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Natural factors influencing strontium concentrations in bulk and throughfall deposition, soil solution and litterfall in forest ecosystems on Olkiluoto Island, southwestern Finland

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We studied the total concentrations of naturally occurring Sr in bulk deposition, stand throughfall, soil solution and litterfall in forest ecosystems located on Olkiluoto Island in southwestern Finland; in order to estimate the importance of sea water, soil chemical processes and plant and soil interactions on the Sr cycling in coastal areas of Baltic Sea. The area is specific because of the brackish sea water and land uplift from the sea. Bulk deposition samples were collected from two plots located in open areas and the other samples from four forest stands typical on Olkiluoto Island. The variation in the Sr concentrations in the stand throughfall and soil solution followed closely the variation in the base cations and anions. The highest individual Sr, base cation and anion concentrations were determined in the black alder-dominated forest stand close to the shore line of the Baltic Sea due to sea, high weathering input and nitrification. Nitrification on this plot led to nitrate leaching and increased buffering of acidity and weathering. All these processes promoted the presence of Sr in soil solution. Increased concentrations of naturally occurring Sr were reflected similarly in all sampled media, i.e., in stand throughfall, soil solution and litterfall.

Introduction

Strontium (Sr) is an element that behaves geochemically similar in many respects to calcium (Ca) in the soils and ground waters, since the cycling and behavior of Sr is strongly based on the chemical nature of ion containing electrical valence of 2+ (Koljonen 1992, Lahermo *et al*. 2002). Sr occurs in the silicate minerals typically with Ca and potassium (K). The concentrations of Sr are usually small compared to the concentration of Ca, another member of the earth alkaline metals (Koljonen 1992, Lahermo *et al*. 2002). Sr occurs naturally in minerals and rocks as ^{86}Sr and ^{87}Sr isotopes (Åberg 1995). To our knowledge only a few studies exist on the factors controlling the total concentrations of Sr in forest ecosystems (e.g., Åberg 1995, Nakano *et al*. 2001).

Sr released in the weathering processes from the fine fraction of till soil is usually originating from relatively poorly-weathered K-feldspar or plagioclase. Micas and dark minerals, which are more easily weathered, contain usually only small amounts of Sr. However, since feldspars

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are very common minerals in the soil, weathering is an important source of Sr. The release of Sr in weathering can, however, be expected to be a relatively slow process (Koljonen 1992, Lahermo *et al*. 2002). In podzols, as well as in arenosols, regosols and cambisols typical in Finland (Tamminen and Tomppo 2008), the weathering of silicate minerals in the topmost parts of the mineral soil is a dominant process providing base cations to the elemental cycling in forest ecosystems (Carey *et al*. 2005, Starr *et al*. 2014). The weathering processes in the topmost part of the forest soil, minerals (e.g., feldspars) containing Sr and base cations are weathered and resistant minerals (e.g., quartz) and elements (e.g., Zr) are enriched (Olsson and Melkerud 1991, Starr *et al*. 1998, Olsson and Melkerud 2000, Starr and Lindroos 2006, Starr *et al*. 2014). Minerals rich in K are also relatively resistant to weathering and they are subsequently enriched in the top soil layers compared to minerals rich in Ca which are depleted (e.g., Lindroos *et al*. 2016). Relative enrichment of ^{87}Sr compared to ^{86}Sr indicates weathering release of Sr especially from Ca-rich minerals to soil solution in top soil layers (Åberg 1995). In young soils containing lots of fresh, not yet strongly weathered material and located in Finland close to the sea shore of the Baltic Sea, the annual weathering rate of minerals releasing base cations is at its highest (Starr and Lindroos 2006), and this is undoubtedly the case also for Sr. An important source of Sr for the coastal areas is also sea water in which the Sr is a common trace element (Åberg 1995).

Radioisotope ^{90}Sr has been released into the atmosphere and to global biogeochemical cycling through nuclear weapon tests as well as through accidents related to the utilization of nuclear energy (Eisenbud and Gesell 1997). Spent nuclear fuel contains also ^{90}Sr, which is an intermediate-lived fission product with a physical half-life of 28.8 years (Eisenbud and Gesell 1997).

The purpose of the forest research activities performed on Olkiluoto Island, southwestern Finland, is to monitor forest conditions and to measure the processes taking place at the island's forest ecosystems. Results are needed as background information for the safety assessment of spent nuclear fuel disposal. Research activities related to forest ecosystems are part of the environmental monitoring programme on Olkiluoto Island carried out by Posiva Oy (Aro *et al*. 2016). As a part of this programme, we have studied the natural occurrence of Sr in main fluxes of water and organic matter in forest stands. We have also studied the natural factors affecting the Sr concentrations.

By studying the elemental cycling of naturally occurring Sr in forest ecosystems, it is possible to increase our knowledge about the general cycling properties of Sr, which can also be important from the point of view of studies related to release of radioisotope ^{90}Sr to the environment. The cation exchange processes as well as the ionic balance in water in deposition and soil solution can be expected to be key processes affecting the cycling of Sr^{2+} as they are important in the cycling of base cations in forest soils (e.g., Lindroos *et al*. 1995, Probst *et al*. 1995). However, no data have been reported so far as to which processes are the most important in coastal areas of the Baltic Sea to regulate biogeochemical cycling of Sr through ion balance and as input fluxes. The area is specific because of the brackish sea water and land uplift from the sea. The possible sources of Sr close to the shoreline are weathering input and brackish sea water; and also tree species may accelerate Sr cycling through soil processes such as nitrification, weathering and cation exchange. In order to estimate the importance of these factors on Sr cycling, we studied the total concentrations of naturally occurring Sr, other cations and anions in the bulk deposition, stand throughfall and soil solution in forest ecoystems located on an island in southwestern Finland. We also hypothesized that if there are elevated concentrations of naturally occurring Sr in the deposition and soil solution in some forest stands, this would be reflected also in other parts of the forest ecosystem. Therefore, we have also studied the concentration of Sr in tree litterfall.

Material and methods

Site

The study area is located on Olkiluoto Island, southwestern Finland (61°14´´N, 21°27´´E). Samples for this study were collected from six monitoring plots. Two of the plots were located in open areas and four plots in forests typical of Olkiluoto Island: a managed, mature Scots pine stand (FIP-4), an old-growth Norway spruce stand (FIP-10), a birch-dominated young stand (FIP-11) and a black alder-dominated stand (FIP-14) close to the shore line of Baltic sea (see a map of the site locations in Aro *et al*. 2018: p. 6, Fig. 3). Soil and stand characteristics are described in Table 1.

Samplings

Bulk deposition in open areas, stand throughfall deposition within the forest stands and soil solution at different depths of the forest soil were collected at 2–4 week intervals throughout 2013–2015. Sr determinations were not included in the deposition and soil solution measurements before 2013, although Sr was studied in litterfall already from 2011 (see below). Bulk deposition and stand throughfall were collected continuously throughout the year; during the snow-free period using funnel-shaped deposition collectors (diameter 20 cm, height 40–60 cm) and during the winter period using specially-designed snow collectors (diameter 36 cm, height 180 cm). There were 20 systematically-located collectors within the forest stand (stand throughfall) during the snow-free period, and five snow-collectors during the winter period. Bulk deposition in the open area was collected by five funnel-shaped (snow-free period) and two snow (winter period) collectors. The subsamples from the collectors were combined to give one composite sample for each sampling occasion for bulk deposition and stand throughfall. There were 13 composite bulk deposition and 13 stand throughfall samples for each sample plot for each year. The experimental set-up was comparable to that of the ICP Forests monitoring programme in Finland (e.g., Lindroos *et al*. 2007, 2008).

Soil solution was collected during the snow-free periods from below the organic layer of the forest soil (a depth of 5-10 cm below the ground surface with organic layer; hereafter "depth 5 cm") using zero-tension plate lysimeters, and at depths of 20 and 30 cm using tension cup lysimeters. A plate lysimeter (depth 5 cm) had a surface area of 0.1 m^2 (40 cm x 25 cm), and it collected water from the organic layer and the top 1-2 cm of the mineral soil. There were a total of eight plate lysimeters at a depth of 5 cm and four suction cup lysimeters at both depths of 20 cm and 30 cm at the pine plot, FIP-4. Soil solution was collected in the spruce stand (FIP-10) using 12 plate lysimeters (depth 5 cm) and 12 suction cup lysimeters per depth (depths 20 cm and 30 cm). The corresponding number of replications for the young birch stand (FIP-11) had eight plate lysimeters (depth 5 cm) and four suction lysimeters per depth (depths 20 cm and 30 cm). There were four plate lysimeters (depth 5 cm) in the black alder stand (FIP-14), but soil solution was not sampled at deeper depths due to stoniness of the soil. The number of lysimeters varied among the sample plots due to the fact that the soil contained high volume of stones, which limited the installing of lysimeters. The samples for each plate lysimeters were analyzed separately and the samples obtained with the suction cup lysimeters were bulked to give one composite sample per depth for each sampling occasion (Aro *et al*. 2018). The number of samples for FIP-4, FIP-10, FIP-11 and FIP-14 were, respectively: depth 5 cm, 2013 (*n*: 32, 36, 26, 17), 2014 (*n*: 30, 24, 22, 14), 2015 (*n*: 38, 48, 38, 21); depth 20 cm, 2013 (*n*: 3, 7, 3, –), 2014 (*n*: 2, 7, 5, –), 2015 (*n*: 4, 7, 4, –); depth 30 cm, 2013 (*n*: 4, 6, 4, –), 2014 (*n*: 3, 7, 5, –), 2015 (*n*: 5, 7, 5, –).

Litterfall was collected during 2011–2015 using 12 litterfall traps located systematically on the pine, spruce, birch and black alder-dominated stands (Pitman *et al*. 2010). Funnel-shaped litterfall traps were placed 1.5 m above the ground surface and a collection area of a trap was 0.5 m^2. Litterfall samples were collected throughout the year. During the snow-free period, the sampling interval was four weeks and samples in May represented litterfall of the whole previous winter. Collected litter was divided into the following fractions: (1) dead pine needles (brown needles), (2) living pine needles (green needles), (3) spruce needles, (4) leaves, (5) remaining litter, and (6) small branches. Branches (fraction small branches) collected by the traps (Pitman *et al*. 2010) are rather small, and therefore in order to collect the whole spectrum of branch litter, "branch traps" were installed on the ground surface (fraction (7): branches from branch traps). "Branch traps"

Table 1. Basic characteristics of soil and vegetation of the study plots.

Plot	Site type	Soil type[a] (bedrock)	Thickness of organic layer (cm)	Dominating tree species	Most abundant plant species in bottom and field layer
FIP-4	Herb-rich heath forest	Haplic Arenosol (Gneiss)	4.4	Scots pine, planted	*Pleurozium schreberi*, *Pteridium aquilinum*
FIP-10	Herb-rich heath forest	Haplic Arenosol/Haplic Gleysol (Gneiss)	9.6	Norway spruce, in natural stage	*Pleurozium schreberi*, *Vaccinium myrtillus*
FIP-11	Mesic heath Herb-rich heath forest	Haplic Gleysol/Histic Gleysol (Gneiss)	7.5	Downy birch, naturally regenerated	*Pleurozium schreberi*, *Vaccinium vitis-idaea*
FIP-14	Herb-rich forest (grove)	Haplic Arenosol (Gneiss)	5.7	Black alder, naturally born	*Brachythecium spp.*, *Dryopteris expansa*

(*continued*)

Total stand volume (in 2014)[b] (m^3 ha^{-1})	Number of all stems (in 2014)[b] (stems ha^{-1})	CEC of humus[c] (mmol(+) kg^{-1})	Base saturation of humus[c] (%)	pH($CaCl_2$) of humus[c]
361	856	287	77	3.5
447	789	446	73	3.5
83	17699	483	86	3.7
172	1155	428[d]	90[d]	3.9[d]

[a]IUSS Working Group WRB (2006)
[b]Aro et al. (2016)
[c]Aro et al. (2014) except FIP-14
[d]Analysis methods according to Aro et al. (2014)

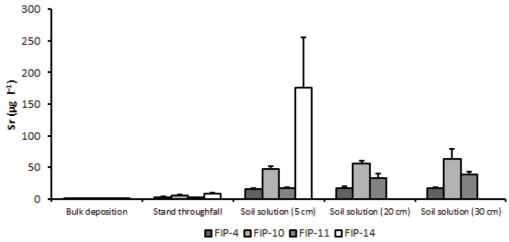

Fig. 1. Sr concentrations in open area bulk deposition, stand throughfall and soil solution (depths 5 cm, 20 cm and 30 cm) on the pine dominated (FIP-4), spruce dominated (FIP-10), birch dominated (FIP-11) and black alder-dominated (FIP-14) stands. Mean and S.D. for 2013–2015. OBS. Soil solution was collected on plot FIP-14 only at a depth of 5 cm.

are open plastic circles that are placed directly on the forest floor and their height is about 2 cm above the forest floor. "Branch traps" consisted of nylon fabric stretched on a frame of approximately 2 cm in height, and the collection area was 0.5 m^2. There were 12 “branch traps” located systematically on the plots close to each funnel-shaped traps (Aro *et al*. 2018). The number of samples was 6–7 per year per fraction for the plot FIP-4 (except for fraction 3, n = 1–2). For the plots FIP-10 and FIP-11, n was 6–7 per year per fraction, except that n was 1 for the fractions 3 and 6 of the FIP-11 in 2011. For the plot FIP-14, n was 6–8 per year per fraction (except fraction 3, n = 1–2).

Chemical analysis and data calculation

The water samples were transported to the laboratory within 24 hours after sampling and were kept cold during the transportation and before analysis. The pH was measured from the water samples. The concentrations of Sr, Ca, Mg, K and Na were determined by inductively coupled plasma atomic emission spectrophotometer (ICP-AES, iCAP 6500 Duo analyzer), NO_3, SO_4 and Cl by ion chromatograph (IC, Dionex ICS-1000). NH_4 was determined by flow injection analysis (Aro *et al*. 2018).

Litterfall fractions were homogenized by grinding and microwave digestion in acid (HNO_3/H_2O_2) preceding the chemical analysis of strontium concentration by ICP-AES. Mean and standard deviation were calculated for the measured parameters and relationships between the measured parameters were determined by calculating Pearson correlation coefficients, which were considered as statistically significant at the $p < 0.05$ level. Regression equations were computed for the Sr and Cl relationships.

Results

Sr and other solute concentrations of TF and soil solution

The mean Sr concentrations in the stand throughfall varied from 2.50–7.91 µg Sr l^{-1} among the plots (Fig. 1). The bulk deposition concentrations in the open area were very low (Fig. 1). The highest mean Sr concentration (176 µg Sr l^{-1}) was determined in the black alder-dominated stand at a depth of 5 cm.

The highest mean Ca, Mg and K concentrations in the stand throughfall and soil solution at a depth of 5 cm were determined in the black alder-dominated stand (Fig. 2). Also the highest individual Na, Cl and SO_4-S concentrations in the soil solution at a depth of 5 cm were determined in the same stand (Fig. 2). The highest mean pH and NO_3–N concentrations at a depth of 5 cm were also determined in the black alder stand (Fig. 3). Accordingly, the highest mean concentrations of Sr (µeq l^{-1}), sum of base cations (BC) and sum of anions (An) in the stand throughfall and soil solution at a depth of 5 cm were determined in the black alder-dominated stand (Fig. 4).

The Cl and Sr concentrations correlated positively in the stand throughfall (Fig. 5), in soil solution at a depth of 5 cm (Fig. 6) and in soil solution at depths of 20–30 cm (Fig. 7). In almost all cases, the correlation was statistically significant (Figs. 5–7). There were also several significant positive correlations between the Sr and Ca, Mg, K, Na and SO_4-S concentrations in the stand throughfall, soil solution at a depth of 5 cm, and in soil solution at depths of 20–30 cm (Table 2).

Sr in litterfall

The highest mean Sr concentrations in the tree litterfall were determined from the black alder

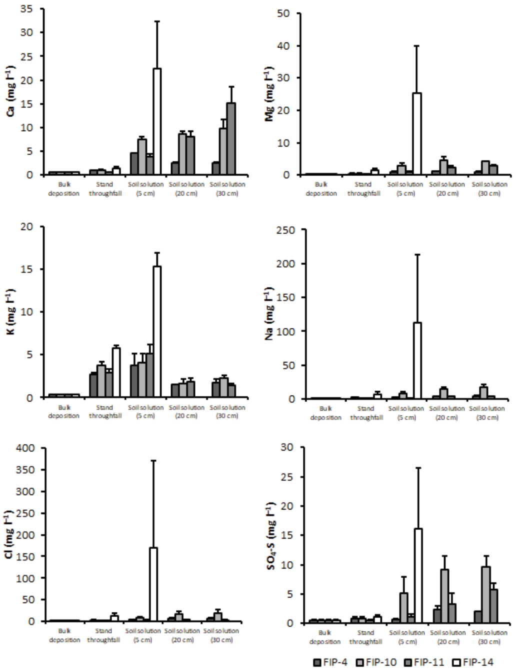

Fig. 2. Ca, Mg, K, Na, Cl and SO_4-S concentrations in open area bulk deposition, stand throughfall and soil solution (depths 5 cm, 20 cm and 30 cm) on the pine-dominated (FIP-4), spruce-dominated (FIP-10), birch-dominated (FIP-11) and black alder-dominated (FIP-14) stands. Mean and S.D. for 2013–2015. OBS. Soil solution was collected on plot FIP-14 only at a depth of 5 cm.

-dominated stand followed by the spruce dominated stand. The Sr concentration was clearly higher in the Norway spruce needles of the black alder plot than in other litterfall fractions (Fig. 8).

Discussion

Sr in TF and soil solution

The mean value of the monitoring plots was 1.38 µg Sr l^{-1} in the open area bulk deposition and the open area mean was quite close to that reported for rainwater elsewhere: < 1 µg l^{-1} (Åberg 1995). However, since our open area value was slightly higher than 1 µg l^{-1}, there was probably some influence of dust on our values. The Sr concentrations in the stand throughfall varied 2.50–7.91 µg Sr l^{-1} (mean

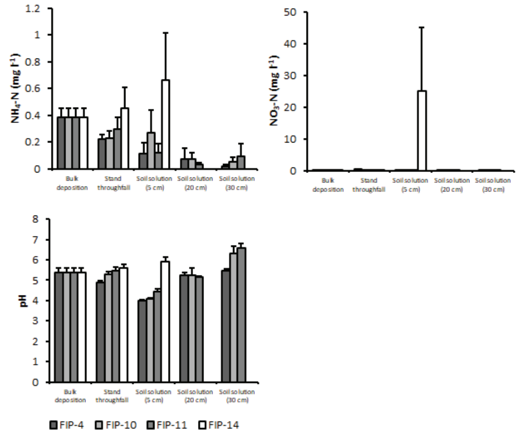

Fig. 3. NH_4-N and NO_3-N concentrations and pH in open area bulk deposition, stand throughfall and soil solution (depths 5, 20 and 30 cm) on the pine-dominated (FIP-4), spruce-dominated (FIP-10), birch-dominated (FIP-11) and black alder-dominated (FIP-14) stands. Mean and S.D. for 2013–2015. Note: soil solution was collected at FIP-14 only at a depth of 5 cm.

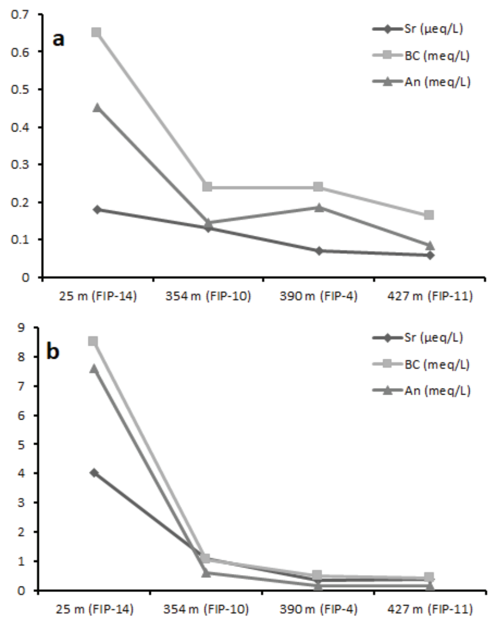

Fig. 4. Concentrations of Sr, sum of base cations (Ca + Mg + K + Na, BC) and sum of anions (Cl + SO_4 + NO_3, An) in (**a**) stand throughfall and (**b**) soil solution (depth 5 cm) in the stands in relation to the distance from the shoreline of the Baltic Sea. Forest stands are marked in parentheses: dominating tree species, black alder (FIP-14), Norway spruce (FIP-10), Scots pine (FIP-4) and birch (FIP-11). Mean values calculated for 2013–2015.

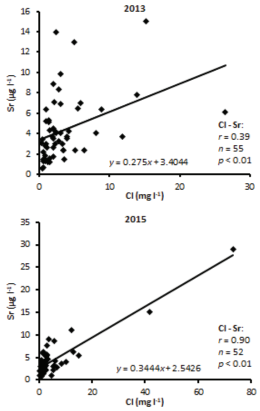

Fig. 5. Relationship between Sr (μg l^{-1}) and Cl (mg l^{-1}) in stand throughfall in 2013, 2014 and 2015 for the combined data from all the plots. Pearson correlation coefficient (r) with a statistical significance (p) and the number of samples (n) are indicated.

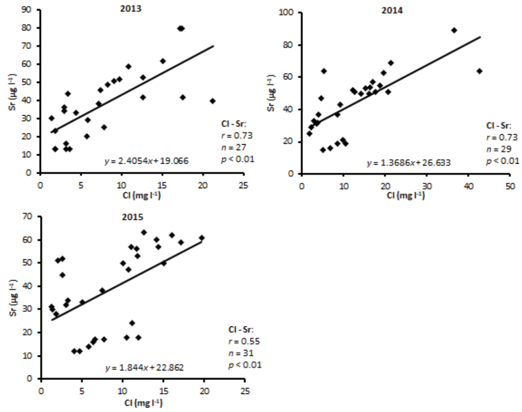

Fig. 7. Relationship between Sr (μg l^{-1}) and Cl (mg l^{-1}) in soil solution (depths 20–30 cm) in 2013, 2014 and 2015 for the combined data excluding the FIP-14 plot (black alder, close to the sea shore, soil solution was collected on FIP-14 only at a depth of 5 cm). Pearson correlation coefficient (r) with a statistical significance (p) and the number of samples (n) are indicated.

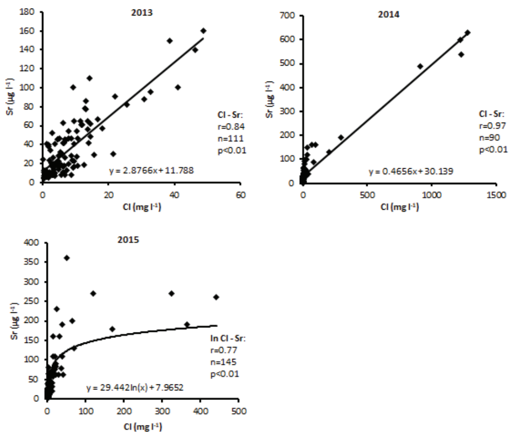

Fig. 6. Relationship between Sr (μg l^{-1}) and Cl (mg l^{-1}) in soil solution (depth 5 cm) in 2013, 2014 and 2015 for the combined data from all the plots. Pearson correlation coefficient (r) with a statistical significance (p) and the number of samples (n) are indicated.

values of the monitoring plots). Based on the isotope ratios of naturally occurring Sr (^{87}Sr/^{86}Sr), it has been reported that stand throughfall represents Sr in precipitation, Sr transported in the atmosphere and caught by vegetation (e.g., dust retained by the tree canopies) as well as Sr in the biogeochemical cycle originating from the mineral soil due to weathering (Graustein and Armstrong 1983, Åberg and Jacks 1985, Åberg 1995).

There was a tendency of Sr concentrations to be higher in the soil solution of the forest soil (especially on the alder plot at a depth of 5 cm) as compared with the concentrations in stand throughfall. This reflects the buffering processes of acidity of the soil solution in forest soil, which is based on cation exchange processes and the weathering input from the silicate minerals containing Sr (Åberg 1995). An increase in the soil solution concentrations may also be caused by evapotranspiration leading to a decrease in the soil water amounts with depth (Lindroos *et al.* 2008).

Effect of sea salt

The high Sr concentrations together with high Cl and SO_4 concentrations in the black alder stand close to the sea shore indicate that an important source for these parameters is brackish sea water of Baltic Sea (Åberg 1995). The variation of the Sr concentration in the stand throughfall and soil solution followed also closely the variation in the base cations and anions. The highest individual Sr, base cation and anion concentrations were determined in the black alder-dominated forest stand located close to the shore line of the Baltic

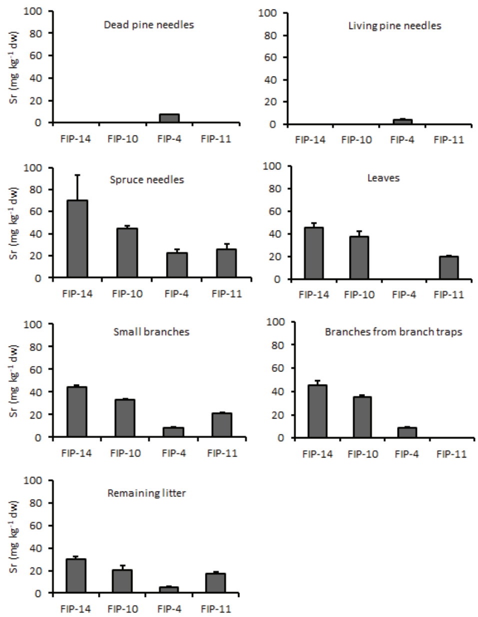

Fig. 8. Sr concentration in different tree litterfall fractions on the plots. Mean and S.D. for 2011–2015.

Sea. This was reflected as a clear positive relationship in the combined data from all the stands between the Sr and SO_4, Cl and base cations.

Soil chemical processes

Another source for Sr can be mineral weathering in the topmost mineral soil layers related to the soil development, since the annual weathering rate of minerals are known to be its highest in Finland close to the current sea shore (Starr and Lindroos 2006). The highest Sr concentrations in soil solution on the black alder plot close to shoreline are at least partly a result of high weathering rate. Weathering rate of base cations, and therefore also Sr, decrease strongly when moving inlands (Starr & Lindroos 2006). Land uplift is taken place at a rate of several millimeters per year currently due to the fact that the level of the land surface is still recovering after the last glaciation prevailing in the area about 10 000 years ago (Starr and Lindroos 2006). Land uplift in these flat terrains causes the fact that new soil material is emerging from the sea and it is subjected to soil forming processes above the sea level. The weathering rate of base cations in fresh, not yet weathered mineral soil material is high (Starr and Lindroos 2006), and this is undoubtedly the fact also for the Sr release from K-feldspar and especially from plagioclase (Koljonen 1992, Lahermo *et al*. 2002). In addition, high input of Cl and SO_4 from the sea affects the ionic balance of the stand throughfall and soil solution as well as high NO_3 concentration in the black alder stand (see below). The high concentration of these anions causes leaching of positively charged cations such as Sr.

Table 2. Statistically significant ($p < 0.05$) correlation coefficients (r) between the Sr (μg l^{-1}) concentrations and SO_4-S, Ca, Mg, K and Na (mg l^{-1}) concentrations for 2013, 2014 and 2015. Results are indicated for stand throughfall ("TF"), soil solution (depth 5 cm, "5"), soil solution (depths 20—30 cm, "20") and n = number of samples. Note: soil solution was collected on plot FIP-14 only at a depth of 5 cm.

Type		SO_4-S	Ca	Mg	K	Na	*n*
TF	Sr-2013	0.64	0.87	0.74	0.74	0.35	55
	Sr-2014	0.70	0.83	0.71	0.64	0.42	52
	Sr-2015	0.88	0.82	0.96	0.57	0.89	52
5	Sr-2013	0.80	0.86	0.94	0.40	0.82	111
	Sr-2014	0.92	0.95	0.99	0.77	0.97	90
	Sr-2015	0.70	0.95	0.93	0.47	0.72	144
20	Sr-2013	0.92	0.63	0.98	0.50	0.84	27
	Sr-2014	0.91	0.65	0.96	—	0.80	29
	Sr-2015	0.90	0.59	0.99	—	0.78	31

Effect of interactions between plant and soil on Sr cycle

Tree species may have an effect on the nutrient cycling in forest ecosystems (Priha and Smolander 2000, Smolander and Kitunen 2001, Lindroos *et al*. 2011). For example, Norway spruce may have an increasing effect on soil acidity and decreasing effect on exchangeable nutrients, and on the other hand, birch may have an increasing effect on base cation concentrations and decreasing effect on acidity (Priha and Smolander 2000, Smolander and Kitunen 2001, Lindroos *et al*. 2011). As a broad-leaved species, black alder has an effect on the concentrations of nutrient elements, but the effects of processes related to the close location of the sea shore, e.g., increased weathering and marine input, seem also to be very clear. Lindroos *et al*. (2011) has reported that although there was a tree species effect on the concentrations of base cations in stand throughfall, soil solution and forest soil, the effect was rather weak in boreal forest stands in northern Finland. However, black alder has a strong effect on the nitrogen cycling because of the symbiosis of the roots of alder and *Frankia* bacteria. *Frankia* can retain atmospheric N into NH_4–N (Smolander and Priha 2003). Therefore, in the black alder stand, there was an increased input of NH_4–N together with high soil solution pH, leading to nitrification as can be seen in highly elevated NO_3–N concentrations in the soil solution. NO_3 affects the ionic balance of the soil solution supporting the presence of cations (e.g., Sr). This tree species effect related to NO_3 on the ionic balance was an important process since the acidity from nitrification was efficiently buffered as can be seen in high pH. Cation exchange buffering processes and mineral weathering caused retention of H+ ions and at same time input of base cations and Sr to soil solution. In this respect, nitrification related to tree species effect on this plot was a key process for the presence of Sr in the soil solution.

Sr in tree litterfall

The variation of the Sr concentrations between the forest stands in the tree litterfall followed also closely the Sr concentrations in the stand throughfall deposition and soil solution. The highest concentrations were detected in the black alder stand. All the plots contained also spruce trees and therefore the needle litterfall fraction is the most comparable among the plots. The Sr concentrations were the highest also in this fraction on the plot close to the sea shore. It was interesting that in our data, increased concentrations of naturally occurring Sr were reflected similarly in all sampled media, i.e., in stand throughfall, soil solution and litterfall. Therefore it can be concluded that if the input of Sr to forest ecosystems is increased due to e.g., atmospheric-derived dry deposition, marine sea spray, increased mineral weathering or the nutrient cycling as intensified by tree species, this can be seen as elevated Sr concentrations in trees and their litterfall.

Conclusions

Close location of sea, high mineral weathering and tree species (black alder) all caused the high Sr concentrations in the soil solution of the tree stand close to the shoreline of the Baltic Sea. These factors must be taken into account when evaluating Sr cycling in forest ecosystems in land uplift areas and close to brackish sea water. High natural input of Sr to the forest ecosystems was reflected in stand throughfall, soil solution and litterfall.

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