



The influence of soil properties on the transfer of ^{137}Cs from soil to plant

Results from a field study 21 years after the Chernobyl accident

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Abstract

^{137}Cs is one of a few radio contaminants from the Chernobyl accident in 1986 that is left in measurable quantities in Sweden. The hazardous radionuclide has a physical half-life of 30 years and enters easily into biological systems. Several studies have been performed on ^{137}Cs and its behaviour in different ecosystems since the fallout. This study is one in a series performed in the five most affected counties of Sweden which were the counties of Uppsala, Gävleborg, Västmanland, Västernorrland and Jämtland.

The aim is to describe the uptake of radiocaesium, originating from the Chernobyl accident, in arable soils and to characterize the soils and investigate the impact of the different soil variables on the ^{137}Cs plant uptake.

The soil characteristics varied both within and between the counties. The highest transfers of ^{137}Cs to grass were found in the counties of Gävleborg and Jämtland which had many sandy and peaty soils. The lowest transfers were found in the counties of Uppsala and Västmanland where most of the soils were rich in clay.

Stepwise regression analyses were used to characterize the importance of each soil property. The clay content was shown to be the most significant soil property that reduced the uptake. Soils with an organic matter content above 25 % had the highest transfers of all soils. The soils with a clay content below 10 % and an organic matter content below 25 % had higher transfer values and larger variances in uptake than soils with a clay content above 10 %. When the clay content reached above 10 % the transfer was much lower but still the variance in clay content was not of importance for the ^{137}Cs uptake according to the regression equation. Instead, soil characteristics such as the concentration of organic matter and sand and potassium in soil were together influencing the uptake. According to the regression analyses, the ^{137}Cs concentration in soil only affected the uptake when the clay content was beyond 10 %.

Key words: Caesium; ^{137}Cs ; Radioactive fallout; Chernobyl; Field study; Plant uptake; Soil; Soil-plant transfer

Markfaktorers inverkan på överföring av ^{137}Cs från mark till växt

– resultat från en fältstudie 21 år efter olyckan i Tjernobyl

Sammanfattning

^{137}Cs är den enda radionuklid från olyckan i Tjernobyl som idag finns kvar i relativt stora mängder i Sverige. Denna radionuklid har en fysikalisk halveringstid på 30 år och tar sig lätt in i biologiska system. Flertalet studier har utförts på ^{137}Cs och dess beteende i olika ekosystem och denna studie är en uppföljning av tidigare studier som utförts i de län i Sverige där nedfallet från Tjernobyl var som störst. Jord och gröda provtogs på ett 70-tal platser i Uppsala, Västmanlands, Gävleborgs, Jämtlands och Västernorrlands län.

Syftet med studien var att beskriva radiocesiumtillståndet i de fem länen samt att karaktärisera jordarna och undersöka olika jordegenskapers påverkan på växtupptaget av radiocesium.

Jordegenskaperna varierade både inom och mellan länen. De högsta överföringarna av ^{137}Cs till gräs skedde i Jämtlands och Gävleborgs län som hade flertalet jordar med höga halter av sand och organiskt material. De lägsta överföringarna skedde i Uppsala och Västmanlands län där de flesta jordarna hade höga lerhalter.

För att undersöka de olika jordegenskapernas påverkan på upptaget av ^{137}Cs användes 'stepwise regression' som statistisk analys. Jordar med en organisk halt över 25 % hade de högsta överföringarna av alla jordar. Lerhalten visade sig vara den jordegenskap som främst reducerade upptaget, det vill säga ju högre lerhalt desto lägre upptag. I jordar med lerhalter under 10 % var lerhalten den enda egenskap som signifikant påverkade upptaget. De jordar som hade lerhalter över 10 % hade mycket lägre överföring till växten på grund av den högre andelen ler. Dock visade regressionsanalysen att lerhalten inte hade någon signifikant påverkan på upptaget för just de jordarna. Istället var jordegenskaper såsom halt organiskt material, sandhalt och växttillgängligt kalium de som tillsammans påverkade upptaget i växterna. ^{137}Cs koncentrationen i jord påverkade endast upptaget för jordar med lerhalter över 10 % enligt regressionsanalyserna.

Nyckelord: Cesium; ^{137}Cs ; Radioaktivt nerfall; Tjernobyl; Fältundersökning; Växtupptagning; Mark; Överföring mark-växt

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APPENDIX 2

1 Introduction

It is now more than two decades since the accident in the Chernobyl nuclear plant, and the fallout has given the opportunity to new research regarding radionuclides and their behavior in nature during a longer period of time. In Sweden, the northern and central parts were the areas most affected by the accident and today radioactive products can still be detected.

^{137}Cs was one of the main radio nuclide contaminants from the Chernobyl accident and is today one of a few radionuclides that occur in measurable quantities in Sweden. ^{137}Cs has a physical half-life of 30 years and enters easily into biological systems. If humans are exposed to high doses during a longer period of time, there is an increasing risk of developing cancer.

To be able to reduce and to control radiation contaminated food, a focus has been set on agriculture. By studying the transport of the radio nuclides within arable ecosystems, methods to reduce the uptake by plants and animals have been developed and applied. Many studies have focused on the ^{137}Cs behaviour in soil as it is mainly from the soil that current radionuclides enter the food chains. There are repeated follow ups to improve the methods and to find out more about the radio nuclides and their behaviour and transport in the soil - plant system.

In this study, soil and grass species from the most affected areas, i.e. the counties of Uppsala, Gävleborg, Västmanland, Västernorrland and Jämtland have been studied. About 70 sites were sampled and analyzed with respect to the ^{137}Cs concentration. Between the years 1986 and 2006 studies have been performed on the same sites. The sampled sites were either pasture or ley and the soil type varied from clayey to sandy to peat soils.

The aims of this study were to:

- describe the present state with respect to radiocaesium, originating from the Chernobyl accident in different arable soils in central and northern Sweden and compare the results with previous data.
- characterize the soils and investigate the impact of different soil characteristics on ^{137}Cs uptake in plants.

2 Background

2.1 Radiation

The proportion between protons and neutrons in the atomic nucleus determines the stability of an atom. Too many or too few neutrons results in an unstable atomic nucleus. The nucleus decays by ‘loosing’ the surplus of energy by emitting radiation as α - or β -particles or electromagnetic waves, γ -radiation.

- α -radiation

The nucleus emits an α -particle which contains two protons and two neutrons, i.e. it is equal to the helium nucleus. This type of radiation can only reach a few centimeters in air and is easily stopped by for instance a sheet of paper.

- β -radiation

This is the most common type of radiation as it appears both when there is a surplus and deficit of neutrons. The radiation consists of electrons which under these circumstances are called β -particles. The particles can reach some meters in the air and a few centimeters through living tissue.

- γ -radiation

This type of radiation is also called electromagnetic radiation. It is emitted as photons and occurs after α - or β -radiation. γ -radiation usually yields the highest radiation doses at nuclear accidents. It can reach hundreds of meters through the air and penetrate through living tissue from a long distance.

Some radioactive elements do not decay to stable isotopes immediately. There could often be a chain of transformations (decay chain) before a steady state is reached. The chain contains a sequence of different radionuclides where each nuclide normally has a half-life of several years. Nuclear power plants use fission to initiate the decay process from uranium in order to yield energy. At the same time numerous radioactive nuclei are generated. The unit of radioactivity is becquerel, which is defined as 1 Bq = 1 decay/second (Isaksson, 2002).

2.1.1 Half-lives

The decay of radionuclides occurs randomly. Hence the time of decay for a single nuclide cannot be predicted.

The physical half-life defines the time it takes for a quantity of radionuclides to decay to half of their initial rate (Bergman *et al.*, 1994). It cannot be affected by external conditions (Lidén *et al.*, 1971) and the half-life varies a lot between radio nuclide species, from a fraction of a second to millions of years (Bergman *et al.*, 1994).

The biological half-life represents the time it takes for the body to eliminate half of a radionuclide intake without considering the physical half-life (Bergman *et al.*, 1994).

As stated above, a nuclide disappears from the body in two ways, by nuclide decay and biological processes. The effective half-life is the combined measure of the physical and biological half-life (Bergman *et al.*, 1994).

The ecological half-life describes the time it takes for a quantity of radio nuclides to be reduced by 50% in a certain ecosystem. The ecological half-life is normally very long, especially in natural ecosystems, as the nuclides are relocated within the systems. It is therefore almost as long as the physical half-life (Johanson, 1996).

2.1.2 Effects

Within a living cell, a radionuclide randomly transfers its surplus of energy to adjacent molecules. As the cell contains 60-70 % water, it is most likely that a water molecule will be targeted. The water molecule is ionized and subsequently transformed to the water radicals $\bullet\text{OH}$ and $\bullet\text{H}$, and hydrated electrons. These very reactive radicals will act on other water or organic molecules in the cell. Depending on the target molecule, the consequences will vary (Johanson, 1996).

There are two types of effects of human irradiation, acute and late effects. The acute effects normally appear a short time after irradiation and require a high dose. Among these effects are nausea, hair loss and damage on blood forming organs. The late effects often appear a relatively long time after exposure and include cancer and genetic damages (Isaksson, 2002).

The effects depend on the type of radiation, the dose and which part of the body that is exposed. Damages on DNA may cause mutations that can at best be easily repaired by the body's 'backup system'. Damage from electromagnetic radiation is normally easier to repair than damage from ionizing radiation. The latter normally results in double bond breakage of the DNA molecule (Johanson, 1996).

Proliferative cells, e.g. in bone marrow and in the small intestine, are the most sensitive ones in terms of radiation exposure. If exposed, these cells will die, and thereby mitosis will cease. The foetal development is the most radiation sensitive stage of human life, where even small doses can have a large impact. The consequences may be spontaneous abortion, mental retardation or microcephaly depending on the foetus' developmental stage (Johanson, 1996).

2.2 The Chernobyl accident

The nuclear plant accident in Chernobyl in Ukraine, the 26th of April 1986, is the most serious nuclear power plant accident of all times. An explosion in the reactor resulted in a complete breakage of the roof and the core was directly exposed to the surroundings. The strong heat in the reactor fire resulted in a radioactive plume that rose more than 1000 meters up in the air. The fire lasted for ten days and winds carried the radioactive plume thousands of kilometres away from the source. Especially areas of the former USSR, Scandinavia and continental Europe were affected (UNSCEAR, 2000).

In the initial phase, the gaseous release of ^{131}I and ^{133}I was of main concern due to the large amounts emitted, and their hazardous characteristics. Within one to two days, radioiodine was transferred from contaminated plants grazed by dairy cows to the produced milk or directly from the plants to human beings. However, because of the short half-life of only 8 days for ^{131}I , the concern was soon shifted to the long-lasting caesium isotopes ^{134}Cs and ^{137}Cs . The two Cs-isotopes have effects on living organisms similar to those of radioiodine but their physical half-life is much longer, 2.1 and 30.6 years respectively (IAEA, 2006).

When the radioactive cloud from Chernobyl reached Sweden, a heavy rain fall commenced which contributed to a large washout of radioactive pollutants. The major fallout occurred in the counties of Västerbotten, Västernorrland, Jämtland, Gävleborg, Uppland and Västmanland. In other parts of the country, the fallout occurred mainly as dry deposition in smaller quantities, Figure 2.1 (Moberg, 2001).

Sweden received about 5 % of the total discharge of ^{137}Cs with the highest concentration reaching 200 kBq/m^2 . The fallout of ^{90}Sr was 1/100 of the amount of ^{137}Cs and that of Pu nuclides 1/1000 of the ^{137}Cs fallout. Measured concentrations of ^{90}Sr in milk were too low to be of any concern. Plutonium is most dangerous to humans if it is inhaled and the main risk for humans therefore occurs during the actual fallout. In Sweden, the plutonium level in the Chernobyl fallout was too small to be of any danger (Moberg, 2001).

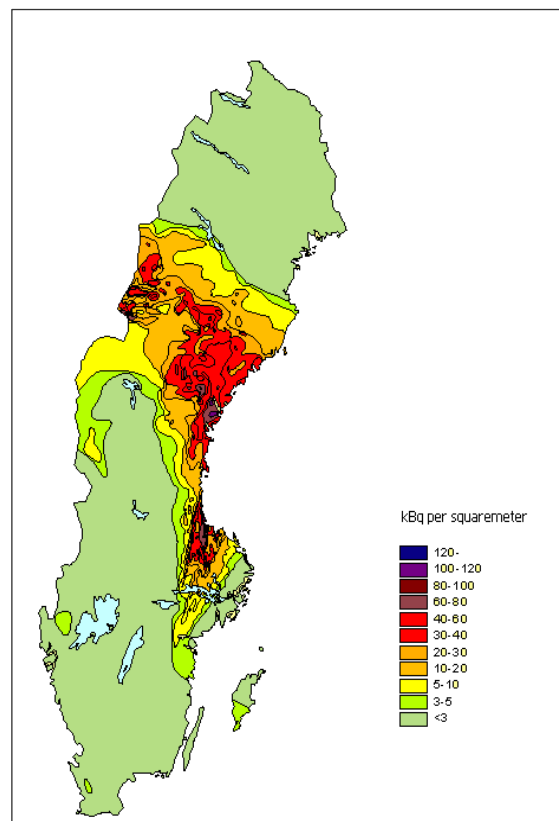


Figure 2.1: The deposition of ^{137}Cs in Sweden after the Chernobyl accident. The map is based on measurements in May-October 1986 (Sveriges Nationalatlas homepage, 2007).

2.3 ¹³⁷Cs

Currently, ¹³⁷Cs is the only harmful nuclide left in measurable quantities in Sweden. The isotope is one of the main products from plutonium and uranium fissioning and enters easily into biological systems. ¹³⁷Cs emits β- and γ-radiation and decays to the stable isotope ¹³⁷Ba. It is the γ-radiation that is measured when determining the ¹³⁷Cs activity.

Just after the fallout, extensive restrictions and countermeasures were applied, especially in agricultural systems. Nowadays concentrations above the threshold limit values (Table 2.1) are mainly found in forests and lakes.

Table 2.1: Threshold limit values for ¹³⁷Cs in foodstuffs on the market after the Chernobyl accident in Sweden (Andersson *et al.*, 2002).

300 Bq/kg for basic foodstuffs	1500 Bq/kg for other foodstuffs
meat and other edible parts of domestic animals	meat from wild animals and reindeer
flour products	wild berries
fruit, except nuts	mushrooms
vegetables	lake fish
dairy products	nuts
baby food	
sea fish	

2.3.1 Soil

In soil, radiocaesium binds to particles or appears in soluble form in the soil solution (Figure 2.3). There are several soil characteristics that affect radiocaesium sorption and the interdependence of these characteristics makes the sorption/desorption mechanisms rather complex.

Clay minerals play an essential role for the caesium accessibility in the soil solution. Increasing clay content enhances sorption of exchangeable caesium to negatively charged colloids. Exchangeable ions are easily adsorbed or desorbed through ion exchange and are readily available for plant uptake (Shenber & Eriksson, 1992). The cation exchange capacity of clay minerals depends partly on pH. Increasing pH will therefore slightly increase the number of exchange sites (Eriksson *et al.*, 2005).

The ability of clay minerals to fix ¹³⁷Cs is the most important retention process in the soil to keep radiocaesium unavailable for root uptake or downward migration. Illitic clay in particular, is known for its selective sorption of caesium ions. It is the frayed edge sites, FES, that strongly fix the Cs ions (Figure 2.2). Caesium has a low hydration energy and if present at the FES it will lose the hydration shell and bind to the negatively charged mineral platelets, resulting in a closing of the FES thus fixating the ion (Cornell, 1993). K⁺ and NH₄⁺ are other competing cations for these sites due to their chemical similarity. NH₄⁺ has been shown to be a 5 to 6 times stronger competitor for the FES than K⁺, and NH₄⁺ is normally present in similar concentrations as K⁺ under field conditions (Wauters *et al.*, 1996).

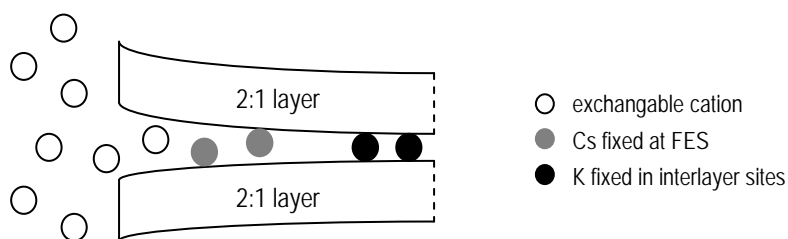


Figure 2.2: Weathering of 2:1 phyllosilicates releases potassium and enables caesium to be fixed to the frayed edge sites (FES) (Modified from Eriksson *et al.*, 2005).

Many of the studies performed on Cs sorption in soils have investigated the role of the particle size in this process. In a study performed by van Bergeijk *et al.* (1992), sand having a larger particle size than clay and loam showed a higher caesium transfer to plants from soil than the other more fine textured soils. However, it must be kept in mind that sand normally has a lower nutrient content than clay soils, which is another factor that increases the soil-plant transfer.

The root uptake of ^{137}Cs is normally very high in soils rich in organic matter. These soils have a high cation exchange capacity but few clay particles. The exchange sites of the humic substances adsorb radiocaesium, but when the Cs^+ concentration is reduced in the soil solution it will be easily replenished from the exchange sites. These exchange sites do not discriminate between caesium and potassium (Valcke & Cremers, 1994).

Dumat & Staunton (1999) studied the reduced adsorption of cesium on clay minerals caused by various humic substances and found that the frayed edge sites are affected by the presence of these humic substances and thus absorb less caesium. In one way or another the humic substances reduce the FES affinity. A possible explanation is that organic macromolecules in the vicinity of FES block the FES closure. Shand *et al.* (1994) and Rosén *et al.* (2006), have both seen that adding a small amount of clay to organic soils reduces the caesium soil-to-plant transfer in a significant way. Also, some caesium seems to be retained by organic matter closely associated with mineral particles.

Studies on Cs behaviour and its pH dependence have been carried out *e.g.* by Van Bergeijk *et al.* (1992), Wang *et al.* (2003) and Giannakopoulou *et al.* (2007). Batch studies of Cs sorption on aluminium oxide ($\gamma\text{-Al}_2\text{O}_3$) in a pH range from 2 to 12 showed that pH had a very weak effect on the Cs uptake (Wang *et al.*, 2003). On the other hand, Mascanzoni (1988) performed a field study in Sweden and found that pH was one of the soil characteristics that most strongly influenced the uptake. A decrease in pH increased the uptake of ^{137}Cs due to the higher availability of cations in the soil solution. This was also found in a batch experiment performed by Giannakopoulou *et al.* (2007). These authors found that less caesium was sorbed at low pH levels but the magnitude of this effect varied with clay content. On the contrary, van Bergeijk *et al.* (1992) found that transfer of Cs within the pH-range 3.9-8.4 was not affected by soil pH.

2.3.1.1 Migration

In this thesis, migration signifies a vertical transport of radiocaesium in the soil. The risk of a downward transport to ground water is of great concern. The two possibilities for transport are as dissolved Cs in the soil solution or as Cs bound to suspended colloidal size particles. Generally the solute transport dominates. Concerning radiocaesium strongly bound to the FES colloidal transport is thought to be the major reason for contamination at greater depths. The colloidal transport occurs through larger paths within the soil such as cracks or holes created by earth worms and roots. Also, the soil mixing by soil fauna contributes to colloidal translocation (Forsberg, 2000).

An eight-year study by Rosén *et al.* (1999) of the migration of caesium in undisturbed soils showed that the migration rate for caesium is generally low and decreases with time probably due to fixation to mineral particles. The caesium migration rate was highest in organic soils and in podzols. Between 50 and 92 % of the total ^{137}Cs was found in the top layer (0-5 cm) after 7 years and the mean migration rate was 0.2-0.6 cm year^{-1} . This indicates that the risk of contaminated groundwater is quite small.

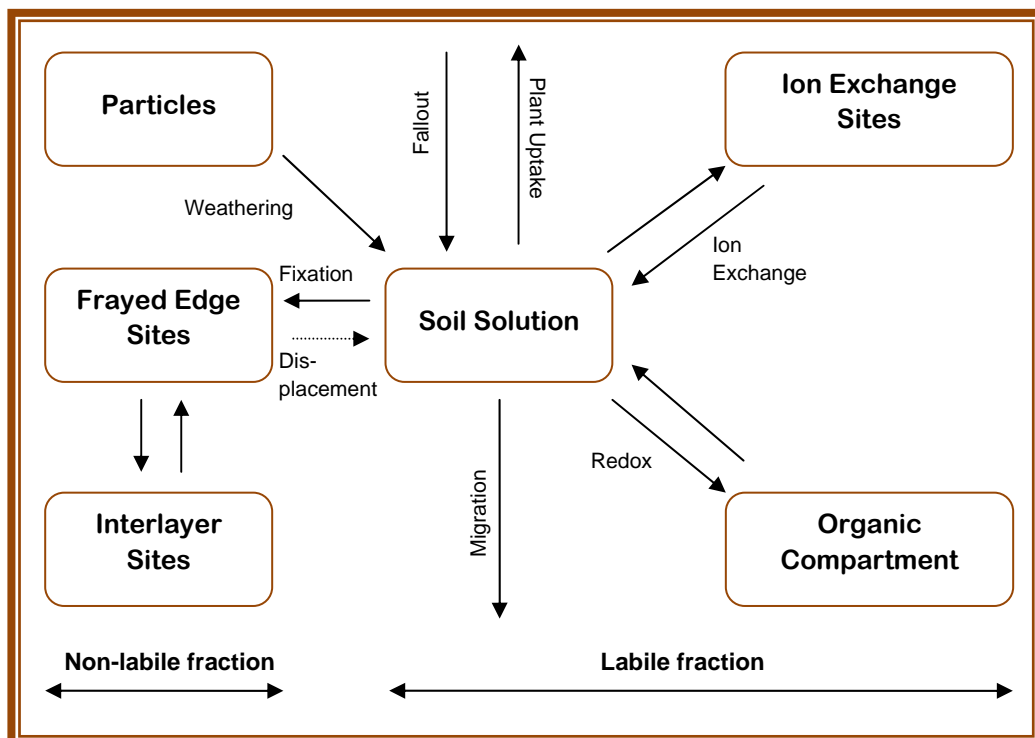


Figure 2.3: Schematic view of caesium pools and flows in soil and some of the processes involved (Modified from Forsberg, 2000).

2.3.2 Transfer to plants

If a radioactive fallout appears during the growing season, plants will be contaminated directly on their leaves. Part of the contaminant will be absorbed through the leaves. The type of fallout, i.e. wet or dry deposition, and shape, structure, leaf area and developmental stage of the plant determine the contamination rate (Andersson *et al.*, 2002). These factors will lose their significance with time and the main pathway of contamination will be by root uptake from the soil (Rosén, 1996).

Radiocaesium uptake varies among plant species. Grasses for instance, cereals included, have a smaller uptake of caesium than lettuce and cabbage (Rosén, 1991; Paasikallio *et al.*, 1994). Root crops have a tendency to accumulate radiocaesium (Coughtrey & Thorne, 1983).

The root uptake of caesium is competitive with that of potassium. Decreasing potassium content in the soil solution increases the caesium uptake (Coughtrey & Thorne, 1983; Rosén, 1991). The availability of caesium varies quite a lot between mineral soils as does the potassium accessibility (Smolders *et al.*, 1997). Inside the plant, radiocaesium follows the same pathway as potassium. Thus Cs is translocated to the most biologically active parts of the plant. About 50 % of the radiocaesium uptake can be expected to be translocated to the growing parts (Forsberg, 2000). This antagonism between Cs and K in plant uptake explains why K fertilization reduces Cs uptake.

Weather conditions does also affect the plant uptake of radioceasium. During warm and dry years the root system penetrates to greater depths to reach available moisture. This means that there will be a smaller uptake from the upper parts of the soil where most of the ¹³⁷Cs can be found, resulting in a lower ¹³⁷Cs uptake. The opposite will occur during wet conditions as the root system will be shallower and thus most of the roots will be present in the top layer where most of the contaminant is found (Mascanzoni, 1988).

2.3.3 Countermeasures

There are several countermeasures that could be applied after a radioactive fallout. The season for the fallout determines the extent of contamination of plants and soil. If a radioactive fallout appears during the growing season, parts of the fallout will be deposited directly onto the plants and may be directly absorbed. Just after the fallout, contaminated vegetation can be removed to further reduce the contamination of the soil. A delayed harvest could be a measure to reduce the concentration. The plants will then continue to grow for some time and thereby the concentration of ¹³⁷Cs in the plant will be diluted. Furthermore, a fallout during the early part of the growing season gives more time for countermeasures to reduce the radioactive content before harvest. If the fallout occurs during winter time, snow can be removed to prevent contamination during snow melt (Rosén & Haak, 2006).

Ploughing a contaminated soil, will dilute the radionuclides in a larger soil volume and they will also get more contact with mineral surfaces thus increasing the fixation to the frayed edge sites of the clay minerals. This was shown in studies made in the county of Gävleborg after the Chernobyl fallout. Sites that were ploughed after the fallout in 1986 afterwards showed a

70 % smaller ^{137}Cs -content in the crop than adjacent unploughed grass fields (Rosén *et al.* 1995).

Adding K-fertilizer to a ^{137}Cs -contaminated soil will increase the available potassium for plants and therefore reduce the ^{137}Cs uptake. One of the most efficient countermeasures to reduce the ^{137}Cs plant uptake is to combine ploughing and K-fertilization (Rosén, 1991). Rosén (1996) found that the ^{137}Cs transfer was significantly reduced when adding 100 kg K ha^{-1} while a double amount only gave a small additional effect. Smolders *et al.* (1997) gained similar results in studies with ryegrass. Also found was that the caesium uptake decreased with an increasing potassium concentration until the potassium content reached about 5 % of the cation exchange capacity. Above that level no further decrease in caesium uptake could be seen.

3 Materials and methods

Repeated studies have been performed since 1986 in the Swedish counties most strongly affected by the Chernobyl accident. The sites visited in this survey are a subsample of the sites included in the previous studies by Rosén *et al.* (1996), Olsson (2004) and Carlsson (2006).

Soil and crops were sampled at the end of growing season between the 18th of August and 21st of September 2007. In total, 77 sites situated in the five most strongly affected counties, Uppsala (C), Gävleborg (X), Västmanland (U), Jämtland (Z), and Västernorrland (Y) county were sampled (Appendix 1). 5 sites were situated in Uppsala, 6 in Västmanland, 16 in Gävleborg, 34 in Västernorrland and 16 in Jämtland. 50 of the sites were ley and 27 were pasture.

3.1 Sampling

The sites were located with help of their positions on old maps and other information from previous samplings at the same sites. Some sites were located with the assistance of GPS.

The sampling was made within a circle as shown in figure 3.2. The central point was fixed and four points, three meters away from the centre, were marked to indicate a full circle. In total, 12 core samples were collected within each circle by using an auger ('Trekanten-auger'), with an inner diameter of 21 mm and set to a 20 cm sampling depth. The core samples were pooled to one bulk sample from each site.

1 m² of grass was harvested at each site. One subplot of 0.25 m² was sampled in each quadrant of the circle. The grass was cut at about 5 cm above ground and the subplot samples were pooled to one bulk sample. Plant remains from previous years were excluded.

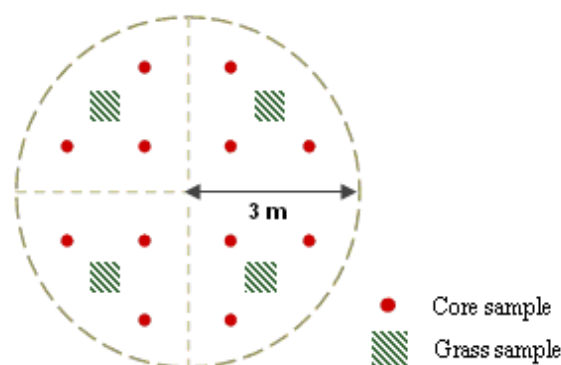


Figure 3.1: Procedure of sampling: 12 core samples with a diameter of 21 mm and a depth of 20 cm were collected within a circle of 3 m diameter. Also 4 grass subplots of 0.25 m² area were collected in the same circle.

3.2 Sample preparation

The soils were air-dried at 20-30 °C in aluminium trays for a minimum of seven days. The dried samples were weighed, crushed if aggregated, and then passed through a 2 mm sieve. Soil particles larger than 2 mm were discarded. Organic material larger than 2 mm was included in the sample. One subsample was collected for chemical analyses and another subsample was collected for ^{137}Cs -measurements. Soil collected for ^{137}Cs -measurements was filled to the lid in a 60 ml cerbo plastic container.

The crop samples were dried at 70-80 °C for a minimum of 24 hours. The samples were then weighed, milled and homogenized. A subsample was collected, weighed and filled to the lid in a 60 ml cerbo plastic container for radioactivity analyses.

3.3 Sample Analyses

3.3.1 ^{137}Cs -measurements

The ^{137}Cs -activity was measured with a computer-aided germanium detector system, placed in a low background laboratory. The samples were measured from three to eleven hours depending on the expected ^{137}Cs -content. The measurement errors were in the range 3–8 % for the soil samples and 3–7 % for the grass samples. Some of the grass samples with a low ^{137}Cs activity (below 40 Bq/kg plant dw) had measurement errors from 10 to 100 % as many of them actually had activities below the detection limit.

3.3.2 Soil analyses

3.3.2.1 pH

5 ml of dried soil was put in a plastic tube. 25 ml of distilled water was added and the sample was shaken for 15 minutes. pH was measured the following day with a pH-meter calibrated with pH 4 and 7 buffer solutions.

3.3.2.2 Dry weight

A crucible was filled to 50 % with soil, weighed and then dried at 105 °C over night. The following morning, the crucibles were placed in a desiccator to cool, thereafter they were weighed and the dry weight was calculated. Thereafter the samples were placed in an oven and ignited at 500°C for 3 hours. The ignited samples were placed in a desiccator to cool and weighed to determine the loss on ignition.

3.3.2.3 Available Potassium

Plant available potassium was extracted with an AL-solution, (0.10 M ammonium lactate plus 0.40 M acetic acid at pH 3.75). 5.00 grams of air dried soil was transferred to an acid-rinsed 250 ml plastic bottle. The AL-solution was added and the samples were shaken for 90 minutes. Thereafter the solution was filtered (OOH) and the first 10 ml of the extract was discarded. Five ml of the extract was mixed with 20 ml of a 0.125 % Cs-solution and the potassium content was measured with flame photometry on an atomic absorption spectrophotometer.

3.3.2.4 Soil texture

The particle size distribution of soils having a loss of ignition below 25 % was determined by using the pipette method. Hydrogen peroxide was added to dry soil to remove the organic matter. The suspension was thereafter diluted with water and potassium polyphosphate plus potassium carbonate was added as a dispersing agent. The samples were then shaken to separate the particles from each other. Sand particles were removed with a 0.2 mm sieve, dried and weighed. The suspension was thereafter vigorously stirred to become homogenous and then left for sedimentation. Samples were continuously collected with a pipette at a preset depth. The collected samples were dried and weighed.

The particle size classes, clay ($d < 0.002$ mm), silt ($0.002 \leq d < 0.06$ mm) and sand ($0.06 \leq d \leq 2.00$ mm), were presented as percent of the mineral fraction.

3.3.3 Calculations

3.3.3.1 TF_g

The transfer factor, TF_g , is a mathematical tool used to compare the transfer of nuclides from soil to plant at different times or at different sites. TF_g depends only on the environmental conditions. Hence differences in deposition level between sites can be ignored (Rosén *et al.* 1995).

In this study the transfer factor was calculated from the activity concentration of the plant dry matter divided by the activity in the 20 cm top layer of the soil (3.1).

$$TF_g = \frac{\text{Activity concentration in plant dry matter} \frac{Bq}{kg dw}}{\text{Activity in upper 20 cm in ground} \frac{Bq}{m^2}} \quad (3.1)$$

3.3.3.2 Organic matter content

The loss on ignition depends on the organic matter content of the soil and the amount of adsorbed water on clay surfaces. For mineral soils, correction factors (K) have been developed to calculate the organic matter content (3.2). The K-value is subtracted from the loss of ignition value.

$$\begin{aligned} \text{Clay} \leq 20 \% & \quad *K=0.1 \cdot \text{Clay} \\ \text{Clay} > 20 \% & \quad *K= 1.06 + 0.047 \cdot \text{Clay} \end{aligned} \quad (3.2)$$

*Correction factor

3.3.3.3 Regression analyses

A stepwise regression analysis was performed using the statistical program MiniTab 15 Statistical Software (2007). The independent variables with a probability value < 15 % were included in the regression equation.

4 Results & Discussion

4.1 Soil properties and ^{137}Cs uptake in each county

The soils were grouped by county regarding soil properties and ^{137}Cs activity in soil and grass (figure 4.1). The figures give a general overview of the ^{137}Cs transfer from soil to plant in different parts of Sweden. Soils with a loss of ignition greater than 25 % were not analyzed with respect to soil texture and were therefore not included in the boxplots showing clay and sand contents. Data for each individual site are found in appendix 2.

The figures show a broad variation in soil characteristics, both within and between the counties. Jämtland for instance, had some of the highest transfers of ^{137}Cs from soil to grass but the lowest soil concentration of ^{137}Cs compared to the other counties. Moreover, the Jämtland soils had a clay content below 10 %, and a comparatively high sand content. The soils also had a low potassium and organic matter content, and the lowest median pH out of all counties. Andersson *et al.* (2001) made an eight-year long study on the transfer of ^{137}Cs from soil to vegetation to grazing lambs at one of the Jämtland sites (BLH-A). These authors also found that the transfer of ^{137}Cs was rather high and that the soil had a long effective ecological half life (19 years).

The highest rates of fallout were found in the county of Gävleborg which also had the highest ^{137}Cs concentrations in grass, but still quite low transfer factors. There was a large variety in soil characteristics, some soils had a very high organic matter content, while others had a rather high clay content. The sand content showed a large variation between the sites in this county, ranging from 22 to 93 %. Site X7A had the highest organic matter content, 89 %, and also the highest TF_g (0.14 m²/kg plant dw) of all sites in the study.

The soils in the two counties of Uppsala and Västmanland were rich in clay as well as potassium. Only two of the sampled soils had a clay content below 20 %. All soils except for soil c711 had an organic matter content below 20 %. The latter soil had an organic matter content above 80 %. It also had the highest TF_g and ^{137}Cs concentration in grass in the two counties. Uppsala and Västmanland had the lowest TF_g and ^{137}Cs concentration in plants of all counties but the ^{137}Cs content in soil was still higher than in Jämtland and Västernorrland.

37 soil samples from the county of Västernorrland were analysed. The soil characteristics varied a lot between the sites. Västernorrland did not have any site with an organic matter content above 50 %, nor were there any extreme TF_g values or ^{137}Cs contents in plants. There were two deviating TF_g values and ^{137}Cs concentrations in grass (at sites Y52A and Y10). The former had an organic content above 40 % and the latter had a sand content close to 50 %.

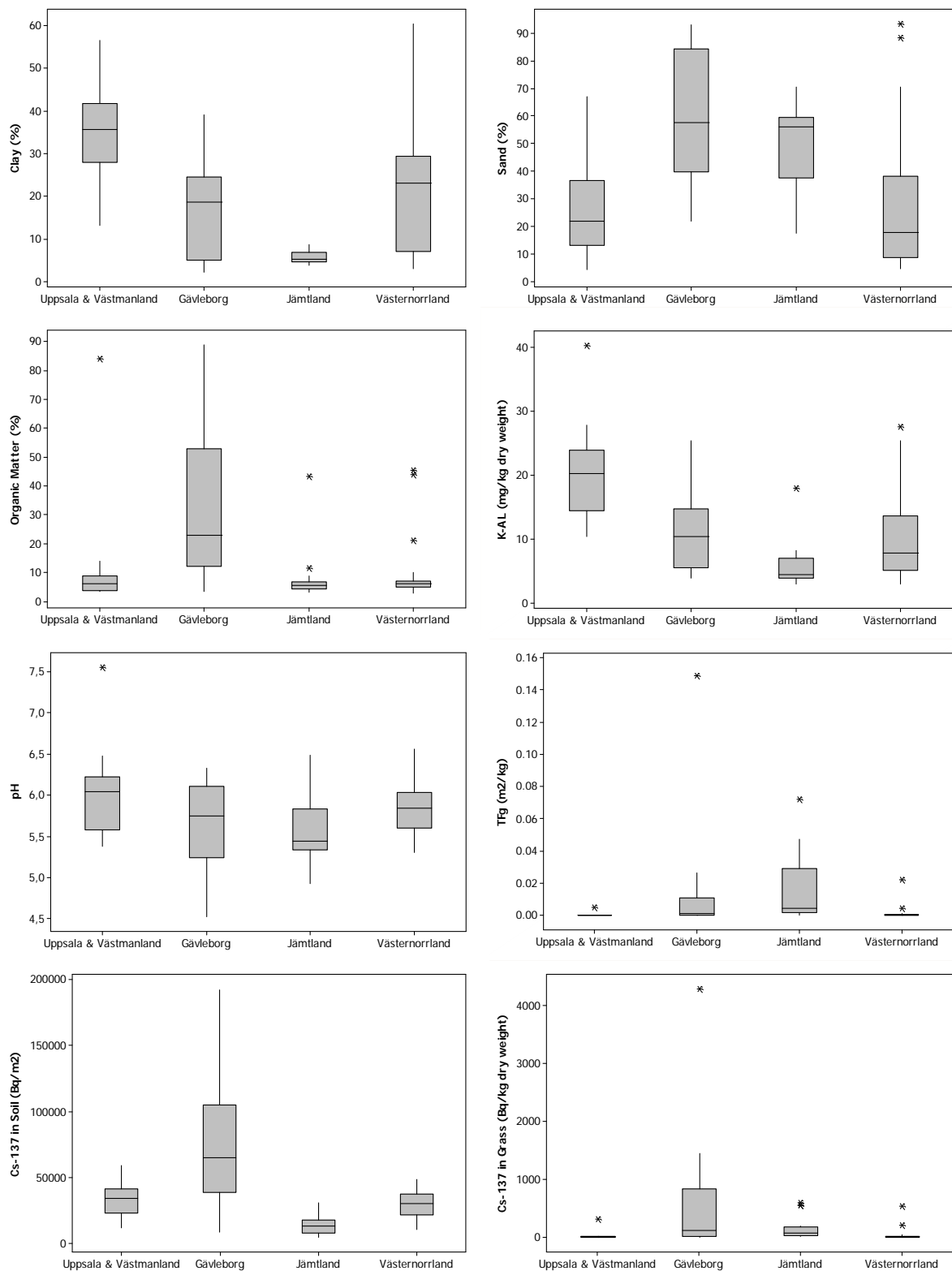


Figure 4.1: Boxplots of soil characteristics and ^{137}Cs concentration in grass and soil in the five sampled counties. The grey box represents the middle 50 % of the data and the median value is indicated by the horizontal line inside the box. The vertical lines (whiskers) represent the lower and upper 25 % of the distribution and the outliers are represented by asterisks. There are 11 sites in Uppsala and Västmanland, 16 in Gävleborg, 34 in Västernorrland and 16 in Jämtland.

Many studies have found that clay content is the major factor determining the root uptake of ^{137}Cs (e.g. Shenber & Eriksson, 1992; Giannakopoulou *et al.*, 2007; Rosén *et al.*, 2006). At high clay contents, the uptake is normally very low, due to immobilization at the frayed edge sites (FES). This was clearly shown for the counties of Uppsala and Västmanland and some of the soils located in the counties of Gävleborg and Västernorrland. A high clay content also contribute to high potassium concentrations because of weathering of the clay minerals and defixation from the FES (Eriksson *et al.*, 2005). The potassium concentration in the soil is another factor that is negatively correlated to the ^{137}Cs root uptake (Coughtrey & Thorne, 1983; Rosén, 1991). Hence the clay content also contributed to a reduction in ^{137}Cs root uptake due to a high potassium content in the clay.

The Jämtland soils, on the other hand, had a low clay content and high TF_g values and ^{137}Cs concentrations in plants. The low clay content was probably the main reason for the high root uptake of ^{137}Cs . The soils had a high sand content which contributed to a larger granular size and also explained the low potassium amount (van Bergeijk *et al.*, 1992). If these soils were exposed to a new fallout in much higher quantities than those emitted from Chernobyl, a high ^{137}Cs content in the grass should be expected.

According to Valcke and Cremers (1994) a soil with less than 40 % organic matter has a FES pool that is large enough to significantly reduce the plant uptake of ^{137}Cs . When the organic matter content exceeds values around 80% the FES pool is too small to reduce the ^{137}Cs in soil solution to any significant extent. Six of the sites with an organic content above 40 % were among the 15 highest with respect to the TF_g-values and four of these sites were located in Gävleborg. There were totally fourteen sites which had an organic content above 25 %. As none of these soils were analysed with respect to clay content it is not possible to evaluate weather the clay content had any significant impact on the ^{137}Cs uptake in organic soils as suggested by Shand *et al.* (1994) and Rosén *et al.* (2006).

It is difficult to judge from the data whether pH had any effect on the uptake or not. Jämtland had lower average pH values than the other counties which might be one of the reasons why there was a high uptake of ^{137}Cs in this county, but the low pH is also probably due to a high sand content. Uppsala and Västmanland had higher pH values combined with a much lower uptake. They also had a high clay content which might be an efficient buffer against pH changes.

Carlsson (2004) and Olsson (2006) have both carried out similar studies at the sites included in this thesis. The study performed by Olsson (2006) included the counties of Gävleborg, Uppsala and Västmanland, and Carlsson (2004) studied all five counties included in the present study. Grass was collected from four microplots (0,25 m²) within an area of 100 m². The ^{137}Cs content was related to soil characteristics determined between the years 1986 and 1988 by Rosén (1996). In both studies it was found that the county of Gävleborg had the highest ^{137}Cs concentrations in grass on pasture as well as ley. Grass samples from the counties of Uppsala and Västmanland had the lowest concentrations. The highest concentrations were found at site X7A (pasture) and at sites X15A and X15D (ley).

Carlsson (2004) and Olsson (2006) collected grass samples over a much larger area than in the present study and their results may therefore not be comparable with mine. However, it can be seen that the county of Gävleborg still had the highest ^{137}Cs concentrations in grass and that Uppsala and Västmanland had the lowest ones. The highest transfer factors were found in soils with high organic matter content, which is similar to what was found in the present study. The ^{137}Cs uptake in grass had not increased compared to the previous years.

4.2 Soil factors influencing uptake

In the previous section the soils were arranged by county. This gives a general overview of the ^{137}Cs behaviour in different parts of Sweden but the soil characteristics vary a lot within the counties and at each site there may be different reasons for the transfer rate of ^{137}Cs . It is therefore more convenient to group the soils according to their characteristics and compare these groups with the transfer factors or ^{137}Cs concentrations in grass. In this way it should be easier to evaluate the importance of each soil property with respect to its effect on ^{137}Cs uptake in plants.

Stepwise regression analysis was used as a statistical method to evaluate which of the investigated soil properties that had a significant impact on the ^{137}Cs transfer from soil to grass and on the ^{137}Cs concentration in grass. The characteristics that showed a significant relation to the dependent variable were selected in this procedure whereas the non-significant ones were removed from the regression equation.

4.2.1 Regression analyses for mineral soils

It is generally known that clay content is one of the main soil characteristics that affects root uptake of ^{137}Cs . This can also be seen in Figure 4.2, where the ^{137}Cs concentration in grass is plotted against the clay content. Please note that soil texture analysis was not performed on soils with an organic matter content above 25 %. The figure shows that the ^{137}Cs concentration in grass increases exponentially with decreasing clay content and that some of the highest ^{137}Cs concentrations in grass were found in those soils with a clay content below 10 %. Some grass samples showed ^{137}Cs concentrations below the detection limit and their ^{137}Cs activity was set to 1 Bq/kg plant dw. All these samples were from sites that had clay contents above 20 %.

The transfer factor (TFg) was also plotted against clay content (Figure 4.3). This was done to test whether the relationship between the ^{137}Cs concentration in grass and clay content was due to a co-variation between deposition rate and clay content i.e. that soils with a high clay content happened to be more frequent in areas with low deposition rates. The figure shows a similar exponential relationship between TFg and clay content as the relationship above between ^{137}Cs concentration in grass and clay content. The transfer of ^{137}Cs from soil to plant was generally higher in soils with a clay content below 10 % and these soils also showed a larger uptake variance between the sites compared to soils with a clay content above 10 %.

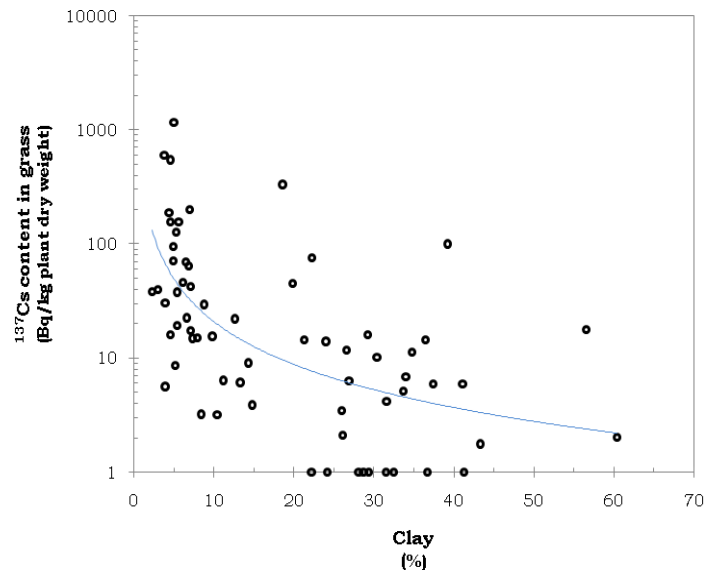


Figure 4.2: ¹³⁷Cs content in grass, \log^{10} , as a function of soil clay content. $R^2=0.39$

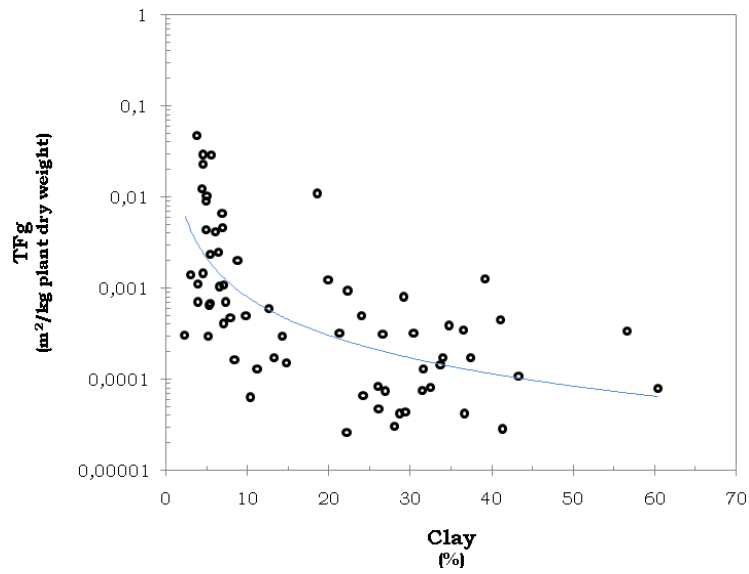


Figure 4.3: ¹³⁷Cs transfer to plants, \log^{10} TF_g, as a function of clay content in soil. $R^2=0.43$

Table 4.1: Soil factors influencing ^{137}Cs transfer to grass (TFg) and ^{137}Cs concentration in grass according to stepwise regression models (15 % level for entry of independent variables into the model). The soils were grouped according to clay content and all soils had an organic matter content below 25 %.

Variable	Regression 1		Regression 2		Regression 3		Regression 4	
	Constant	Prob. value	Constant	Prob. value	Constant	Prob. value	Constant	Prob. value
	Clay \leq 10 %		Clay $>$ 10 %		TFg*1000		^{137}Cs content in grass	
TFg*1000	18.13	-	237.7	-	-0.868	-	-0.8317	-
Org. Matter (%)	-	-	-	-	0.0334	0.00	3.03	0.00
Clay (%)	-2	0.12	-25	0.12	I	-	-0.37	0.11
Sand (%)	-	-	-	-	0.0053	0.06	I	-
pH	I	-	I	-	0.19	0.13	II	-
K-AL	II	-	II	-	-0.0212	0.00	-0.48	0.09
^{137}Cs soil content (Bq/m ²)	n.i	-	-	-	n.i	-	$3.0 \cdot 10^{-4}$	0.06
	n=28		n=28		n=35		n=35	
	R ² =0.09		R ² =0.09		R ² =0.53		R ² =0.70	

n.i = not included in analysis

I = best alternative

II = 2nd best alternative

The stepwise regression analysis was first tested for all mineral soils (65 sites). This analysis suggested that clay and sand contents were the soil characteristics that affected the ^{137}Cs transfer from soil to plant, but the R^2 -value of the model was very low. A better result was obtained when the soils were split into two groups. One group contained the mineral soils with a clay content below 10 % and the other group contained those soils with a clay content above 10 % (compare with Figures 4.2 and 4.3). 28 soils were included in the group with a low clay content, (excluding site X15A), and 35 soils were included in the group with a high clay content, (excluding site X4A). The two excluded sites were shown to be statistical outliers.

Two stepwise regression analyses were performed for each group. Clay, organic matter, sand and potassium contents together with pH were independent variables (x-variables). These variables were tested against either TF_g or ^{137}Cs concentration in grass as the dependent variable (y-variable). In the model with ^{137}Cs concentration in grass as the dependent variable, ^{137}Cs concentration in soil was also included as an independent variable (Table 4.1).

The regression equations showed that in soils with a clay content below 10 %, the clay content was the only soil factor that significantly affected both TF_g and ^{137}Cs concentration in grass (Regressions 1 and 2, Table 4.1). In both analyses the R^2 -value was very low, 0.09. pH and plant available potassium were selected as the two best but still non-significant alternatives. According to Regression 1, a soil without any clay has a TF_g of 0.018 m²/kg plant dw which is the value of the intercept (constant) divided by 1000. The TF_g-value decreased with 0.002 m²/kg plant dw (slope term/constant divided by 1000) with each percent increase in clay content.

For those soils with a clay content above 10 % more independent variables were included in the regression models than for the soils with a low clay content (Regressions 3 and 4, Table 4.1). The organic matter content was the variable that most significantly affected both TF_g and ^{137}Cs content in grass. Regarding TF_g in Regression 3, plant available potassium was almost as significant as the organic matter content. Moreover, sand content and pH influenced the uptake, but with higher probability values. The R^2 -value was 0.53 in Regression 3.

Apart from the influence of the organic matter content, the ^{137}Cs concentration in grass (^{137}Cs -grass) was also influenced by the ^{137}Cs concentration in soil, plant available potassium and clay content (Regression 4, Table 4.1). The latter three independent variables had probability values ranging from 0.06 to 0.11. The R^2 -value for regression 4 was 0.70.

According to Regressions 1 and 2 (Table 4.1), the clay content was the only soil property that significantly affected the ^{137}Cs uptake in soils with a clay content below 10 %. This shows the importance of the clay minerals. The regression equations indicated that even at a very low clay content a small increase in clay would cause a significant decrease in the ^{137}Cs uptake. There is probably an influence of the frayed edge sites in the clay minerals. The frayed edge sites may be very efficient to eliminate ^{137}Cs from the soil solution, which in this case seems to diminish the influence of the other variables.

However, the remarkably low R^2 -value, 0.09, in Regressions 1 and 2 makes the result a somewhat uncertain. While one set of sites tended to have a high uptake in grass at low clay content, the four sites, X11, Y59, Z3B and Y40, which had the lowest clay content of all sites had very low TF_g and ^{137}Cs concentrations in grass (Figure 4.4). These sites had a sand content ranging from 68 to 93 %. Moreover, they showed a large variation in deposition rate, from 124 to 5 kBq/kg plant dw, and all four sites had an organic matter content below 10 % (Appendix 2). The reasons for the low uptake at these four sites could be the weather conditions during the growing season, the topography or another natural variability that cannot be explained from the collected data. It should also be pointed out that only 28 sites were included in these two regression analyses. Analyses with few observations are very sensitive to any random representation of values that deviates from the general pattern. A set of more than a 100–200 observations would be more reliable in this respect.

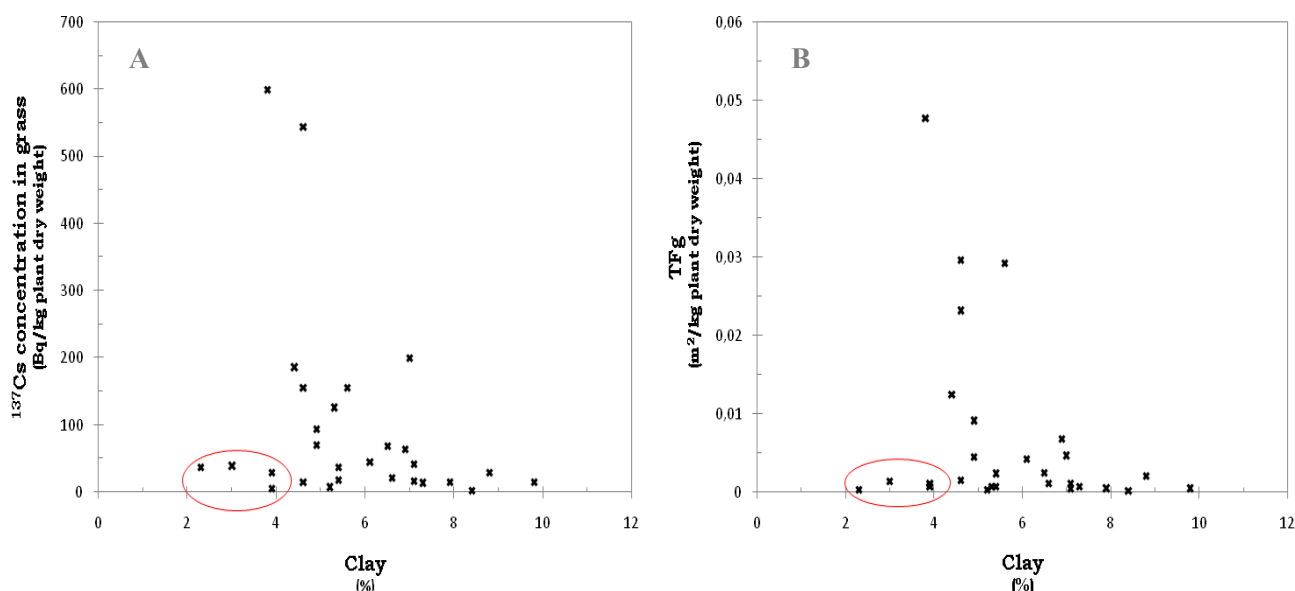


Figure 4.4: ^{137}Cs concentration in grass (A) and transfer factor (B), as a function of clay content for mineral soils with a clay content below 10 % and an organic matter content below 25 %. The circles highlight four sites, X11, Y59, Z3b and Y40, which have ^{137}Cs concentrations in grass and TF_g -values that deviate from the trend.

Since the clay content had a strong influence on the Cs uptake there is generally a lower uptake from soils with a clay content above 10 % (Table 4.2). Despite its importance, the clay content was not included in regression 3 and it had a probability value as high as 0.11 in Regression 4 (Table 4.1). The small influence of clay content on Cs in grass and the TF_g value that was found in these cases suggests that a further increase of the clay content in soils with more than 10 % clay had a small effect on the ^{137}Cs uptake. All soils with more than 10 % clay generally had a low Cs uptake with other soil characteristics explaining the variation still present.

Table 4.2: Average and median values of ^{137}Cs concentration in plants and of transfer factor (TF_g) in soils with organic matter content above 25 %, soils with clay content below 10 % and soils with clay content above 10 %. All soils grouped according to clay content have an organic matter content below 25 %.

	^{137}Cs concentration in grass (Bq/kg plant dw)		TF_g (m^2/kg plant dw)	
	Average	Median	Average	Median
Organic Matter > 25 % <i>n</i> = 9	801	534	0.0278	0.0085
Clay ≤ 10 % <i>n</i> = 29	132	40	0.0069	0.0015
Clay > 10 % <i>n</i> = 37	21	6	0.0006	0.0002

For soils with a clay content above 10 %, the organic matter content is the most significant variable that seems to affect the uptake (Regressions 3 and 4, Table 4.1). Dumat and Staunton (1999) have shown that humic substances that form complexes with clay reduce the FES affinity for Cs. The soils included in Regressions 3 and 4 have organic matter contents ranging from 2 to 22 % where only six of the soils have an organic matter content above 10 % (Appendix 2). Probably clay-humus complexes are more important for the ^{137}Cs uptake than the variation in clay content even at low concentrations of organic matter. However, more organic matter does not cause any dramatic changes in the uptake.

Another possible explanation for the weak correlation with clay content in Regressions 3 and 4 may be that plant available potassium (K-AL) was included in the model. Clay content and K-AL are not independent of each other and K-AL increases with clay content (Figure 4.5). If the stepwise procedure selects K-AL first and it is strongly correlated with clay, there is little residual variation to be explained by the clay content factor. Consequently clay will not be included in the regression equation.

Also, potassium has chemical properties that are rather similar to those of caesium and the ^{137}Cs concentration in plants decreases with increasing potassium content. This was found by Coughtrey & Thorne (1983). The root uptake of potassium and caesium are competitive processes. Consequently an increase in potassium concentration in the soil solution will reduce the uptake of caesium.

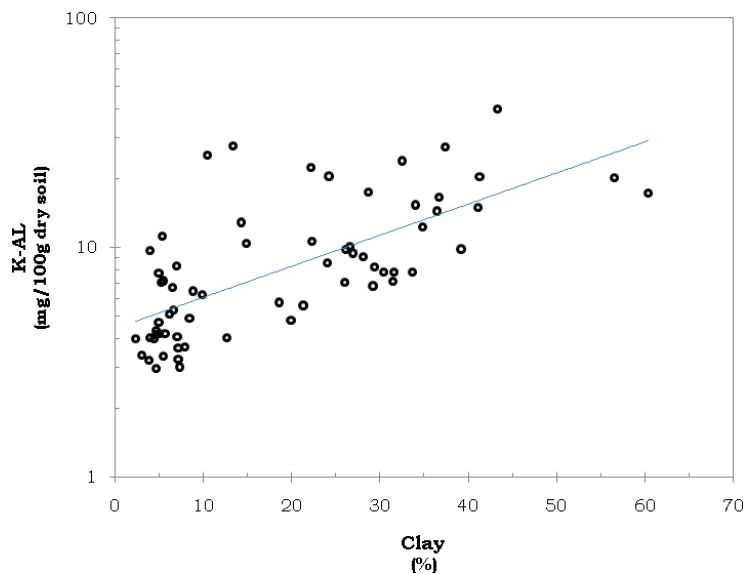


Figure 4.5: Plant available potassium, K-AL, on a logarithmic scale, as a function of clay content. $R^2=0.47$

Sand content and pH were selected as independent variables that affected TFg in soils with a clay content above 10 % (Regression 3). The probability values of these variables were higher than those for organic matter and potassium content. Sand does not have any ability to fix the caesium ions. Moreover, sandy soils have a lower nutrient level than clay soils. Consequently, an increasing sand content may increase the caesium uptake. A high content of sand usually means a low clay content and the fact that sand was included in the regression model may be another explanation why clay was not included.

The positive slope of the pH factor in the regression analysis suggests that TFg increases with an increasing pH which is unexpected (Regression 3, Table 4.1). Increasing pH decreases the availability of free cations in the soil solution which also should decrease the availability of ^{137}Cs . This was found by Giannakopoulou *et al.* (2007) and Mascanzoni (1988). On the other hand, van Bergeijk *et al.*, found no correlation between ^{137}Cs uptake by plants and pH in a pH-range from 3.9 to 8.4. I cannot explain why I obtained a positive correlation between pH and TFg but as mentioned earlier, there should have been more observations included in the regression analyses to obtain more reliable results.

In Regression 4 (Table 4.1), where ^{137}Cs content in grass was the dependent variable, the ^{137}Cs concentration in soil and clay content were selected in addition to organic matter and potassium content while pH and sand content, which were selected in Regression 3, were rejected. As discussed previously, clay and sand content are not independent of each other and one of them can be selected in the regression equations as a substitute for the other.

4.2.2 Regression analyses for soils with an organic content above 15 %

Texture analysis was not possible to perform on soils with a loss of ignition above 25 %. Those soils were therefore not included in the regression analyses presented in the previous section. In Figure 4.4, TF_g is plotted against the organic matter content. The figure shows a very large variance in TF_g values at low levels of organic matter. The sites that had a high organic matter content generally had a higher transfer of ¹³⁷Cs from soil to plant than those with a low content.

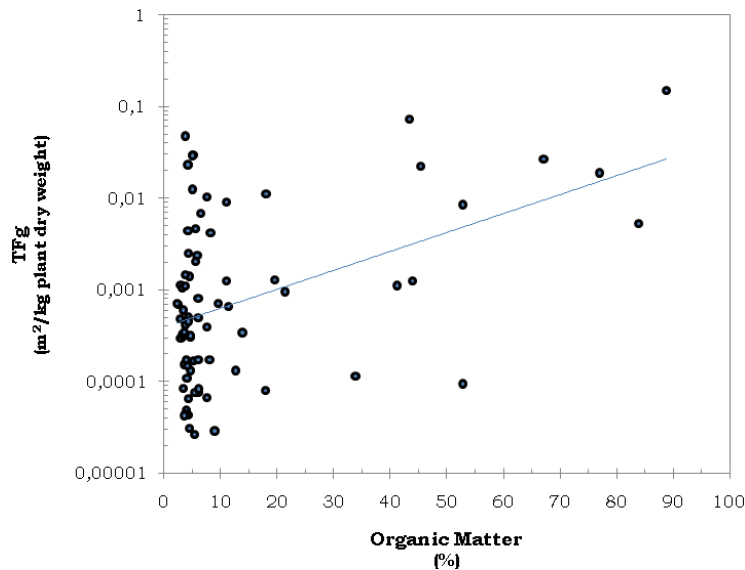


Figure 4.6: Transfer of ¹³⁷Cs from soil to plant (TF_g) on a logarithmic scale as a function of soil organic matter content. R²=0.20

There were 14 sites that had a loss of ignition above 15 % (ranging from 16 % to 89 %) and two stepwise regression analyses were performed for these sites (Table 4.3). In one regression analysis loss on ignition, pH and potassium content (K-AL) were independent variables tested as predictors of TF_g. In the other regression analysis the same independent variables were used together with ¹³⁷Cs concentration in soil as predictors of ¹³⁷Cs content in grass (¹³⁷Cs-grass).

The two analyses showed that loss on ignition was the factor that most strongly affected both TF_g and ¹³⁷Cs-grass (Regressions 5 and 6, Table 4.3). Caesium uptake increased with increasing loss of ignition. The R²-values for Regressions 5 and 6 were 0.22 and 0.33 respectively. K-AL also significantly reduced the uptake in the model with ¹³⁷Cs-grass as dependent variable (Regression 6).

Table 4.3: Soil factors influencing ^{137}Cs transfer to grass (TFg) and ^{137}Cs concentration in grass according to stepwise regression models (15 % level for entry of independent variables into the model). The soils have a loss on ignition between 19 % and 89 %.

Variable	Regression 5		Regression 6	
	Organic matter > 15 %			
	TFg*1000		^{137}Cs content in grass	
	Constant	Prob.value	Constant	Prob.value
Intercept	-120.1	-	-3872	-
log. Loss on ignition (%)	87	0.09	3553	0.02
pH	I	-	II	-
K-AL	II	-	-86	0.12
^{137}Cs soil content (Bq/m ²)	n.i	-	I	-
	n=14		n=14	
	R ² =0.22		R ² =0.33	

n.i = not included in analysis

I = best alternative

II = 2nd best alternative

According to the regression analyses loss on ignition had a great influence on the ^{137}Cs uptake. Soils with an organic matter content above 25 % generally had higher values of TFg and ^{137}Cs content in grass compared to the mineral soils (Table 4.2). The presumably limited amount of clay in these organic soils and the surplus of organic substances, that could block the frayed edge sites of any clay fraction present, resulted in a higher concentration of ^{137}Cs in soil solution. As no analysis of soil texture was made on these soils it is difficult to make any conclusion about the impact of the clay content.

Potassium affected the uptake negatively in Regression 6 where ^{137}Cs concentration in grass was the dependent variable. As discussed in the previous section (“Regression analyses for mineral soils”), there is an antagonism in plant uptake between potassium and caesium and the potassium concentration also reflects the clay content, at least in mineral soils. If this also applies to the soils with an organic matter content above 25 %, the potassium concentration could to some extent reflect the effect of the clay content. Still, the soils rich in organic matter did not contain much clay and it is difficult to say how much a few percent increase in clay content would affect the potassium concentration.

The ^{137}Cs concentration in the soil ranged between 10 and 200 kBq/m² (Appendix 2). A higher activity in the soil is generally expected to increase the uptake in plants. However, the regression analyses indicated that the specific soil characteristics of the sites, i.e. other soil properties, were often more important for the uptake than the ^{137}Cs concentration in the soil, at least within the documented ^{137}Cs concentration range.

4.3 Conclusions

- According to the regression analyses, clay content was the soil property that most strongly affected the ^{137}Cs plant uptake. At very low clay contents, below 10 %, each percent increase in the clay content significantly reduced the uptake. About 10 % of clay seemed high enough to significantly reduce the uptake and a further increase in clay was of much less importance. Instead other soil properties such as organic matter, plant available potassium and sand content together explained the remaining variation in uptake at a high clay content.
- In this investigation, the ^{137}Cs concentration in soil was not, according to the regression models, the most important factor explaining the ^{137}Cs uptake in plants. This shows that site specific characteristics in many cases may have a larger influence on the uptake. Furthermore, there are presumably other factors which were not analyzed that also had an impact on the ^{137}Cs transfer from soil to plants.
- The highest ^{137}Cs transfer from soil to plant was found in soils rich in organic matter and a low transfer was generally found in mineral soils with a clay contents above 10 %.
- It is important to understand the effects of soil properties and other variables influencing the ^{137}Cs availability in soil solution and the transfer to plants to be able to predict effects of a possible future fallout. Field studies are a very helpful tool in order to evaluate the importance of each characteristic as well as the relationships between them.

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Appendix 1

ID, site name, GPS positions (rikets nät) and sampling dates for the sampled sites in Uppsala (C), Västmanland (U), Gävleborg (X), Jämtland (Z) and Västernorrland (Y) county.

County	ID	Site Name	Position		Sampling Date	
			East	North		
Uppsala	CIngstarbo	Ingstarbo	175123	602114	2007-09-21	
	C117	Marma	172817	602932	2007-09-21	
	C119	Åkra	173726	600820	2007-09-10	
	C711	Möjsjövik	171413	595733	2007-08-18	
	C818	M/E Blacksta vall	171526	600026	2007-09-06	
Västmanland	U2-bete	Öhn	171310	600506	2007-09-10	
	U3	Viby	171215	600555	2007-09-10	
	U4	Buckarby	170116	601204	2007-09-10	
	U11-Skogsvallen	Östervåla	171057	601005	2007-09-10	
	U118	Fråganbo	172617	603540	2007-09-21	
Gävleborg	U703	Vittinge	-	-	2007-09-06	
	X1	Björke	171131	604537	2007-09-14	
	X2	-	171108	604323	2007-09-18	
	X4A	Hedesunda	165407	602323	2007-09-18	
	X4B	Hedesunda	165422	602321	2007-09-21	
	X7A	Hade	170532	601836	2007-09-21	
	X7B	Hade	170529	601839	2007-09-21	
	X8A	Kessmansbo	171013	603043	2007-09-21	
	X8B	Kessmansbo	170956	603040	2007-09-21	
	X9B	Hillesjön	157601	673613	2007-09-21	
	X11	Trödje	171345	604907	2007-09-18	
	X12A	Österfärnebo	164736	602218	2007-09-21	
	X14	Hille Skjutbana	171143	604352	2007-09-14	
	X15A	Iggön	171746	605218	2007-09-18	
	X15D	Iggön	171746	605223	2007-09-18	
	X18	Hille	171181	604453	2007-09-18	
	X19	Utnäs, Forsa	-	-	2007-08-19	
	Jämtland	BLH-A	Blomhöjden	-	-	2007-08-22
		BLH-B	Blomhöjden	-	-	2007-08-22
Z1		Hammarstrand	162158	630555	2007-08-19	
Z3		Meslien	140856	645039	2007-08-20	
Z3B		Backe	162532	634209	2007-08-23	
Z4		Ragundasjön, Näset	162919	630344	2007-08-30	
Z5A		Ankarvattnet	-	-	2007-08-20	
Z5B		Ankarvattnet	-	-	2007-08-20	
Z8		Ankarvattnet	141350	645234	2007-08-20	
Z13A		-	-	-	2007-08-21	
Z13B		-	-	-	2007-08-21	
Z17		Jormvattnet	140242	644314	2007-08-21	
Z18		Jormlien	140048	644355	2007-08-21	
Z19		Jormlien	135855	644336	2007-08-21	
Z21		Jormlien	135733	644339	2007-08-21	
Z25	Röyrviksvägen	140351	645051	2007-08-21		

(continued)

	ID	Site Name	Position		Sampling Date
			East (X)	North (Y)	
Västernorrland	Y3	Matfors	-	-	2007-08-26
	Y4	Klingsta	171141	621906	2007-08-26
	Y5	Silje	171119	622530	2007-08-26
	Y8	Rö	175750	624253	2007-08-25
	Y9	-	174855	624756	2007-08-25
	Y10	-	174532	625005	2007-08-25
	Y14	-	-	-	2007-08-27
	Y15	-	173719	624013	2007-08-27
	Y20	-	175020	624946	2007-08-25
	Y22	Överfälle	174351	625612	2007-08-24
	Y26	Forsed	173112	630005	2007-08-24
	Y27	Nyland	174227	630018	2007-08-24
	Y28	-	-	-	2007-08-24
	Y31	-	173229	630446	2007-08-24
	Y32	-	172136	630908	2007-08-24
	Y33	-	171230	631160	2007-08-24
	Y36B	Offer	-	-	2007-08-29
	Y37	Hallsta	175356	625509	2007-08-25
	Y38	-	180310	625220	2007-08-25
	Y39	Dal	174923	623418	2007-08-25
	Y40	-	173534	622826	2007-08-26
	Y43	Kubbe	-	-	2007-08-29
	Y44	-	174755	625422	2007-08-24
	Y44-mull	-	-	-	2007-08-24
	Y44-vall	-	-	-	2007-08-24
	Y45	Säbrå	175053	623839	2007-08-25
	Y46	Vålånger	175617	624402	2007-08-25
	Y47	-	171248	631342	2007-08-24
	Y48	Holmsta	164255	631615	2007-08-24
	Y52A	Alnön	-	-	2007-08-26
	Y53	-	164056	633039	2007-08-23
	Y55	-	174727	624858	2007-08-25
	Y56	-	175153	624229	2007-08-27
	Y59	Lustgården	172632	622543	2007-08-26

Appendix 2

Appendix 2.a: ¹³⁷Cs activity in soil and grass, year 2007, and soil characteristics at the sampled sites in the county of Uppsala. The soil samples were taken from 0 to 20 cm depth.

ID	Soil													Vegetation			
	Activity		¹ Clay		² Silt		³ Sand		Loss on ignition		Organic matter		pH	K-AL	Crop	Activity	TFg
	Bq/kg dw	kBq/m ²	%	%	%	%	%	%	%	%	mg/100g dw	Bq/kg plant dw	Bq/m ²	m ² /kg			
CIngstarbo	71	12	33	32	36	8.7	6.2	6.1	23.9	Ley	1	0	8.3E-05				
C117	139	29	35	40	25	10.2	7.7	6.5	12.3	Pasture	11	1	3.9E-04				
C119	75	16	43	42	15	7.0	4.1	7.6	40.3	Ley	2	0	1.1E-04				
C711	1080	60	-	-	-	84.0	-	5.4	20.3	Pasture	316	225	5.3E-03				
C818	205	39	34	31	35	8.6	6.1	6.0	15.4	Pasture	7	0	1.7E-04				

Appendix 2.b: ¹³⁷Cs activity in soil and grass, year 2007, and soil characteristics at the sampled sites in the county of Västmanland. The soil samples were taken from 0 to 20 cm depth.

ID	Soil													Vegetation			
	Activity		¹ Clay		² Silt		³ Sand		Loss on ignition		Organic matter		pH	K-AL	Crop	Activity	TFg
	Bq/kg dw	kBq/m ²	%	%	%	%	%	%	%	%	mg/100g dw	Bq/kg plant dw	Bq/m ²	m ² /kg			
U2-bete	365	52	57	34	10	17.1	13.9	6.2	20.3	Pasture	18	1	3.4E-04				
U3	202	35	41	40	19	11.8	9.0	6.2	20.4	Ley	1	0	2.9E-05				
U4	176	35	13	20	67	9.3	8.1	5.6	27.9	Pasture	6	1	1.7E-04				
U11-Skogsvallen	203	41	37	46	18	6.2	3.6	5.7	14.4	Pasture	14	4	3.5E-04				
U118	114	25	15	46	39	5.1	3.7	6.0	10.4	Ley	4	0	1.5E-04				
U703	100	24	37	59	5	6.3	3.6	5.4	16.6	Ley	1	0	4.3E-05				

¹ d < 0.002 mm

² 0.002 ≤ d < 0.06 mm

³ 0.06 ≤ d ≤ 2 mm

* Percent of the mineral fraction

Appendix 2.c: ¹³⁷Cs activity in soil and grass, year 2007, and soil characteristics at the sampled sites in the county of Gävleborg. The soil samples were taken from 0 to 20 cm depth.

ID	Soil				Vegetation							TFg m ² /kg	
	Activity		¹ Clay %	² Silt %	³ Sand %	Loss on ignition %	Organic matter %	pH	K-AL mg/100g dw	Crop	Activity Bq/kg plant dw		
	Bq/kg dw	kBq/m ²											
X1	846	78	39	35	26	22.1	19.6	6.1	9.9	Ley	100	11	1.3E-03
X2	680	80	22	24	53	23.1	21.4	5.9	10.6	Ley	76	12	9.5E-04
X4A	204	30	19	24	58	19.6	18.1	5.4	5.8	Ley	333	24	1.1E-02
X4B	193	36	20	24	56	12.8	11.1	6.0	4.8	Ley	45	1	1.2E-03
X7A	522	30	-	-	-	88.8	-	5.2	13.8	Ley	4290	495	1.5E-01
X7B	694	60	-	-	-	52.9	-	5.7	25.4	Ley	6	1	9.4E-05
X8A	996	55	-	-	-	67.2	-	6.3	0.0	Pasture	1450	141	2.7E-02
X8B	270	48	11	15	74	13.7	12.8	6.2	0.0	Pasture	6	1	1.3E-04
X9B	1750	112	-	-	-	41.3	-	5.4	11.0	Pasture	125	39	1.1E-03
X11	547	124	2	5	93	3.5	3.3	6.1	4.0	Ley	38	4	3.1E-04
X12A	826	48	-	-	-	77.1	-	5.8	10.3	Ley	906	16	1.9E-02
X14	449	84	27	51	22	8.3	6.1	6.3	9.5	Pasture	6	1	7.5E-05
X15A	531	112	5	10	85	8.2	7.7	5.5	4.2	Pasture	1160	56	1.0E-02
X15D	1680	193	5	11	84	11.9	11.4	5.2	11.2	Pasture	127	4	6.6E-04
X18	918	71	-	-	-	52.9	-	4.5	20.4	Pasture	607	74	8.5E-03
X19	99	9	-	-	-	33.9	-	4.9	17.7	Pasture	1	0	1.2E-04

¹ d < 0.002 mm

² 0.002 ≤ d < 0.06 mm

³ 0.06 ≤ d ≤ 2 mm

* Percent of the mineral fraction

Appendix 2.d: ¹³⁷Cs activity in soil and grass, year 2007, and soil characteristics for the sampled sites in the county of Jämtland. The soil samples were taken from 0 to 20 cm depth.

ID	Soil				Vegetation							TFg m ² /kg	
	Activity Bq/kg dw	kBq/m ²	¹ Clay * %	² Silt * %	³ Sand * %	Loss on ignition %	Organic matter %	pH	K-AL mg/100g dw	Crop	Activity Bq/kg plant dw		
													4
BLH-A	59	10	7	34	60	7.1	6.5	5.3	8.3	Pasture	65	4	6.8E-03
BLH-B	100	8	-	-	-	43.4	-	5.0	18.0	Ley	550	31	7.2E-02
Z1	126	31	8	74	18	3.7	2.9	5.7	3.7	Pasture	15	2	4.8E-04
Z3	93	16	5	44	52	4.8	4.3	5.4	4.7	Pasture	71	9	4.4E-03
Z3B	22	5	4	29	68	3.4	3	5.5	4.0	Pasture	6	1	1.1E-03
Z4	83	21	7	73	20	3.1	2.4	6.3	3.0	Ley	15	1	7.1E-04
Z5A	74	15	4	39	56	5.5	5.1	5.6	4.0	Ley	187	9	1.2E-02
Z5B	105	18	5	39	56	5.6	5.2	5.5	4.2	Ley	545	40	3.0E-02
Z8	41	7	5	33	63	4.7	4.3	4.9	4.3	Ley	156	14	2.3E-02
Z13A	61	13	4	39	57	4.2	3.8	5.4	3.2	Ley	600	17	4.8E-02
Z13B	49	5	6	44	51	5.6	5.1	5.9	4.2	Ley	156	6	2.9E-02
Z17	64	10	5	25	70	11.5	11.1	6.1	7.7	Ley	94	9	9.1E-03
Z18	121	28	7	71	23	5.0	4.4	5.4	6.7	Ley	70	5	2.5E-03
Z19	69	14	9	53	38	6.4	5.6	5.4	6.5	Ley	29	2	2.1E-03
Z21	61	11	6	37	57	8.9	8.3	6.5	5.1	Ley	46	4	4.2E-03
Z25	89	16	5	47	48	6.4	5.9	5.3	7.2	Pasture	38	9	2.4E-03

¹ d < 0.002 mm

² 0.002 ≤ d < 0.06 mm

³ 0.06 ≤ d ≤ 2 mm

* Percent of the mineral fraction

Appendix 2.e: ¹³⁷Cs activity in soil and grass, year 2007, and soil characteristics at the sampled sites in the county of Västernorrland. The soil samples were taken from 0 to 20 cm depth.

ID	Soil		Vegetation										TFg m ² /kg
	Activity Bq/kg dw	kBq/m ²	¹ Clay * %	² Silt * %	³ Sand * %	Loss on ignition %	Organic matter %	pH	K-AL mg/100g dw	Crop	Activity		
											Bq/kg dw	Bq/m ²	
Y3	97	20	29	65	6	8.4	6.1	5.5	6.8	Ley	16	1	8.1E-04
Y4	88	23	29	63	8	6.2	3.9	5.9	8.2	Ley	1	0	4.4E-05
Y5	141	31	30	52	17	6.0	3.6	5.5	7.9	Ley	10	0	3.2E-04
Y8	123	29	5	24	71	3.5	3	6.1	7.1	Ley	9	1	3.0E-04
Y9	160	35	34	52	15	6.7	4.2	5.7	7.8	Pasture	5	0	1.5E-04
Y10	212	43	7	46	47	6.3	5.6	5.8	4.1	Pasture	201	19	4.7E-03
Y14	151	31	10	79	12	7.0	6.1	6.3	6.2	Ley	16	5	5.0E-04
Y15	172	37	27	51	22	7.0	4.8	5.5	10.1	Pasture	12	1	3.2E-04
Y20	126	28	24	37	39	6.5	4.4	6.0	8.6	Ley	14	0	5.0E-04
Y22	176	32	28	48	23	6.8	4.5	5.7	9.1	Ley	1	0	3.1E-05
Y26	133	30	14	54	32	6.1	4.8	6.4	12.9	Ley	9	1	3.0E-04
Y27	198	34	37	53	10	6.7	4	6.5	27.6	Ley	6	1	1.7E-04
Y28	111	28	5	61	34	3.0	2.5	5.7	3.4	Ley	19	1	6.9E-04
Y31	71	13	32	58	10	7.9	5.5	5.7	7.1	Ley	1	0	7.6E-05
Y32	203	45	21	70	9	5.3	3.3	5.6	5.6	Ley	15	1	3.2E-04
Y33	161	37	13	77	11	4.6	3.4	6.6	4.0	Ley	22	3	6.0E-04
Y36B	151	32	32	64	5	7.1	4.7	6.2	7.8	Ley	4	0	1.3E-04
Y37	64	13	41	52	7	7.2	4.4	6.0	15.0	Ley	6	1	4.5E-04
Y38	75	15	24	67	9	9.8	7.7	6.4	20.5	Pasture	1	0	6.7E-05
Y39	175	38	22	46	32	7.4	5.4	5.9	22.4	Ley	1	0	2.6E-05
Y40	245	43	4	8	89	10.0	9.6	5.9	9.7	Ley	30	3	7.1E-04
Y43	44	11	5	60	36	4.4	3.9	5.9	3.0	Ley	16	1	1.5E-03
Y44	226	25	60	31	8	21.3	18	5.9	17.3	Pasture	2	0	8.0E-05
Y44-mull	304	20	-	-	-	44.0	-	5.8	19.6	Pasture	25	2	1.3E-03
Y44-vall	109	24	29	63	8	6.6	4.3	5.7	17.5	Ley	1	0	4.3E-05
Y45	203	44	26	49	25	6.2	4	5.8	9.8	Pasture	2	0	4.8E-05
Y46	173	39	7	25	68	4.5	3.8	5.3	3.3	Ley	42	8	1.1E-03

(continued)

ID	Soil				Vegetation								
	Activity Bq/kg dw	kBq/m ²	¹ Clay	² Silt	³ Sand	Loss on ignition	Organic matter	pH	K-AL	Crop	Activity	TFg	
			%	%	%	%	%	mg/100g dw	Bq/kg plant dw	Bq/m ²	m ² /kg		
Y47	183	42	7	84	9	4.5	3.8	6.3	3.6	Ley	18	2	4.2E-04
Y48	182	41	26	66	8	5.7	3.5	6.0	7.1	Ley	3	0	8.4E-05
Y52A	339	24	-	-	-	45.5	-	5.5	13.3	Ley	534	73	2.2E-02
Y53	88	19	8	73	19	6.1	5.3	5.6	4.9	Ley	3	1	1.7E-04
Y55	86	21	7	33	60	3.9	3.3	5.6	5.4	Ley	23	2	1.1E-03
Y56	188	49	10	49	41	5.4	4.4	6.0	25.4	Ley	3	0	6.4E-05
Y59	128	29	3	4	93	4.8	4.5	5.4	3.4	Pasture	40	2	1.4E-03

¹ d < 0.002 mm

² 0.002 ≤ d < 0.06 mm

³ 0.06 ≤ d ≤ 2 mm

* Percent of the mineral fraction