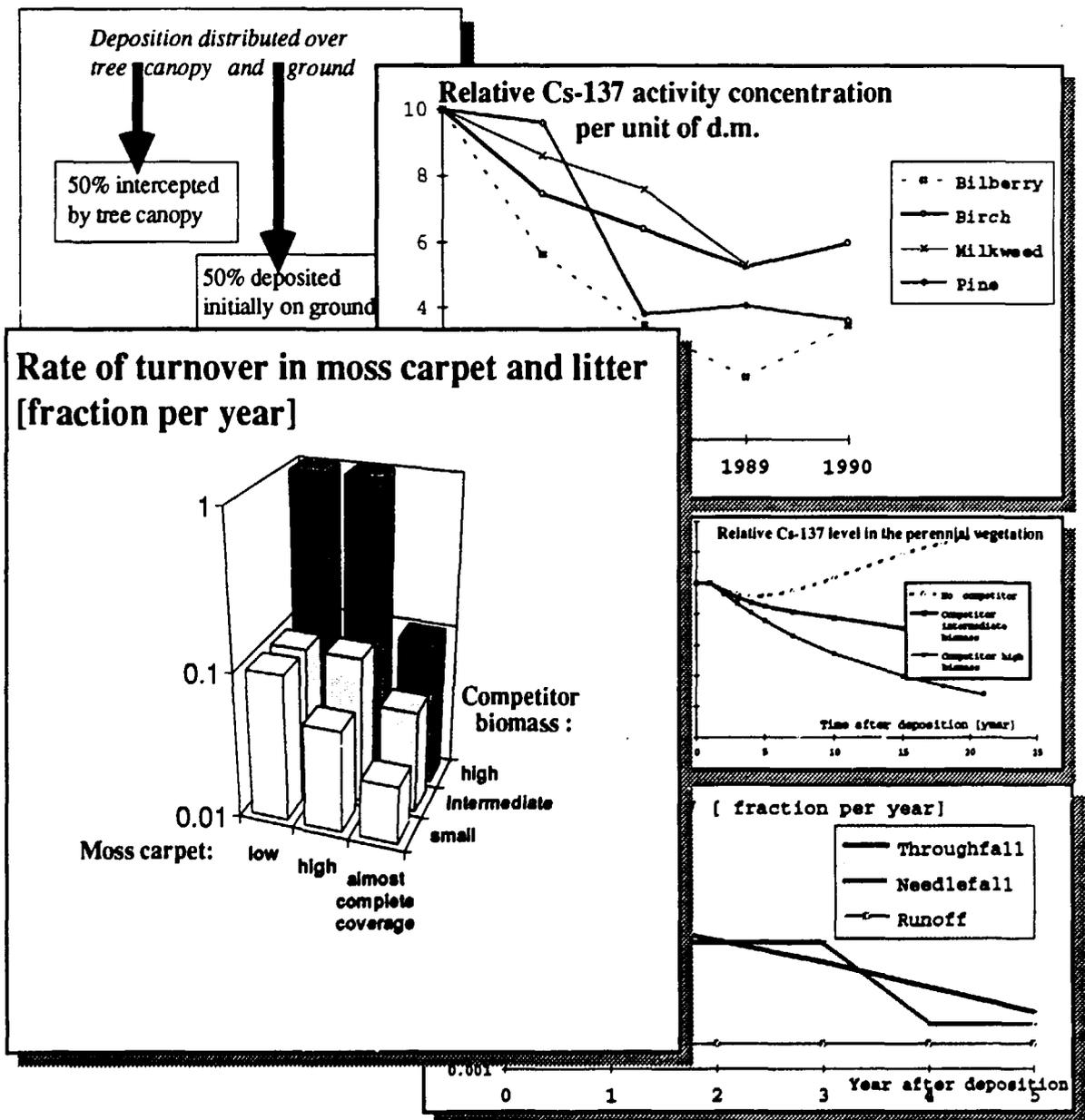


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## Caesium-137 in a boreal forest ecosystem

*Aspects on the long-term behaviour*

Ronny Bergman, Torbjörn Nylén, Per Nelin and Thomas Palo



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## INTRODUCTION

Cycling of radioactive caesium, particularly the isotope Cs-137, is studied in boreal forest biotopes mainly located at the Vindeln experimental forest, 60 km NW of Umeå, Sweden, (64°16'N, 19°48'E). The distribution of radioactive caesium in this forest ecosystem, prior to and in different periods after the Chernobyl accident, reflects the existence of fast changes particularly at an early stage after the deposition, superimposed on slow redistribution over long time periods (Bergman et al. 1988, Palo et al. 1989, Nelin and Palo 1989, Nylén and Grip 1989, Nylén and Ericson 1989, Nelin and Nylén 1992). The definite causes to this complex dynamic behaviour are not yet unambiguously established. In this work we use the specific results from local field studies as a basis to describe the general pattern and time dependence of Cs-137 redistribution in a boreal forest.

We raise the hypothesis that: "Cs-137 present in a boreal forest tends towards a homogenous distribution among the living cells of that system". This hypothesis is based on physiological characteristics concerning transport over cell membranes and intracellular distribution in comparison to potassium, and the apparently conservative conditions prevailing for caesium in boreal ecosystems – e.g. the facts that very little of the radioactive caesium deposited over the forest area is lost from the system by run off (Nylén and Grip 1989), more than 90 % of the total deposition of Cs-137 resides in the upper organic horizon in podzol areas, and that the availability in the ecosystem, as can be seen from the Cs-137 concentration in moose meat, is not significantly different in 1985 (i.e. prior to the Chernobyl accident) in comparison to the period 1986-1990 (Bergman et al. 1991).

The aim of this work is to elucidate how predictions, based on our hypothesis about redistribution processes in the boreal forest, corroborates with the main features in the time-dependent change of Cs-137 activity, according to measurements on perennial vegetation from the local sites. In particular the implicit dependence of the dynamics of the redistribution processes on primary production and growth at different sites is indicated.

## Characteristics of the Cs-137 behaviour during the first five years

The following is a short review concerning results from the Vindeln experimental forest, of relevance for analysis of the dynamics of redistribution of Cs-137 in a forest ecosystem. Detailed presentations of the different topics appear in the references given below or in the introduction.

### The phase of initial deposition and snowmelting

#### *Deposition of "Chernobyl"-caesium*

Direct deposition (i.e. not including resuspension), due to release of radioactive caesium from the reactor in Chernobyl, occurred mainly within some weeks after the accident (IAEA 1987). At the Vindeln experimental forest most of the fallout originates from wet deposition during a rainfall that lasted for 14 hours on April 29, 1986, yielding a precipitation of between 3 and 6 mm, depending on local variations within the area (Degermark 1987). The protracted input mediated by a particularly light rainfall probably made the initial distribution relatively homogeneous within the forest. This is indicated by the fact that in June 1986, when the first sampling was performed, there was no significant difference in the concentration of radioactive caesium in needles from different heights in individual trees or between the average values from different sampling sites in a pine stand (Bergman et al. 1988, Nylén and Ericsson 1989).

The average deposition of Cs-137 over the whole area based on soil samples (Bergman et al. 1991) was  $24 \text{ kBq/m}^2$ ,  $s = 9 \text{ kBq/m}^2$ .

#### *Run off*

The content of radioactive caesium in water has been studied with regard to run off from a catchment area (Nylén and Grip 1989, Nylén and Grip in prep.). Based mainly on waterflow and radioactive concentration in 1986, 1989 and 1990, the amount of radioactive caesium leaving the terrestrial compartment by water has been estimated.

At the time, when the main deposition of Chernobyl caesium occurred (April 29th), snowmelting and run off reached their maximum intensity (Degermark 1986). The amount of Cs-137 discharged from the studied  $0.5 \text{ km}^2$  catchment (average deposition  $21 \text{ kBq/m}^2$ ,  $s = 7 \text{ kBq/m}^2$ ) during this period was about 600 MBq, corresponding to 5 % of the total deposition in that area (Bergman et al. 1988). In the following years only low levels of radioactive caesium were detected in the stream (Nylén and Grip 1989) leading to a loss of about 0.2 % per year of the total Cs-137 deposition by run off from the catchment as a whole (Fig.2). However, at this event peat areas apparently were losing considerably amounts of radioactive caesium during the initial phase after deposition, which coincided with intense snowmelting. Under the assumption that only peat areas are responsible for the release of activity to the stream, an early fractional loss of  $1/3 - 2/3$  occurred from such peat sites under the "Chernobyl" conditions. The fractional loss per year during the subsequent period, 1987-1990, has been 1-2 % (Bergman et al. 1991). A similar behaviour may be expected for the loss of Cs-137 by run off during several decades. This supposition is based on the fact that the amount of Cs-137 from nuclear weapons test remaining about 20 years after the main deposition in samples from the peat bog is relatively small even in comparison to the average level in adjacent podzol areas, and that the loss over a 25 year period (i.e. from the middle of the sixties to the end of the eighties) is estimated to be of the order of 1 % per year from peat. Thus it is similar to the leakage rate found for the Chernobyl caesium.

It is of particular interest that this correspondence (with fast loss from peat areas and, in comparison to the physical half-life of Cs-137, slow loss from the rest of the forest ecosystem) seems to be valid, despite the very different deposition history and residence time in the forest ecosystem for the two types of fallout.

## Distribution and transfer in vegetation

### *Cs-137 concentration in certain plants*

In figure 1 is illustrated the concentration of Cs-137 during 1986-1990 based on pooled data from samples in July (*Vaccinium myrtillus*, bilberry twigs; and *Betula pubescens*, birch twigs) and October (bilberry twigs; birch twigs; and *Pinus sylvestris*, pine twigs). In order to focus on the principal feature in the change over time, the level of Cs-137 is normalized to initially 10 units in 1986 for each plant species. Similarly the concentration of Cs-137 in *Epilobium angustifolium*, milkweed, during 1986-1989 is illustrated in figure 1 based on pooled data from samples in July (Bergman et al. 1991, Nelin and Nylén 1992).

Birch, pine, bilberry, and milkweed constitute perennial "key"-plants with respect to their importance in food-chains to man (over moose or berries) and their abundance in the boreal forest ecosystem. They also represent specific categories of vegetation exposed under qualitatively different conditions during the wet deposition:

The pine, due to effective scavenging by its needles, captures in the canopy much of the caesium transferred during wet deposition according to our measurements after the Chernobyl accident (Nylén and Ericsson 1989). This is also evident from other studies (Melin 91, Steines and Njåstad 1992).

The birch, on the other hand, indicates a category of directly exposed vegetation with comparably low capacity to retain the initial wet deposition. Apparently this reflects the small surface area of its canopy, due to the lack of leaves during the time, when the deposition occurred.

The dwarf shrubs were completely covered by a thick (> 50 cm) layer of snow at the time of deposition. Bilberry therefore represent a category of the understorey vegetation, not directly exposed during the initial wet deposition, although it became thoroughly contaminated during snowmelting in the subsequent week.

Milkweed contains no aerial parts during the winter season (in contrast to the three species above). It belongs thus to the type of vegetation that became exposed indirectly during the growing season subsequent to the deposition. The level found in the aerial parts in July 1986 reveals a fast uptake to maximum concentration already the first summer (Fig. 1). Consequently the fraction of Cs-137 that has entered into circulation (and not resides as a potential source after deposition on e.g. the lichen or moss carpet) appears to have a very fast turnover in the ecosystem.

As is evident from figure 1, pine, birch, bilberry and milkweed exhibit a similar pattern with a slow decrease in Cs-137 concentration during the first 5 years after the deposition. This is true despite the very different exposure history, the different ecological conditions for trees visavis dwarf shrubs in the understorey, and proportions of Cs-137 initially retained on and in their aerial parts.

## Relative Cs-137 activity concentration per unit of d.m.

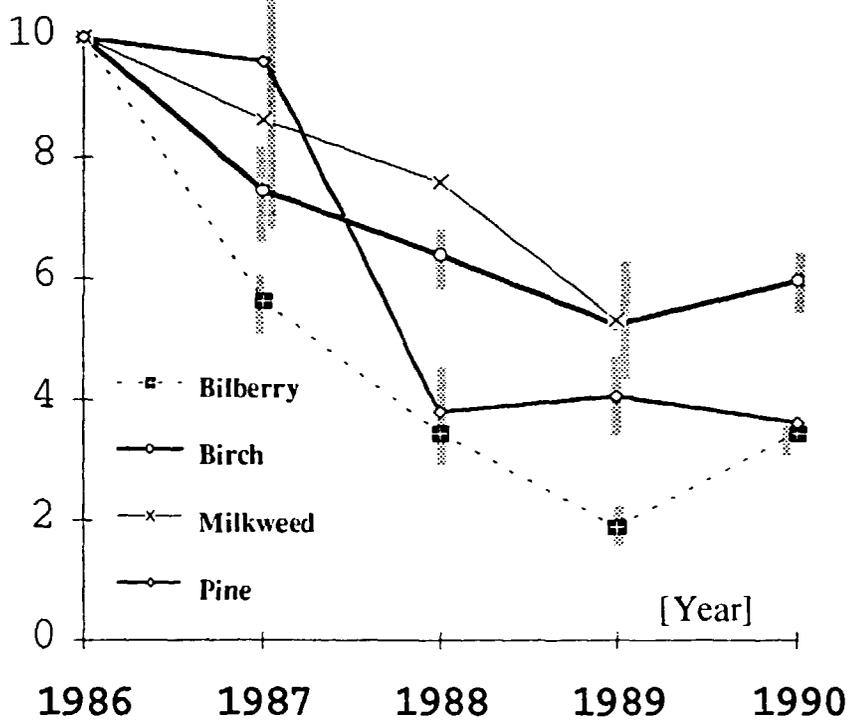


Figure 1. Concentration of  $^{137}\text{Cs}$  during 1986-1990 based on pooled data from samples in July (milkweed, bilberry- and birch twigs) and October (bilberry-, birch- and pine twigs). For each species the level in summer 1986 is set to 10 units. Standard errors of the mean are illustrated by bars.

### *Needlefall and throughfall*

That part of the litterfall in a pine forest (15 m average height, stem density 1200 stems/ha) consisting of needles transfer about 700 Bq/m<sup>2</sup> Cs-137 to the forest floor in the year after the Chernobyl accident. A slow decrease of the Cs-137 activity concentration is found in the old year classes of needles during the four years period after 1986. This may result from the combined effects of internal translocation and leakage. A further much faster decrease to about half the previous level has been found by Melin (1992) concerning the last weeks before needlefall in forests at nemo-boreal latitudes. It is expected that this fast decrease also will take place in the boreal forest, and is in fact observed for potassium (Mälkönen 1974). Although no direct evidence yet is available for caesium, the rise in Cs-137 concentration observed in all except the oldest year classes of pine needles shortly before the needlefall (Nylén and Ericson 1989) is in accord with translocation of Cs-137 from the oldest to the other year classes in this time period. Shoots not directly exposed to the fallout contain in the period 1986-1990 about 10 % of the activity concentration in needles present in April 1986 (Nylén and Ericson 1989). Consequently it is expected that the litterfall in each of the first four years after the

Chernobyl accident (i.e. composed of directly exposed needles) transfer similar quantities of Cs-137 – i.e. about  $700 \text{ Bq/m}^2$  – and from the fifth year and onwards will transfer about 10 % of that amount. According to our measurements (number in brackets are the estimated total throughfall during the whole year) throughfall in a mature pine and spruce forest transferred  $2.1 (3.0) \text{ kBq/m}^2$  and  $2.9 (4.5) \text{ kBq/m}^2$  respectively of Cs-137 to the forest floor during the period June-October in 1986, (i.e. the first year) (Nylén and Grip in prep.), and about 40 % of this amount the second year. In 1990 the transfer had been reduced to about  $240 \text{ Bq/m}^2$ .

The transfer from the canopy by throughfall and needlefall to the forest floor, and transfer (i.e. loss) from the whole catchment by run off are shown in figure 2. The levels are expressed as percent of the average deposition,  $21 \text{ kBq/m}^2$ , in the catchment. The transport from the canopy to the ground floor by throughfall and needlefall appears to be of such a magnitude during the growing season in the first year, that significant contribution to the contamination of the understory vegetation cannot be excluded. The loss from the system by run off, however, may generally be neglected. In comparison to the loss by physical decay of Cs-137 (2.3 %) the contribution by run off from the whole catchment is about one order of magnitude lower except for the first month after the deposition (Nylén and Grip 1989).

Transfer rate of Cs-137 [ fraction per year]

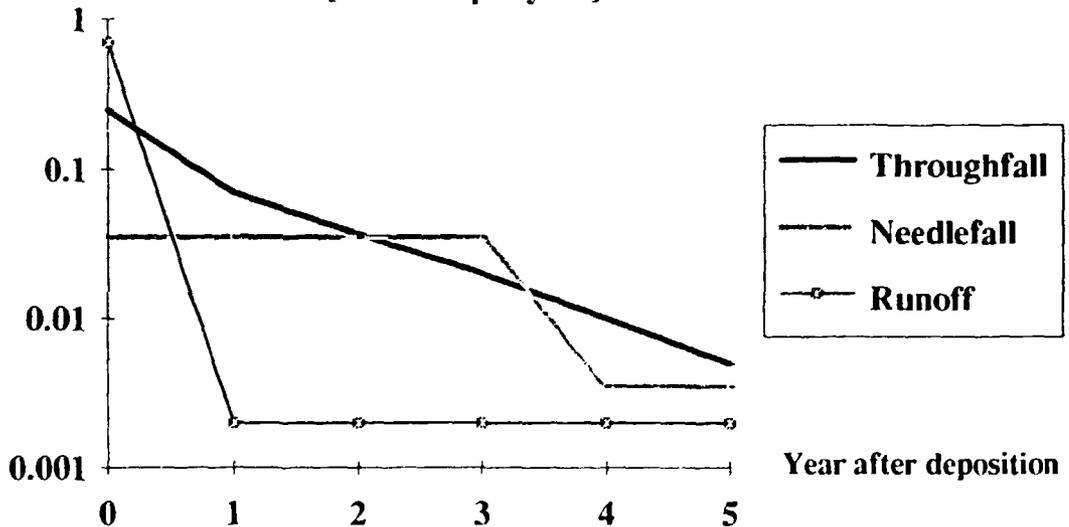


Figure 2. Rate of Cs-137 transfer per year from the canopy and by runoff. The fraction transferred is normalized to the initial deposition. [ $21 \text{ kBq per m}^2$ ].

## Aspects on the long term behaviour

Certain physiological characteristics concerning transport of caesium over cell membranes and intracellular distribution, and the apparently conservative conditions prevailing for caesium in boreal ecosystems, establish important clues to the general long-term behaviour and expected time dependence of Cs-137 redistribution in a boreal forest:

Potassium, the dominant intracellular cation, is an essential element for the living cell with a key-function in particular for energy transfer and active transport over cell membranes. Despite the fact that caesium transport over cell membranes is slower than that of potassium (which among other leads to somewhat different distributions in the organism) (Fujita et al. 1965), the two elements appear to be rather similar in the present physiological respect (Guerin and Wallon 1979, Rosoff et al. 1963, Spiers 1968) and as a consequence participate in the same way in the processes of the living cell (Rickard 1967, Coughtrey and Thorne 1983).

Very little of the radioactive caesium deposited over the forest is lost from the system by run off (Fig.2), and more than 90 % is with few exceptions distributed within the upper organic horizon in podzol areas at the Vindeln experimental forest. That this generally is the case in boreal podzol soils is apparent from numerous Nordic studies (e.g. Mattsson 1975, Varskog et al. 1988, Melin 1991, Strandberg 1992, Skålberg 1992, Raitio and Rantavaara 1993). Evidently the change in Cs-137 activity in the boreal forest will be mainly caused by physical decay.

Moose, due to its herbivory, constitutes a well-defined monitor of the average activity level in the plants predominant in its food within about a month prior to the meat sampling. Birch, pine, bilberry and milkweed (Fig.1) belong to the key-plants for the moose during different seasons. The observed ratio, in terms of activity concentration (Bq/kg) of Cs-137 in moose meat (Fig. 8) to the total Cs-137 activity density (Bq/m<sup>2</sup>) present in the soil column, is not significantly different in 1985 (i.e. prior to the Chernobyl accident) in comparison to the period 1986-1990 (Bergman et al. 1991). The level in 1985 reflects the distribution of Cs-137 that mainly become deposited in the middle of the sixties (and that thus has resided in the ecosystem for about twenty years), because of the atmospheric nuclear weapons tests (DeGeer 1987). The availability in the ecosystem, as can be seen from the Cs-137 concentration in moose meat, apparently will be the same over several decades (Bergman et al. 1988, Bergman and Johansson 1989).

It thus seems probable that caesium is affected similarly to potassium, although with different dynamics, concerning the extra- and intracellular distribution within an organism. It is also evident that loss of Cs-137 from a forest catchment is governed by physical decay, and that the availability (in terms of observed ratios between activity concentration in vegetation or moose to the cumulative deposition) will not change significantly over several decades in the boreal forest.

Based on these observations we raise the hypothesis that: "Cs-137 deposited in a boreal forest tends towards a homogenous distribution among the living cells of that system".

Generally, plants utilizing the same horizons for nutritional uptake are expected to approach similar activity concentrations of Cs-137 in their cellular components. However, several important feed-back pathways in the forest ecosystem (e.g. involving growth and decomposition cycles for trees) are notably slow. As a consequence, physical decay – even of the relatively long-lived nuclide Cs-137 –

probably will prevent the system as a whole to come close to a homogenous distribution, while there still remains significant amounts of the radioactive nuclide.

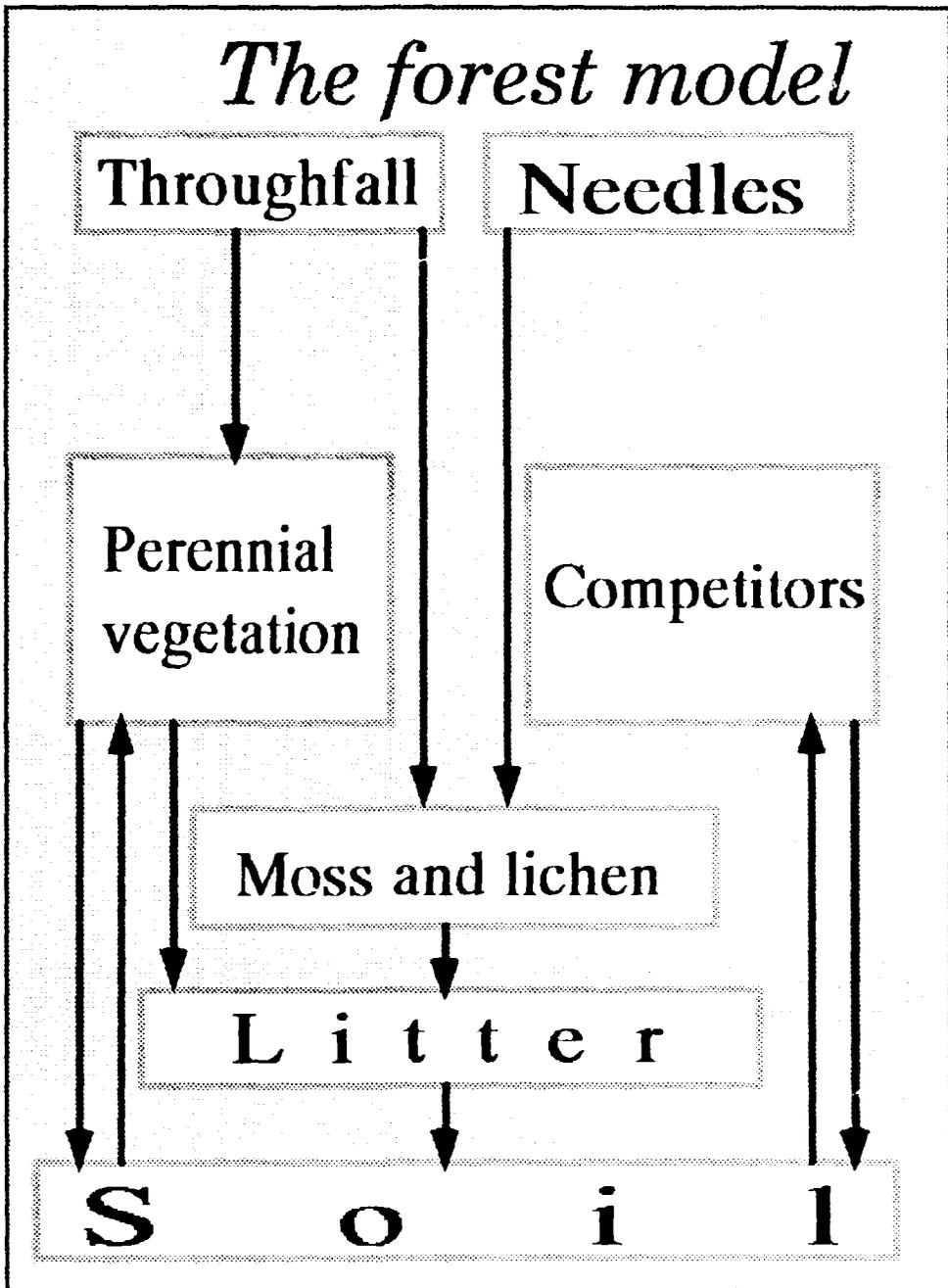
### Principal features of the forest model

Primary production and its distribution on growth and litterfall constitute major regulators with regard to the dynamics of the redistribution processes of organic matter in the forest (Lundmark 1986). The same conditions should be true for redistribution effects on potassium, due to its essential role in the living cell. Potassium and caesium is to a high degree exchangeable in active transport over cell membranes in living tissue (Cuering and Wallon 1979). As both elements evidently may serve in the same vital processes, the turnover of caesium is expected to be closely related to that of potassium. Their time dependent distributions in the ecosystem may nevertheless differ considerably, as the dynamics of their respective exchange and transfer processes at the cellular and ecological levels are not quantitatively identical. Yet, primary production should be of similar importance for the behaviour of caesium as for potassium in the forest ecosystem. The models employed for comparisons between results based on measurements and theoretical calculations, therefore include qualitatively effects of primary production and growth on turnover of caesium.

#### *Structure of an explanatory model*

The principal model structure shown in figure 3. has been used to simulate the turnover of caesium in forest biotopes. This compartment model is based on the actual results for the time-dependent transfer of Cs-137 from secondary sources in the canopy by throughfall ("throughfall") and needlefall ("needles") found at the Vindeln experimental forest (Fig.2), in addition to the release to the environment of Cs-137 deposited on the moss and lichen carpet ("moss and lichen"). It also includes a compartment ("competitor"; i.e. indicating the increase in biomass competing for the available caesium) to simulate effects on the redistribution processes of primary production and growth, as well as the perennial vegetation ("perennial vegetation"), litterfall from this compartment, decomposition ("litter"), and exchange of caesium between the vegetation compartments and soil ("soil").

The emphasis is thus on attempting to explain observed data in terms of more basic known mechanisms, and on showing the principal trend in the dynamic behaviour e.g. of radioactive caesium in a forest ecosystem. The treatment accordingly belongs to the category of EXPLANATORY MODELS; i.e. models that are not primarily used to make precise predictions in contrast to PREDICTIVE MODELS. Models of the latter type, simulating ecological systems, tend to be very complex and generally need to be based on a rather intricate network including several compartments.



**Figure 3.** The principal features of the forest model.

### Mathematical model description

The mathematical description of the forest model is based on compartment theory with first order kinetics. The cycling in the system and content of radioactive matter in different components of the forest is therefore described by a system of first order ordinary differential equations. The general equation for this model is based on the following assumptions: (a) the functional components or compartments of the forest ecosystem can be described by continuous mathematics; (b) the radionuclide flowing into a compartment is completely mixed with the quantity of the same radionuclide that may already be present in the compartment, and (c) the rate of radionuclide transfer from one compartment to another is established by the product of a transfer coefficient and the amount of radionuclide in the transmitting compartment. The range in parameter values and the different conditions considered in the calculations are summarized in table 1.

Table 1. Transfer coefficients [ $y^{-1}$ ] in the forest model.

Transfer to	Perennial vegetation	Mosses	Litter	Soil	Competitor
from					
Perennial vegetation		0.01	0.05		
Mosses			0.1-1.0*		
Litter				0.1-1.0*	
Soil	0.06				0-6.0**
Competitor			-- ***	0.06	
Needles#	cf. fig.2	cf. fig.2			
Throughfall##	cf. fig.2	cf. fig.2	--##		

\* The four possible combinations of the values 0.1 and 1.0 (defining the interval for transfer from moss and litter) have been used to analyse the sensitivity of the redistribution dynamics in the system to the rate of release of caesium from secondary sources.

\*\* (I): No competitor means that transfer from soil to competitor  $\lambda_{s-c} = 0$ ;

(II): competitor biomass 10 times that of the "perennial vegetation" corresponds to  $\lambda_{s-c} = 0.6$ ;

(III): competitor biomass 100 times that of the "perennial vegetation" corresponds to  $\lambda_{s-c} = 6.0$ .

\*\*\*Needlefall constitutes a major pathway for transfer of organic matter from the aerial parts of the vegetation to the litter compartment in a coniferous forest. This is true also for fallout of Cs-137, although herbivory generally appears to be of about comparable importance (Bergman et al. 1992). The relatively minor contribution by litterfall from the understorey vegetation is disregarded and only the route by needlefall (transfer from the needle compartment) has been considered for feed-back over litter from aerial parts of the competing vegetation

#The time dependent change in the transfer rate is illustrated in fig. 2.

## At growing sites with sparse or no moss and litter carpet (the "0%" alternative) 90% of the Cs-137 transferred to the ground by throughfall is received by litter and the rest by the perennial vegetation.

The relationship between the amounts of activity in the compartment system is expressed mathematically in vector form by

$$\dot{Y} = K * Y(t) - \lambda * Y(t) \quad (1)$$

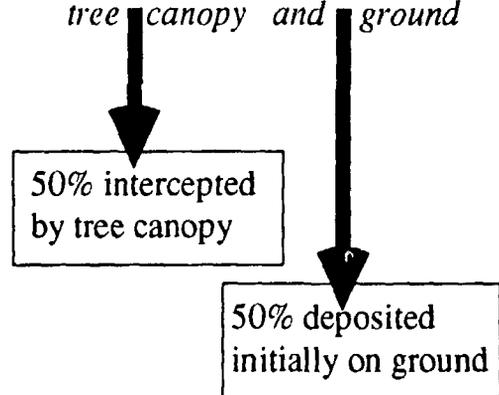
The vectors  $Y$  and  $\dot{Y}$  refer to activity and activity changes per unit time in the different compartments of the system at time  $t$ . The coefficient matrix  $K$  [ $\text{year}^{-1}$ ] describes the rates of transfer between the compartments according to table 1. The decay constant  $\lambda = \ln 2 / T_{1/2}$ , where  $T_{1/2}$  is the physical half-life.

Solution of the equation system and calculations of  $Y(t)$  is based on numerical treatment according to Einarsson (1984) by the use of the LSODE code (Hindmarsh 1980).

#### *Growth conditions, secondary sources and sinks*

The size of the competitor, limited by the net primary production, has been varied in the range 0-100 times that of the understorey vegetation (Table 1) to simulate the turnover of caesium in forest biotopes differing in primary productivity. This will cover the whole span of growth conditions encountered at particularly low primary production in poor environments – e.g. peat bogs and pine moors of low podzolisation – and at high primary production – e.g. clear cut areas, where it is directed mainly into growth of new biomass. The biomass distribution between (a) moss and lichen and (b) all other understorey vegetation has been studied for three categories (Tab. 2): two with a moss and lichen carpet covering 90 and 99 % respectively of the ground surface, and a third lacking a ground cover of mosses and lichen. This is of importance regarding the fraction of the Cs-137 deposition that initially has become transferred to such recipients (e.g. lichen and mosses) that constitute potential secondary sources in the understorey vegetation from which the release into circulation is known to be relatively slow. The initial deposition on the ground has in the model been distributed between perennial understorey vegetation and the moss and lichen carpet in proportion to the assumed surface area occupied by these populations. This means that respectively 90 and 99 % of the deposition on ground will initially reside in the moss and lichen carpet in the first two of the cases above, while in the third 90 % of the deposition on ground is assumed to fall directly on litter. The mean residence time for caesium-137 in lichen and mosses (after direct deposition) and in litter (with regard to litterfall from the canopy and understorey) is varied in the interval 1 to 10 years. This corresponds to the range derived from our results, as well as that commonly found in estimations based on results from other forest biotopes in boreal and sub-alpine areas of the Nordic countries (Lidén and Gustafsson 1967, Mattsson 1972, Varskog et al. 1990, Gaare 1990, 1992).

Table 2 *Deposition distributed over tree canopy and ground*



#### *Three alternative cases for surface cover of understorey, moss and lichens*

Alt I: The carpet of moss and lichens covers **99%**

" II: " " " " " " " **90%**

" III: The ground cover by moss and lichens is negligible

The interactions between biological components of the forest system constitute a complex network of feed-back loops. Over some of these the redistribution of caesium is expected to be fast, as for instance the microbiotic components, the fine root fraction and annual plants. For other the turnover rate will be relatively slow. That fraction incorporated in the heart wood of tree trunks (Melin 1991, Holm 1992) or deposited on lichen (Eriksson 1991, Mattsson 1972) represent the latter category. For the very protracted turnover processes related for instance to the lifetime of a tree, the cycling of caesium might be too slow to contribute substantially to the redistribution over a period corresponding to the physical half-life of Cs-137. As a consequence the effects of such slow processes will quantitatively appear similar to that of a sink for Cs-137. This will decrease the amount of available caesium. However, sinks have not explicitly been introduced in the present model, as qualitatively their effects on the change of Cs-137 activity in the perennial compartment will essentially be similar to that of the competing growth of new biomass.

The calculated time dependent change of the Cs-137 content in perennial vegetation has been compared to that actually observed at different local study sites with focus particularly on bilberry. The primary purpose of applying this model is to elucidate qualitatively how the predictions corroborate with the main features in the time-dependent change of Cs-137 activity according to our measurements on perennial vegetation.

## RESULTS

### Calculated changes of Cs-137 in perennial vegetation

The change of the Cs-137 content in the perennial understorey vegetation has been calculated with parameter variations to allow for different rates of turnover, growth conditions and importance of secondary sources in the canopy and the moss carpet, according to the strategy discussed above under "Principal features of the forest model". In all, 36 cases have been studied using parameter values for the four combinations of upper and lower limits for the transfer from moss and litter; three sizes on competitor biomass; and three different surface areas covered by the moss carpet.

In figure 4 the Cs-137 content in the perennial understorey vegetation is shown as a function of time after the deposition, when the moss and lichen carpet covers 90 % of the ground surface. The mean residence time for caesium in moss and litter is respectively 10 and 1 year. The assumed early distribution after the fallout: 50 % of the deposited Cs-137 initially retained in the canopy and 50 % on the understorey vegetation and ground floor, describes the distribution prevalent at the Vindeln experimental forest a few days after the wet deposition according to our findings. Effects of competitor for available caesium at the growing site, and of Cs-137 mean residence time in secondary sources is illustrated in figure 4 for three cases: (I) the net increase of biomass is negligible in comparison to the size of the existing perennial vegetation ("no competitor"); (II) the increase in biomass described by the size of the competitor compartment is 10 times that of the perennial vegetation ("competitor intermediate biomass"); and (III) 100 times that of the perennial vegetation ("competitor high biomass").

All three cases conform with the observed decrease in the perennial vegetation according to figure 1 and 2 during the time period 1986-1991. This time span is relatively short in comparison to the assumed mean residence time in the moss and lichen carpet. Consequently, the release of Cs-137 from such secondary sources integrated over the elapsed period of time have been of comparatively minor importance.

## Relative Cs-137 level in the perennial vegetation

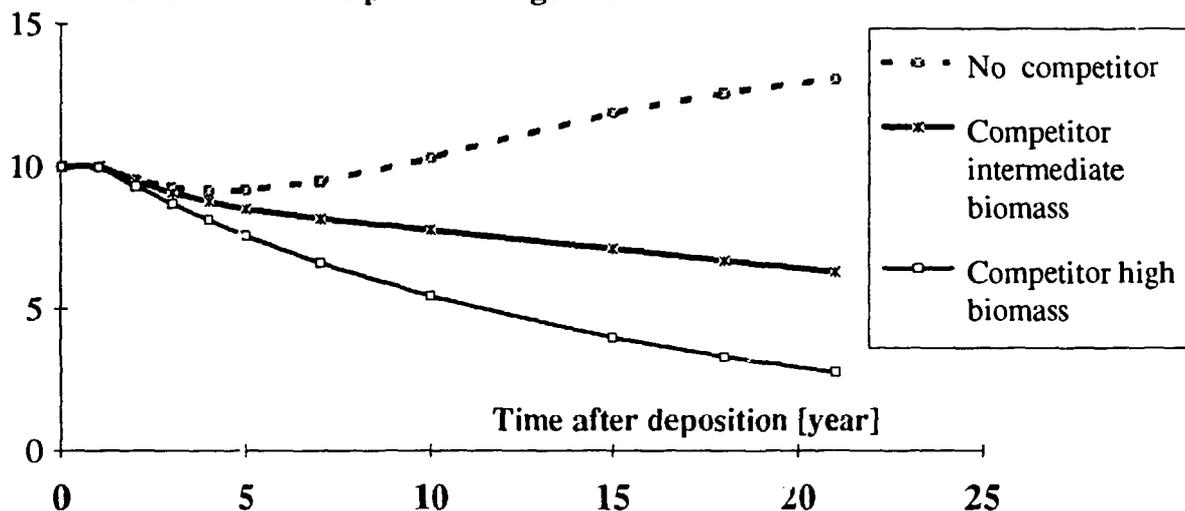


Figure 4. The change of  $^{137}\text{Cs}$  content in the perennial understorey vegetation compartment, when mosses cover 90 % of the ground surface. The mean residence time for Cs in moss and litter is assumed to be respectively 10 and 1 year.

Small primary production typical for peat soil conditions limits biomass growth. Such sites therefore belong to the alternative (I), where the continuous release of Cs-137 from secondary sources in the moss and lichen carpet partly or completely may compensate for losses by physical decay or transport of Cs-137 out of the system. This appears to increase the total Cs-137 content in the perennial vegetation after a time period corresponding to the mean residence time for caesium in moss and litter. Removal of Cs-137 from a catchment by run off generally may be neglected in comparison to loss by physical decay, and is therefore not included in the model. However, peat seems to constitute an exception in that respect, since about 1 % per year of the Cs-137 content (Bergman et al. 1991) is estimated to be lost specifically by run off from peat in discharge areas. Therefore a potential increase, as in figure 4, is expected to be partly counterbalanced also by the continuous loss by run off from such sites.

Even at high net primary production the increase in biomass may be small, due to the combined effects of growth and litter production. This is for instance a characteristic of the mature boreal forest, where growth and decomposition processes to a large extent neutralize each other, resulting in relatively small net contributions to the total biomass. A maturing forest therefore pertains to a category, whose response is expected to approach that of alternative (I) during aging of the growing site.

In a young forest, or at a clear cut area, a relatively large fraction of the primary production is directed into growth. As a consequence the Cs-137 content in the perennial vegetation at such sites is predicted to decrease monotonously in accord with alternatives (II) and (III) in figure 4. These two alternatives represent the effects of new growth at a level commonly found in the boreal forest depending on the stage of development and the limit for growth set by the local primary production capacity.

## Predicted versus observed effects on the caesium distribution of primary production and growth

The similar trends towards lower concentrations of Cs-137 in pine, birch, and bilberry shown in figure 1 are based on pooled data from regular sampling at 10 different sites at the Vindeln experimental forest. At the 10 sampling sites of about one hectare each, 10 separate subsamples (for statistical assessment of the variability within and between sites) have been taken regularly twice a year (July and October) in the period 1986-1990 (Bergman et al. 1991). The sites comprise 3 in mature mesic spruce forests, 4 in dry pine forests, and 4 in young forest at areas, which have been clear cut within 5-10 years before the Chernobyl accident. The uniform pattern of changes in Cs-137 content exhibited by the perennial vegetation in figure 1 agrees well with the model predictions that the caesium levels in the vegetation should primarily not be a characteristic of the single species, but the growing site. The information lost by pooling data over the different ecological conditions occurring at the 10 study sites concerns site specific factors such as age of the forest stand and primary productivity. These factors are of particular importance according to the model. The two comparisons below therefore test the model predictions against the actual results by specifically focussing on the expected differences in the redistribution dynamics of Cs-137 between (a) young and mature forest stands; and (b) growing sites with high or low primary production.

### Cs-137 in bilberry:

#### *The dynamics of redistribution in mature and young forests*

The increased competition for available caesium caused by the addition of new biomass affects the rate of decrease of the Cs-137 content in the vegetation. This is indicated by the different dynamics in figure 4 concerning the change of the Cs-137 content in perennial vegetation in the cases "no competitor" and "competitor intermediate (or high) biomass". The categories (a) mature coniferous forests (i.e. comprising the pine and mixed coniferous forests at the study sites), and (b) young forests or clear cuts have been used to separate the material used for bilberry in figure 1 in populations belonging to the mature or young forest respectively. In figure 5a the Cs-137 activity concentration in bilberry from mature forests and young forests on recently clear cut areas at the Vindeln experimental forest is shown for three periods: 1) 1986; 2) 1987-1988; and 3) 1989-1990. The quotient between the Cs-137 concentration (according to figure 5a) in bilberry from recently clear cut areas and mature forests is illustrated in figure 5b. At the first sampling occasion in July 1986 the Cs-137 concentrations are not significantly different in young- and mature forest areas (Nelin and Nylén 1992). The quotient in figure 5b therefore starts in 1986 at a value close to 1, but decreases significantly over the following two periods down to about 1/3. Thus the change towards lower concentrations in bilberry is faster in the young forest or clear cut areas, where the increase in biomass is relatively high, in comparison to that in the mature forest. Concerning the redistribution dynamics for caesium this qualitative dependence on competing biomass is exactly what is predicted by the model. The consistency between predicted and measured changes consequently supports our hypothesis about the major regulators of caesium behaviour in the boreal forest.

# Cs-137 concentration

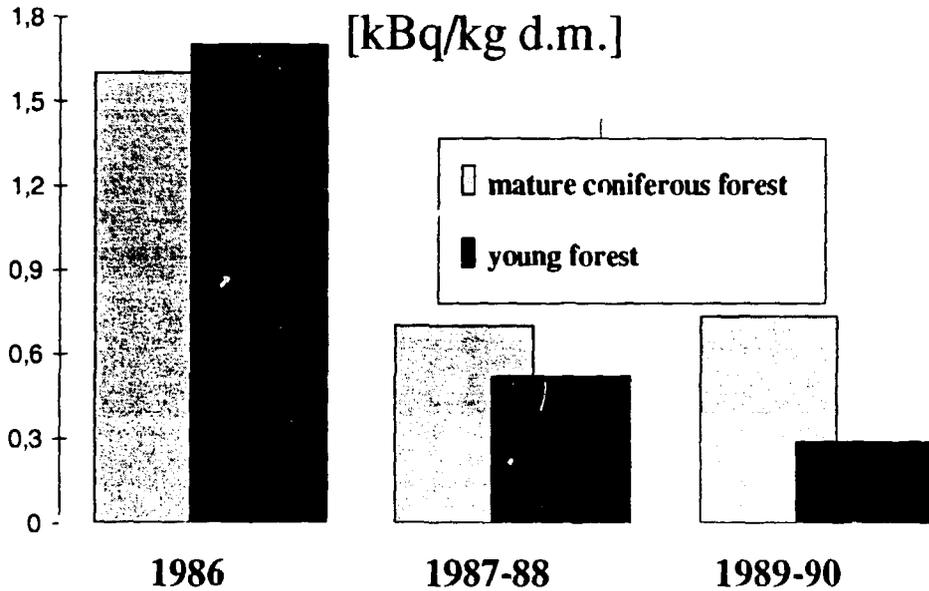


Figure 5a Mean Cs-137 concentration [kBq/kg] in bilberry in young and mature coniferous forests during 1986 (from June); 1987-88; and 1989-90.

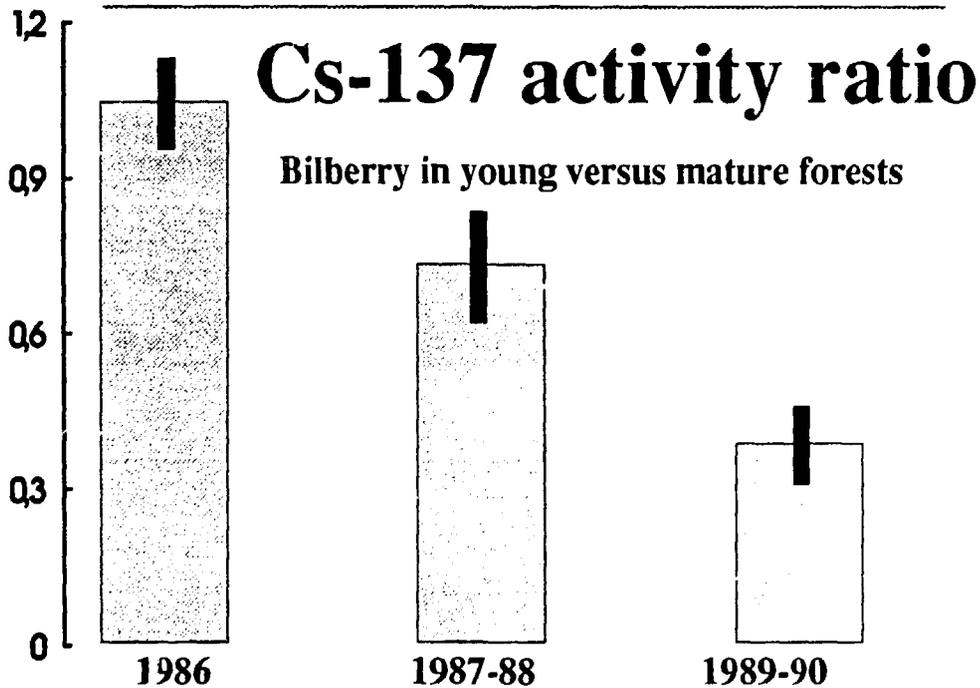


Figure 5b The ratio of Cs-137 concentration in young- versus mature coniferous forests. The vertical bar (■) represents standard error.

*Relationship between the activity concentration and primary production or thickness of organic layer*

In a boreal podzol forest biotope the primary production capacity is generally indicated by the thickness of the organic soil layer (Lundmark 1986). In a poor environment we should thus expect a relatively thin organic layer. The model predicts the Cs-137 concentration to be high in the vegetation at such sites with a low primary production.

Results on the Cs-137 activity concentration in bilberry and the thickness of the organic horizon in the soil, based on sampling of vegetation and soil columns from a large number of different growing sites at the Vindeln experimental forest in the period 1990-1991, has been used to analyse this aspect.

**Cs-137 activity concentration in bilberry**

[Bq/kg d.m.]

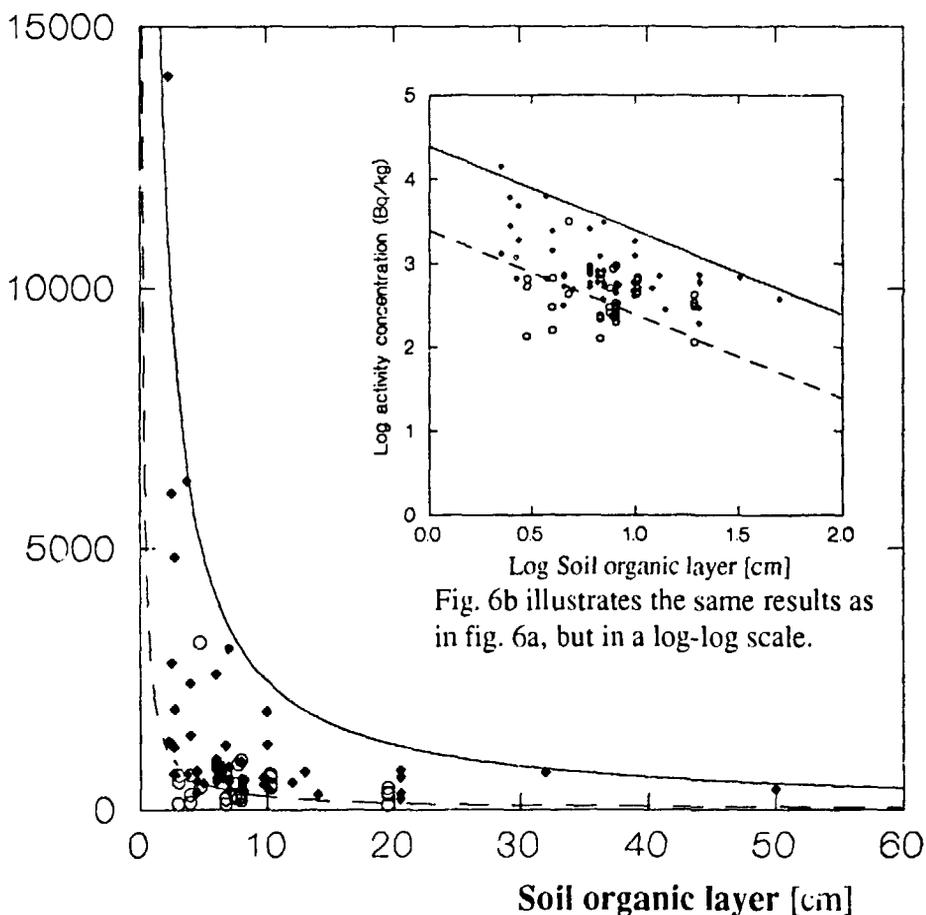


Figure 6 Cs-137 activity concentration in bilberry versus thickness of the organic soil horizons at boreal growing sites. Samples from young forests are indicated by unfilled circles. Samples from mature forests are indicated by black diamonds. The hyperbolic curves represent theoretical upper limits for activity concentration at (a): "competitor low biomass" (i.e. its biomass is less than that of bilberry) – continuous line; and (b): "competitor intermediate biomass" (i.e. ten times that of the bilberry population) – dashed line.

Figure 6 a illustrates the relationship between Cs-137 activity concentration in bilberry and thickness of the organic soil layer. A thin organic layer evidently corresponds, as predicted by the model, to relatively high concentration of Cs-137 in bilberry. Furthermore, samples from young forests (indicated by unfilled circles) frequently corresponds to positions (Fig. 6b) which are relatively low in comparison to the solid curve connecting the maximum values for the mature forests (indicated by black diamonds). This is also in accordance with the expected stronger influence at a young forest from growth of new biomass, which effectively competes for the available caesium (Fig. 4).

Under the assumption that primary productivity is proportional to the thickness of the organic soil layer, the relationship between  $C_b$  (the maximum Cs-137 concentration in bilberry; obtained in the absence of "competitors") and  $T_{Oh}$  (the thickness of the organic horizon) may be written as :

$$C_b * T_{Oh} = K_{max} \quad (2);$$

where  $K_{max} [Bq.m.kg^{-1}]$  is a constant.

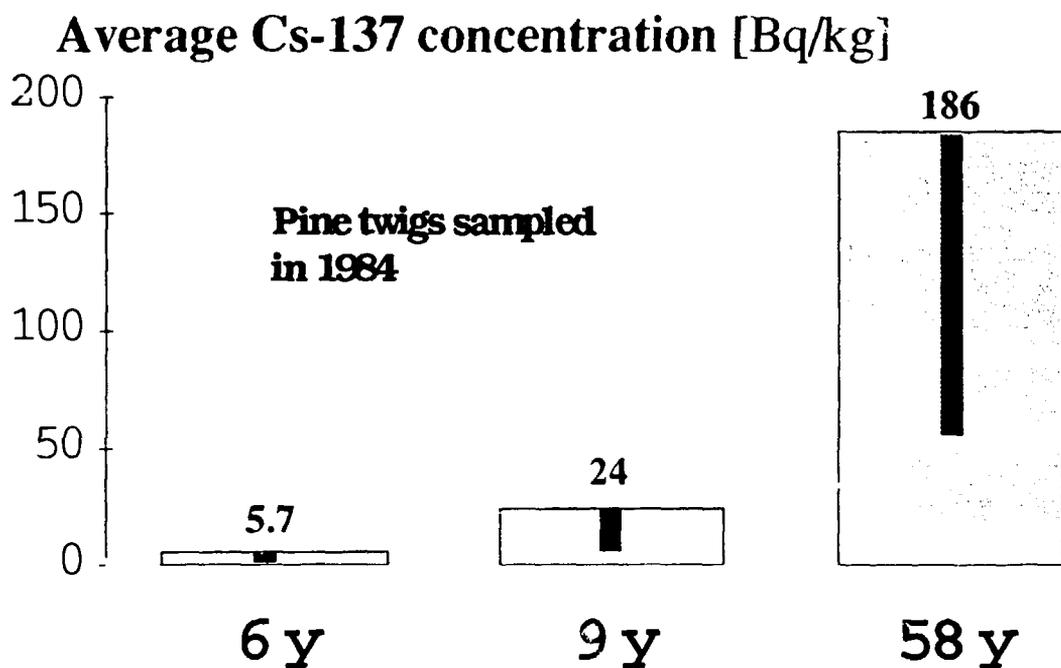
The upper hyperbolic curve (continuous line) in figure 6 describes this relation with the value for  $K_{max}$  equal to the average for the relation (1) over the 10 points closest to the upper limit. Competition for caesium by new biomass at a particular site reduces the amount of Cs-137 available for the older vegetation. This implies that, in case of competitive growth, the constant  $K_{comp}$  to be used in (1) must be smaller than the maximum value, i.e.  $K_{comp} < K_{max}$ . The calculated upper limit for the Cs-137 concentration in bilberry at sites where growth of new biomass has increased the competitor to 10 times the biomass of the bilberry population (Fig.4 "competitor intermediate biomass") – which means that  $K_{comp} = 0.1 * K_{max}$  – is also indicated (by the dashed line) in figures 6 a and b.

### **Distribution and availability of Cs-137 in a long-term perspective**

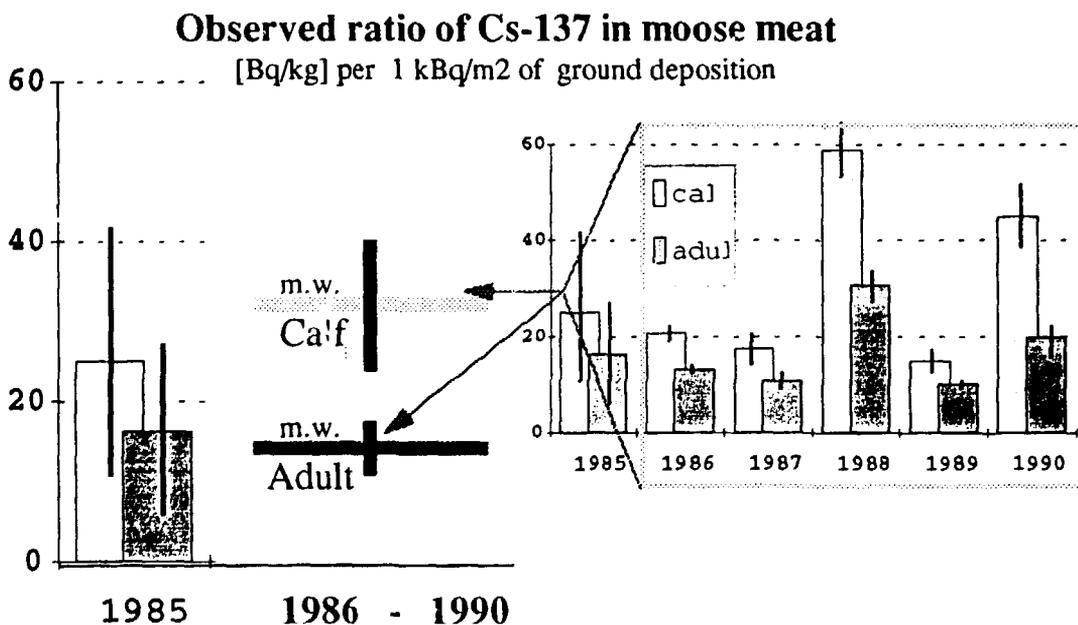
Most of the deposition of Cs-137 from atmospheric tests has its origin in fallout during the middle of the sixties (UNSCEAR 1977, DeGeer et al. 1987). There is still remaining  $1.9 \text{ kBq/m}^2$  (S.E. =  $0.1 \text{ kBq/m}^2$ ) of Cs-137 (Bergman et al. 1991) at the Vindeln experimental forest according to our measurements on samples of soil and vegetation. Furthermore collection and measurements of particulate radioactivity in air was performed at Lycksele (about 60 km from the study site and 130 km NV of Umeå) till the beginning of the eighties by the National Defence Research Establishment. The cumulative deposition calculated using the activity concentrations in air at the Lycksele site is  $1.8 \text{ kBq/m}^2$  (DeGeer et al. 1977, DeGeer private comm.). Based on these two assessments the average cumulative fallout over different areas in the district of Västerbotten appears to have been similar concerning the deposition due to the nuclear weapons tests. About 90 % of what is still remaining at these latitudes had been in the environment for more than 15 years at the time of the Chernobyl accident. We have used various samples from the boreal forest ecosystem containing this "old" Cs-137 to estimate the behaviour of caesium in a long-term perspective (Bergman et al. 1988, Bergman and Johansson 1989, Bergman et al. 1991).

#### *"Old" Cs-137 in different pine stands*

Twigs sampled in 1984 from three different pine stands with trees of age 58; 9; or 5 years (Fig.7) indicate that pine trees born before the fifties (i.e. earlier than the start of fallout from nuclear weapons tests) have of the order of 10 times higher levels of Cs-137 in the twigs, as compared to plants of the same size, but less than 10 years of age in 1986. Whether the difference in concentration



**Fig. 7** Activity concentration [Bq/kg] of Cs-137 in pine twigs from stands of different ages. Standard deviation ( )



**Fig. 8** Cs-137 concentration in calf and adult moose meat at the September hunt 1985 - 1990 with 95% conf. level ( ). Average 1986-90 in calf ( ) in adult ( ) and S.E. ( ).

of Cs-137 mainly depends on the soil characteristics, on effective retention after deposition directly on old trees, or on cumulative retention as a function of the age of the tree is not clear. In spite of that, it exemplifies that between nearby areas with almost the same deposition of Cs-137 the levels in the vegetation might differ very much in future time. However, the growth at the oldest forest stand had been very low, as indicated by the fact that the pine trees, from which samples were taken, were of the same size (about 2 m) as those at the other two sites with young forest. The inverse relationship between Cs-137 content in the perennial vegetation and growth capacity (i.e. high content in the vegetation at low net increase of biomass) found at these sites agrees with the predictions made by our model (Fig. 4 and 5b).

#### *Cs-137 concentration in moose meat 1985-1990*

The observed ratio of the activity concentration (Bq/kg) and the cumulative deposition of caesium-137 (kBq/m<sup>2</sup>) with regard to moose muscle from the hunting season 1985 in the vicinity of the Vindeln experimental forest at Svartberget (Bergman et al. 1988) has been compared to that corresponding to the period 1986-1989 (Bergman and Johansson 1989). Moose, due to its herbivory, constitutes a well-defined monitor of the average activity level in the plants predominant in its food. Birch, pine, bilberry and milkweed (Fig. 1) belong to the key-plants for the moose during different seasons. The ratio "moose versus ground deposition" for 1985 did not differ significantly at the 95 % confidence level from that estimated as an average for the post-Chernobyl period. This is true also after inclusion of results for 1990 (Fig. 8). The availability of Cs-137 in the ecosystem and the concentration in the food-plants appear therefore to be of the magnitude over several decades after the deposition.

## DISCUSSION

### The complex forest ecosystem

#### *Comprehensive whole-system approach to describe caesium behaviour*

The boreal forest ecosystem constitutes an ordered but complex entity. The behaviour of caesium, resulting from the interdependencies and effective interactions within the community, is probably intractable to grasp by constructing a theoretical model based on a detailed pattern of these interrelationships. However, the multiple pathways for feed-back, inherent in the comprehensive network of interactions, favours a whole-system or holistic approach. In this the major regulators of energy flow, as well as of caesium turnover, may be expressed by primary production and its constraints on the growth capacity, in addition to fundamental physiological processes governing the metabolism of living matter in the biotope. These aspects, together with the redistribution pattern of radioactive caesium exhibited in vegetation and soil at the study sites, form the basis for our hypothesis and qualitative design of a forest model.

Similar experiences are apparent in the findings by Nimis et al. (1990) giving particular attention to the relations between Cs-137 concentration in different plant species, and the average depths of their root system in the forest soil. By multivariate analysis best correlation between activity concentration in the plants and the Cs-137 deposition were obtained in their study, when the species were subdivided into 3 groups, so that each group was characterized by a specific ecology within the forest (shallow-rooting wood species, deep-rooting wood species, and plants of forest clearings). This conforms excellently with the assumptions that the Cs-137 content in the vegetation in general reflects the conditions in certain ecological niches rather than being an expression of species specific characteristics. Yet, there are exceptions. For instance some vascular plants as the herb *Rumex*

acetuosa (Hove et al. 1990) and several fern species, Pteridophyta, (Giovani and Nimis 1992) usually exhibit concentrations of Cs-137 markedly higher than the average over the rest of the local plant community.

Different plant species, or different parts of the same species, may have very different content of cellulose or lignine. However, the biomass of the living cells proper is better related to the plant weight after subtraction of such matrix components. The expression of Cs-137 activity concentration on a "water basis" (Nimis et al. 1990), i.e. difference between fresh and dry weight in higher plants, seems to be a more appropriate parameter than dry weight, when the aim is to analyse the absorption rates of Cs-137 from the soil and interpret the uptake in different plant species. The cardinal role ascribed by our hypothesis to competition for caesium among the living cells within the complex forest system, and the resulting force towards equal sharing of Cs-137 over the cell population, are consistent with Nimis findings.

Forest practice will temporarily more or less extensively disrupt the system of ecological interactions. Yet, the forest generally may be considered as an undisturbed system in the sense of a comprehensive intact network. The practice in agriculture, often focussed on optimal growth, implies radical disturbances and extensive disruption of the network attained in a natural undisturbed ecosystem. It therefore in general remains a reduced number of feed-back pathways operative in the system. A successful model of transfer between soil and plant may under such circumstances be based on a few major factors and pathways, e.g. clay content in soil and uptake by the root. We believe that problems encountered in extrapolations of strategies for radioecological studies of caesium behaviour in agricultural ecosystems to the forest environment, may be traced back to these qualitatively different conditions. It appears to be due to, rather than despite of, the complex network in the forest that a holistic approach may be successful in describing caesium behaviour in long-term perspectives.

#### *Extrapolations to future time*

The model predicts only minor dependence on growing site characteristics concerning the relative change with time of the Cs-137 content in the perennial vegetation (Fig. 4) during a period of the order of the mean residence time of Cs-137 in mosses and lichen. In this period much of the original deposition is still kept in these secondary sources, although continuous release occurs to the environment. This response in the vegetation is confirmed at the study sites (Fig.1). The long term behaviour, however, is predicted to be governed mainly by the productivity and age of the forest stand. The dynamics of the redistribution processes over about the first five years at the different growing sites fit to the predicted behaviour as a function of age and growth capacity (Fig.5a, 5b and 7). The observed Cs-137 concentration in pine twigs sampled in 1984 from stands of different productivity (Fig.7), and the observed ratio in 1985 of Cs-137 in moose meat to the cumulative deposition from the atmospheric nuclear weapons tests fallout about twenty years earlier in comparison to the same ratio over the post-Chernobyl period 1986-1990 (Fig.8) also agree with respectively the predicted long-term dependence on site specific primary production and availability in the perennial vegetation .

The satisfactory agreement between observed and predicted behaviour of Cs-137 in the boreal forest

(A): in the early phase ( i.e. over the first five years after the Chernobyl accident) ,

and

(B): the distribution and availability about two decades after deposition exhibited by the content in pine twigs and moose meat some years prior to the Chernobyl accident,

provide important clues to the expected general behaviour in the forest over a time span comparable to the physical half-life of Cs-137.

The contention is that:

- *at the same primary production capacity the decrease in Cs-137 activity concentration in the perennial vegetation will be faster in the young as compared to the mature forest;*
- *at a particular growing site the rate of decrease of the Cs-137 content in perennial vegetation will be positively related to the local primary production capacity (at sufficiently low productivity, e.g. peat soil conditions, decrease may not occur or be extremely low during several decades).*

Our interpretation is that during the successional stages of development, the dynamics of the Cs-137 redistribution will comply with this general characteristics, not only in the five year interval for which direct observations are available concerning the Chernobyl fallout, but practically as long as the caesium isotope still remains in the ecosystem. If this interpretation is true, the pattern of redistribution will be repeated at sites, where for instance a mature forest stand is clear cut, even at an occasion far in the future. Depending on the forest practice, we expect a transient phase to occur initially, during which the prerequisites of a sufficiently intact feed-back network may not be satisfied. The reestablishment of a functional complex network, which mainly relies on the recovery of the microbial, mycelial and fine root systems, will probably be fast. This means that the Cs-137 content in the perennial vegetation, after a shortlasting transient phase, will undergo the same dynamic stages of redistribution, as described for the forest exposed to direct deposition. This assumption is supported by the fact that 3-18 % of the total deposition over a mature forest is contained in the tree biomass (Block 1990, Melin 1992, Strandberg 1992). About two-thirds of this will be removed with the tree trunks, as can be estimated from the internal distribution. Consequently only about 2-12 % of the total deposition is lost by that route. This in turn implies that the total inventory of Cs-137 will not change considerably due to logging.

As long as the large scale pattern (e.g. on a regional basis) of clear cut areas and forest stands of various ages not becomes radically changed by forest practice or extremely extensive forest fires, the distribution of biotopes prevalent at the time, when deposition of radioactive caesium occurred, will persist or at least be similar over a long time. Our model predictions indicate that in this time span a regional average will be essentially unchanged over the different growing sites concerning the Cs-137 concentration in the key-plants for moose. The average Cs-137 content in the moose population should thus also remain on a similar level under these conditions. It is apparent from figure 8 that no significant change has occurred in the average concentration of Cs-137 in the moose population (normalized to 1 kBq/m<sup>2</sup> ground deposition) in comparisons between the post-Chernobyl period 1986-1990, i.e. an early phase after deposition, and the level obtained in the pre-Chernobyl situation 1985, representing the state about twenty years after deposition. This supports the assumption that despite the dynamic behaviour of redistribution observed for Cs-137 at a particular growing site, the cycle provided by aging of the forest stands and the change (by succession and forest practice) to young forest or clear cut areas will preserve the Cs-137 content in the forest vegetation on a relatively stable level, which essentially only is subjected to a decrease due to physical decay.

### Model predictions and consistency with the factual distribution pattern

Theoretical treatments frequently are based on DESCRIPTIVE MODELS. These models attempt only to describe a set of observations in mathematical form, for example, by fitting a curve to a set of points. No explanatory mechanism is built into this model, although the model itself may be used to suggest possible mechanisms.

If the emphasis is on attempting to explain observed data in terms of more basic known mechanisms, and on showing the principal trend in the dynamic behaviour e.g. of radioactive caesium in a forest ecosystem, the treatment belongs to the EXPLANATORY MODELS. The model dealt with in the preceding text (Fig.3-4) thus pertains to this category.

Explanatory models are not primarily used to make precise predictions in contrast to PREDICTIVE MODELS. Models of the latter type, simulating ecological systems, tend to be very complex and generally need to be based on a network including several compartments.

#### *Basic criterion for Model success*

In order to be defended as a successful process model and not a simple "curve fit" a candidate model must satisfy at least three criteria (Blackwell 1982):

- it must describe the process behaviour asymptotically in the extremes, and it must accommodate the intermediate conditions quantitatively,
- it must be compatible with scientific principles and laws pertinent to the process,
- and the parameters in the model must be compatible with validly acquired field and laboratory data related to the process

A model may be considered successful (not proved valid, but merely shown to be successful) if it predicts observed system behaviour within the limits of uncertainty of those observations and of the criteria above are satisfied.

These requirements are evidently fulfilled by the present forest model in the sense that it corroborates with the main trends in the observed short- and long-term redistribution. We therefore maintain that a model of boreal forest ecosystems validly constructed from such a qualitative process principle, as used in the present explanatory model, will indicate certain characteristic features in the behaviour of caesium compatible with observations in the actual system.

### **Implications for assessments of dose to man**

A holistic aspect on the behaviour of caesium in the boreal forest ecosystem offers particular advantages concerning assessments of dose to man from transport of Cs-137 over forest food-chains. The model approach we consider successful for prediction of the Cs-137 distribution in the boreal forest in different time perspectives indicates that the overall distribution pattern is essentially conserved, and primarily subjected to changes due to physical decay. This conclusion is valid despite the dynamic redistribution processes operating on the scale of the local growing site. Therefore assessment becomes straightforward of the activity concentration in forest products such as moose meat and certain berries or the subsequent internal exposure, due to consumption of these forest products by man.

The transfer factor (UNSCEAR 1977), or transfer coefficient (UNSCEAR 1982), has been defined as the quotient of the infinite time integral of the appropriate quantity in one compartment to the infinite time integral of the appropriate quantity in the preceding compartment. The ratio discussed here for Cs-137 concentration in e.g. compartment moose to that in compartment ground over the time interval 1985-1990 does not comply with this definition of a transfer factor. The conservative role of the forest ecosystem regarding the inventory of Cs-137 facilitates the translation of the properly used "observed ratio" from single years or short time periods to a transfer factor and offers a confident way for estimates of the precision in the results.

## CONCLUSIONS

Primary production and its distribution on growth and litterfall constitute major regulators with regard to the dynamics of the redistribution processes of organic matter in the forest (Lundmark 1986). We expect this to be true also for caesium.

The boreal forest ecosystem constitutes an ordered but complex entity. The behaviour of caesium, resulting from the interdependencies and effective interactions within the community, is probably intractable to grasp by constructing a theoretical model based on a detailed pattern of these interrelationships. However, the multiple pathways for feed-back, inherent in the comprehensive network of interactions, favours a whole-system or holistic approach. In this the major regulators of energy flow, as well as of caesium turnover, may be expressed by primary production and its constraints on the growth capacity, in addition to fundamental physiological processes governing the metabolism of living matter in the biotope. These aspects, together with the redistribution pattern of radioactive caesium exhibited in vegetation and soil at the study sites, form the basis for our hypothesis that "Cs-137 present in a boreal forest tends towards a homogenous distribution among the living cells of that system".

Forest practice will temporarily more or less extensively disrupt the system of ecological interactions. Yet, the forest generally may be considered as an undisturbed system in the sense of a comprehensive intact network. It appears to be due to, rather than despite of, the complex network in the forest that a holistic approach may be successful in describing caesium behaviour in long-term perspectives.

A model has been developed based on compartment theory and first order kinetics for the turnover of caesium in the boreal forest. The calculated time dependent change of the Cs-137 content in perennial vegetation has been compared to that actually observed at different local study sites with focus particularly on bilberry. The primary purpose of applying this model is to elucidate qualitatively how the predictions corroborate with the main features in the time-dependent change of Cs-137 activity according to our measurements on perennial vegetation.

The contention is that:

- *at the same primary production capacity the decrease in Cs-137 activity concentration in the perennial vegetation will be faster in the young as compared to the mature forest;*
- *at a particular growing site the rate of decrease of the Cs-137 content in perennial vegetation will be positively related to the local primary productivity (at sufficiently low productivity, e.g. peat soil conditions, decrease may not occur or be extremely low during several decades).*

A holistic aspect on the behaviour of caesium in the boreal forest ecosystem offers particular advantages concerning assessments of dose to man from transport of Cs-137 over forest food-chains. The apparently conservative role of the forest ecosystem regarding the inventory of Cs-137 facilitates a proper translation of "observed ratios" from single years or short time periods to a transfer factor and offers a confident way for estimates of the precision in the results.

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Dokumentets titel Cesium-137 i ett skogsekosystem - synpunkter på dess omfördelning på lång sikt			
Huvudinnehåll <p>Kretsloppet för radioaktivt cesium, särskilt isotoper Cs-137, studeras i boreala skogsbiotoper vid Vindelnns forskningsstation, 60 km NV Umeå. Fördelningen av radioaktivt cesium i detta skogsekosystem före - och under olika perioder efter - Tjernobylyolyckan, återspeglar förekomsten av snabba förändringar, särskilt i tidiga skeden efter depositionen, överlagrat på långsam omfördelning över långa tidsperioder. De definitiva orsakerna till denna komplexa dynamik i omfördelningen har ännu inte otvetydigt kunnat fastställas. I detta arbete använder vi oss av de specifika resultaten från lokala fältstudier vid Vindelnns forskningsstation, för att beskriva det allmänna fördelningsmönstret och tidsberoendet för Cs-137 under omfördelningen i ett borealt skogsekosystem. Vi ställer hypotesen att: "Det Cs-137 som förts in i kretsloppet i en boreal skog konvergerar under omfördelningen mot en homogen fördelning bland de levande cellerna i systemet".</p> <p>Syftet med detta arbete är att belysa hur förutsägelser baserade på vår hypotes om omfördelningsprocesserna i den boreala skogen stämmer med det kända svaret enligt resultaten från de lokala studieområdena. I synnerhet diskuteras olika indikationer på att det existerar ett implicit beroende i dynamiken för omfördelningsprocesserna av primärproduktion och tillväxt. Möjligheterna att utveckla enkla men nöjaktiga modeller utgående från dessa processer berörs också med avseende på beräkning av dos och dosintekning på lång sikt från konsumtion av skogsprodukter, t ex bär eller älgkött.</p>			
Nyckelord Radioaktivt cesium, Cs-134, Cs-137, skogsekosystem, Tjernobyl, upptag, omfördelning			
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