



**HAL**  
open science

## Timescale of radium and alkaline earth cations ascent in the trees: Use of isotopic ( $^{228}\text{Ra}/^{226}\text{Ra}$ ) ratio

François Chabaux, Peter Stille, Jonathan Prunier, Sophie Gangloff, Damien Lemarchand, Gilles Morvan, Justine Négrel, Eric Pelt, Marie-Claire Pierret, Sophie Rihs, et al.

### ► To cite this version:

François Chabaux, Peter Stille, Jonathan Prunier, Sophie Gangloff, Damien Lemarchand, et al.. Timescale of radium and alkaline earth cations ascent in the trees: Use of isotopic ( $^{228}\text{Ra}/^{226}\text{Ra}$ ) ratio. Applied Geochemistry, 2024, 165, pp.105938. 10.1016/j.apgeochem.2024.105938 . irsn-04570938

**HAL Id: irsn-04570938**

**<https://irsn.hal.science/irsn-04570938>**

Submitted on 13 May 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



**HAL**  
open science

## Plant-soil-water interactions: Implications from U-Th-Ra isotope analysis in soils, soil solutions and vegetation (Strengbach CZO, France)

François Chabaux, Peter Stille, Jonathan Prunier, Sophie Gangloff, Damien Lemarchand, Gilles Morvan, Justine Négrel, Eric Pelt, Marie-Claire Pierret, Sophie Rihs, et al.

### ► To cite this version:

François Chabaux, Peter Stille, Jonathan Prunier, Sophie Gangloff, Damien Lemarchand, et al.. Plant-soil-water interactions: Implications from U-Th-Ra isotope analysis in soils, soil solutions and vegetation (Strengbach CZO, France). *Geochimica et Cosmochimica Acta*, 2019, 259, pp.188 - 210. 10.1016/j.gca.2019.05.045 . hal-03480705

**HAL Id: hal-03480705**

**<https://hal.science/hal-03480705>**

Submitted on 20 Dec 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 **Plant-Soil-water interactions: implications from U-Th-Ra isotope analysis in**  
2 **soils, soil solutions and vegetation (Strengbach CZO, France)**

3

4 Chabaux François<sup>1\*</sup>, Stille Peter<sup>1\*</sup>, Prunier Jonathan<sup>1,2\*</sup>, Gangloff Sophie<sup>1</sup>,  
5 Lemarchand Damien<sup>1</sup>, Morvan Gilles<sup>1</sup>, Négrel Justine<sup>1</sup>, Pelt Eric<sup>1</sup>, Pierret Marie-  
6 Claire<sup>1</sup>, Rihs Sophie<sup>1</sup>, Schmitt Anne-Désirée<sup>1</sup>, Trémolières Michèle<sup>1,3</sup>, Viville Daniel<sup>1</sup>.

7

8 1- Laboratoire d'Hydrologie et de Géochimie de Strasbourg (LHyGeS), Université de  
9 Strasbourg, CNRS, ENGEES, 1 rue Blessig, 67000 Strasbourg, France.

10

11 2- Present address: Laboratoire des Sciences du Bois, UMR EcoFoG, CNRS, Campus  
12 Agronomique de Kourou, BP 316, 97387 Kourou, France.

13

14 3- Present address: Laboratoire Image, Ville, Environnement (LIVE), Université de  
15 Strasbourg, CNRS, ENGEES, 3 rue de l'Argonne, 67000, Strasbourg, France.

16

17 \*Corresponding authors:

18 [fchabaux@unistra.fr](mailto:fchabaux@unistra.fr) , [pastille@unistra.fr](mailto:pastille@unistra.fr) , [Jonathan.Prunier@ecofog.gf](mailto:Jonathan.Prunier@ecofog.gf)

19

20

21

22 *Keywords:* <sup>238</sup>U-<sup>234</sup>U-<sup>230</sup>Th-<sup>226</sup>Ra radioactive disequilibria, <sup>230</sup>Th/<sup>232</sup>Th activity ratios,  
23 soils, soil solutions, vegetation, Strengbach catchment.

24 **ABSTRACT**

25 This study presents U-Th-Ra isotope data for soils, soil grain size fractions, soil  
26 solutions, throughfall, rainwater and tree samples from two experimental plots  
27 under spruce and beech trees, in the Strengbach catchment (France) that highlight  
28 the importance of the  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$ - $^{226}\text{Ra}$  nuclides and the ( $^{230}\text{Th}/^{232}\text{Th}$ ) for the  
29 tracing of biogeochemical cycles in the plant-soil-water system of the critical zone  
30 (CZ).

31 The results highlight the very contrasting impact of trees on the U-Th and Ra (Ba)  
32 budgets in forest ecosystems with Ra-Ba being strongly and U-Th very little cycled  
33 by vegetation, leading to high ( $^{226}\text{Ra}/^{230}\text{Th}$ ) and ( $^{226}\text{Ra}/^{238}\text{U}$ ) in trees. Thorium-  
34 Ra(Ba) fractionations in soil solutions and soils are therefore strongly influenced by  
35 tree uptake and litter decay but U-Th fractionations are little influenced. Compared  
36 to other classical isotope systems such as Sr or Nd that are routinely used in the  
37 study of the CZ and significantly affected by vegetation cycling, U-Th isotopes are  
38 probably among the few tracers to be specific tracers of water-rock interactions in  
39 the CZ. The Th activity ratios of soil minerals, especially of minor and secondary  
40 mineral phases, show a large range of variation, from 0.7 to 5 in the Strengabch case.  
41 These different characteristics give Th activity ratio an important role for tracing  
42 the sources of chemical fluxes in soils, soil solutions and vegetation that is currently  
43 under-exploited. The Strengbach study illustrates the utility of this approach and  
44 the methodology is further strengthened by the combination of U, Th activity ratios  
45 and Sr isotope ratios, which also provides additional constraints on the weathering  
46 processes affecting the Strengbach bedrocks and the nature of the reservoirs  
47 involved in the plant-soil-water transfers. The results emphasize that minor mineral  
48 phases such as zircon, sulfate and phosphate are important sources of the U-Th  
49 fluxes transiting soil solutions and significantly control the U and Th budget of the  
50 Strengbach soil samples and their Th activity ratios. Furthermore, the comparison of  
51 the U-Th-Sr isotopic characteristics of soil solutions and soil grain size fractions  
52 allows the recognition of two stages of weathering of the bedrock i.e. 1- dissolution  
53 of the primary minerals and formation of the secondary ones in the deep soil  
54 horizons, and 2- dissolution of both primary and secondary minerals mainly from  
55 the finest soil grain size fractions in the nearest surface soil horizons. The latter  
56 might be related to recent modifications of the weathering processes in the

57 catchment, stronger and older under the spruce than the beech plot. We propose  
58 that degree of weathering modification is related to the nature of tree cover because  
59 spruce plantations have caused an increase of soil acidity and hence of weathering  
60 intensity of some minerals and likely also of Ca leaching from the Ca-poor  
61 Strengbach soils over the past decades. The U-Th-Sr results of this study also point  
62 to the occurrence of isotopically different reservoirs of these elements for trees and  
63 gravity soil solutions collected by lysimetric plates. This further suggests that for the  
64 Strengbach watershed the gravity soil solutions cannot be the main tree nutrient  
65 reservoir.

66

67

68 **1. INTRODUCTION**

69 Soil horizons play a key role in the evolution of the critical zone, as dynamic and  
70 porous interfaces that connect the atmosphere, vegetation, rocks, groundwaters and  
71 surface waters (Banwart et al., 2017; 2019). Precise knowledge of the relationships  
72 and inter-relationships between the different components of this highly complex  
73 system is necessary when one seeks, for instance, to model precisely the soil and  
74 critical zone evolution (Banwart et al., 2019) or the chemical composition of stream  
75 and surface waters (e.g., Li et al., 2017; Lucas et al., 2017; Ackerer et al., 2018).  
76 Knowledge of key parameters including the nature and extent of weathering  
77 processes active in the soil horizons and the interplay between biological processes,  
78 water circulation and water-rock interactions, is certainly still insufficient. Advances  
79 in the description/understanding of the main key hydro-biogeochemical reservoirs  
80 and processes that are active in the surface soil horizons are still required.

81 Geochemical and especially isotopic approaches have been developed to address  
82 these issues, both to specify the sources of elements and constrain their pathways in  
83 plant-soil-water systems (e.g., Blum and Erel, 2005; Bouchez et al., 2013; Bullen and  
84 Kendall, 1998; Kendal and Doctor, 2005). Significant efforts have been made over  
85 recent decades to evaluate the potential of using geochemical proxies for  
86 hydrogeochemical processes and biogeochemical cycles active within the soil  
87 system. Understanding the parameters and processes that control the behavior of  
88 geochemical tracers during plant-soil-water interactions has progressed from  
89 studies conducted at the experimental watershed scale down to the laboratory  
90 experiment scale. Such studies have included a large number of geochemical tools:  
91 trace elements, traditional and non-traditional stable isotopes, and radioactive and  
92 radiogenic isotopes (e.g., Akerman et al., 2014; Aubert et al., 2001; 2002; Babcsányi  
93 et al., 2014; 2016; Braun et al., 1998; Bouchez et al., 2013; Bullen and Eisenhauer,  
94 2009; Chabaux et al. 2015a,b; Cividini et al., 2010; Ladouche et al., 2001; Laveuf and  
95 Cornu, 2009; Ma et al., 2011; Négrel et al., 2018; Opfergelt and Delmelle, 2012;  
96 Opfergelt et al., 2014; Schmitt et al., 2003, 2012; 2013; Steinmann and Stille, 1997;  
97 2009; Stille et al., 2006; 2009; 2011; Viers et al., 2015; Voinot et al., 2013).

98 These different studies have emphasized the potential of using these geochemical  
99 tools to characterize biogeochemical cycles and hydrogeochemical transfer in plant-  
100 soil-water systems. These studies also clearly demonstrated interest in coupling

101 geochemical proxies in water, soils and vegetation to understand the critical zone  
102 processes and their dependence on environmental conditions (e.g., Sullivan et al.  
103 2016 and references therein).

104 In the framework of these efforts, little attention has been paid so far to  $^{238}\text{U}$ - $^{234}\text{U}$ -  
105  $^{230}\text{Th}$ - $^{226}\text{Ra}$  nuclides and to Th isotope ratios as potential proxies/tracers of critical  
106 zone function. To date, studies on U-series nuclides in soils, surface waters and  
107 sediments have been mainly undertaken to determine the time constants of  
108 alteration and erosion processes in the critical zone (e.g., Ackerer et al., 2016;  
109 Bourdon et al., 2009; DePaolo et al., 2006; 2012; Dequincey et al., 2002; Chabaux et  
110 al., 2003a,b; 2012; 2013; Gontier et al., 2015; Maher et al., 2006; Pelt et al., 2008;  
111 Dosseto et al., 2008; 2014; Dosseto and Schaller, 2016; Ma et al., 2010; 2012; 2013;  
112 Vigier et al., 2001). However, few studies have suggested the potential of using  $^{238}\text{U}$ -  
113 series nuclides to trace hydro- and biogeochemical transfers in watershed and soils.  
114 For instance, the coupling between U and Sr isotopes has successfully elucidated the  
115 hydrogeochemical fluxes in watershed and soil solutions (Riotte and Chabaux, 1999;  
116 Bagard et al., 2011; Chabaux et al., 2001; Riotte et al., 2003; Durand et al., 2005;  
117 Pierret et al. 2014; Schaffhauser et al., 2014; Prunier et al., 2015; Tricca et al., 2001).  
118 The ( $^{230}\text{Th}/^{232}\text{Th}$ ) activity ratios (hereafter, activity ratios will be noted in brackets)  
119 in the different rock minerals were also observed to span a large range of values  
120 (Bosia et al., 2016; 2018) that could thus, once combined with Sr or Nd isotopes, be  
121 relevant to characterize the mineralogical source of elements in watersheds. Finally,  
122 several studies have indicated the potential impact of vegetation on the Ra  
123 geochemical cycle (e.g., Cerne et al., 2010; Gerzabeck et al., 1998; Greeman et al.,  
124 1999; Jeambrun et al., 2012; Million et al., 1994; Pourcelot et al., 2017; Rihs et al.,  
125 2011; 2016; Soudek et al., 2004; Lascar, 2019). These results suggest that  $^{238}\text{U}$ - $^{234}\text{U}$ -  
126  $^{230}\text{Th}$ - $^{226}\text{Ra}$  nuclides and ( $^{230}\text{Th}/^{232}\text{Th}$ ) ratios are anticipated to be relevant for  
127 tracing sources of elements, weathering processes and hydrogeochemical pathways  
128 in the plant-soil-water system. So, in this study these nuclides along with the  
129 ( $^{230}\text{Th}/^{232}\text{Th}$ ) were analysed in the soils, soil solutions and trees of the Strengbach  
130 Critical Zone Observatory (<http://ohge.unistra.fr>) in order to constrain better their  
131 contribution to our understanding of the plant-soil-water system. The Strengch CZO  
132 is an instrumented watershed, very well suited for this type of work, as already  
133 illustrated for other geochemical tools, because it allows for the different

134 hydrogeological and biological components involved in plant-soil-water transfers to  
135 be sampled (e.g., Aubert et al., 2004; Gangloff et al., 2014; Lemarchand et al., 2010;  
136 Stille et al., 2006; 2009; 2011; 2012; Tricca et al., 1999; Cenko-Tok et al., 2009;  
137 Cividini et al., 2010; Lemarchand et al., 2010; Lemarchand et al., 2012; Schmitt et al.,  
138 2003; 2017; 2018).

139

## 140 **2. SITE AND SAMPLING**

141

### 142 **2.1. Site description**

143 The uppermost Strengbach watershed (0.8 km<sup>2</sup>) is situated in the Vosges mountains  
144 (northeastern France) at altitudes between 880 and 1150 m (a.m.s.l.) and has  
145 relatively steep slopes (mean 15°) (Fig. 1). This area is an instrumented  
146 environmental observatory (<http://ohge.unistra.fr>) involved in the French critical  
147 zone observatories network OZCAR (French network of Critical Zone Observatories:  
148 Research and Applications) (<http://www.ozcar-ri.org>), where meteorological,  
149 hydrological and water chemistry data have been collected since 1986 (e.g., Viville  
150 et al., 2012; Pierret et al., 2014; 2018 for additional details). It was recently used to  
151 carry out a study of in-situ dissolution rates of silicate minerals in the critical zone  
152 (Wild et al., 2019). The climate is temperate oceanic mountainous with an average  
153 rainfall of 1400 mm.yr<sup>-1</sup>, with ≈20% under snowfall. Forest covers 90% of the  
154 geographical area of the watershed. The forest area is composed of 80% spruces  
155 (*Picea abies L.*) and 20% beeches (*Fagus sylvatica*).

156 The bedrock is mainly composed of Hercynian base-poor granites (the Brezouard  
157 granite Massif), locally marked by petrological and mineralogical variabilities linked  
158 to the polyphased history of these granites. As detailed in Hasalova et al. (2015) and  
159 Tabaud et al. (2015), granites are derived from two main generations of granitic  
160 magmas: a first and extensive K-Mg granitoid magmatism around 340 Ma, followed  
161 by magmatic events occurring at ca. 325 Ma, which produced a large amount of  
162 felsic anatectic melts, which pervasively intruded and compositionally and  
163 texturally reworked previously formed granitoids (in Hasalova et al., 2015). Such a  
164 magmatic history in the Strengbach watershed results in a continuum between  
165 porphyritic granites with large feldspars and plagioclase phenocrysts, which were  
166 formed during the first magmatic stage, to fine-grained more isotropic granites,



167 which were formed by crystallization of the late felsitic magmas, via intermediate  
168 granites where the two magmatic assemblages are recognizable. Such a magmatic  
169 history can lead to the coexistence of different types of K-feldspars in the same rock,  
170 with Ba-rich K-feldspars crystallized from the primary magmas and Ba-poor K-  
171 feldspars recrystallized from secondary anatectic magmas (Hasalova et al., 2015).  
172 The granitic bedrock has undergone late hydrothermal alterations, which are more  
173 important on the northern slope of the catchment than on the southern slope  
174 (Fichter et al., 1998 a,b). Field observations also indicate the occurrence of more or  
175 less developed veinlets of secondary minerals, including Fe and Mn oxyhydroxides,  
176 quartz, and barite, which can be related to hydrothermal or meteoritic alterations.  
177 Some of the meteoritic alterations might be of ante-Triassic age (Wyns et al., 2004;  
178 Dewandel et al., 2006).

179 A sandy saprolite, which can reach several meters of thickness, usually separates  
180 soil and granite. The soils are 80-100 cm deep and vary from Dystric Cambisol to  
181 Albic Podzol (brown acidic to ochreous brown podzolic) (WRB 2014). The soils are  
182 very coarse-grained, sandy and rich in gravel (Fichter et al., 1998a,b). The shallow  
183 soils (upper 50 cm) under spruce (VP site) and beech (HP site) are acidic (pH=3.7-  
184 4.5) (Aubert et al., 2001; Solovitch-Vella et al., 2007). Distric Cambisols are mainly  
185 located on the northern slope, and Albic Podzols are located on the southern slope.  
186 This soil difference likely results from the differences in the lithology, vegetation  
187 cover and local climate between the north- and south-facing slopes (e.g., Pierret et  
188 al., 2014).

189

## 190 **2.2. Sampling**

191 Samples were collected between 2004 and 2006 from two experimental sites: one  
192 under spruce trees that were planted between 1890 and 1900, which is locally  
193 named the VP site and hereafter the “spruce site”, and the other under beeches that  
194 were planted between 1860 and 1870, hereafter named HP or the “beech site”  
195 (Location Fig. 1). The beech site is developed on the gently hydrothermally altered  
196 granite, while the spruce site has a bedrock that has undergone a much more  
197 intense hydrothermal alteration (e.g., Fichter et al., 1998). Fine earth (<2 mm) from  
198 two soil layers (30-40 cm and 90-100 cm), which were marked by the highest and  
199 weakest root density in the two soil profiles, was collected and separated into four

200 particle size fractions: < 2  $\mu\text{m}$  (clay), 2-50  $\mu\text{m}$  (silt), 50-100  $\mu\text{m}$  (fine sand) and  
201 1600-2000  $\mu\text{m}$  (coarse sand). Soil solutions were collected by zero-tension  
202 lysimeter plates at -5, -10, -30 and -60 cm (noted VP-5, VP-10, VP-30 and VP-60)  
203 next to the VP spruce soil profile and at -10 and -70 cm (noted HP-10 and HP-70)  
204 next to the HP beech soil profile (see caption Fig. 1). Different parts of spruce and  
205 beech trees (sapwood, roots, branches and needles or leaves) and litters from the  
206 VP spruce and HP beech sites were collected from 2004 to 2007. Throughfall and  
207 rainwater samples were also collected.

208

### 209 **3. ANALYTICAL METHODS**

#### 210 **3.1. Grain size fractions and granite rocks**

211 Before crushing the fine earth fractions of the four sampled soil horizons, a  
212 representative subsample (100 g) was dispersed for 30 min in a cylindrical Pyrex  
213 container with 750 ml of ultrapure water to disaggregate the soil and separate the  
214 different grain size fractions. The dispersion was sieved at 50  $\mu\text{m}$  through a nylon  
215 sieve. The nonpassing fraction was dried at 60°C and used to separate the fine sand  
216 (50-100  $\mu\text{m}$ ) and coarse sand (1600-2000  $\mu\text{m}$ ) fractions using a set of nylon sieves.  
217 The clay fraction (<2  $\mu\text{m}$ ) and the silt fraction (2-50  $\mu\text{m}$ ) was separated from the  
218 50 $\mu\text{m}$ -passing fraction via sedimentation in deionized ultrapure water based on  
219 Stokes law, followed by centrifugation at 3500 rpm, as detailed in Prunier et al.  
220 (2015).

221 Bedrocks and coarse sands (> 100  $\mu\text{m}$ ) of the two soil samples were crushed in an  
222 agate disk mill. The major and trace element concentrations of these different  
223 samples were measured by ICP-AES (Jobin Yvon) and ICP-MS (VG Plasma Quad  
224 Thermo Electron), respectively, after lithium tetraborate fusion. The analytical  
225 uncertainty was <3% for major element concentrations and <10% for trace element  
226 concentrations at  $2\sigma$  (Dequincey et al., 2005; Chabaux et al., 2012). For isotopic  
227 measurements, an aliquot of approximately 100 mg of granite and particle size  
228 fraction powders were spiked with  $^{233}\text{U}$  and  $^{229}\text{Th}$  tracers and digested by ultrapure  
229 HF,  $\text{HNO}_3$ ,  $\text{HClO}_4$ ,  $\text{HCl}$  and  $\text{H}_3\text{BO}_3$  acids (Pelt et al., 2013). After separation and  
230 purification using Biorad AG1x8 anionic resin (e.g., Pelt et al., 2008; Granet et al.,  
231 2010), the U-Th concentrations and ( $^{234}\text{U}/^{238}\text{U}$ ) and ( $^{230}\text{Th}/^{232}\text{Th}$ ) ratios were  
232 measured by thermal ionization mass spectrometry (TIMS, Thermo-Scientific

233 Triton) using  $^{233}\text{U}$  and  $^{229}\text{Th}$  tracers.  $^{87}\text{Sr}/^{86}\text{Sr}$  was determined after separation and  
234 purification following chromatographic standard procedures on a VG Sector mass  
235 spectrometer using a dynamic multicollection (Lahd Geagea et al., 2007).  $^{226}\text{Ra}$   
236 concentration measurements were performed by TIMS (Triton Thermo-Scientific)  
237 from another powder aliquot using a  $^{228}\text{Ra}$ -enriched spike after digestion,  
238 separation and purification according to the protocol given in Pelt et al. (2013) and  
239 adapted from previous works by Chabaux et al. (1994) and Ghaleb et al. (2004).  
240 Blanks ranged between 30 and 171 pg for U and 160 and 190 pg for Th and were <  
241 0.1 fg for Ra and <1 ng for Sr; thus, the blanks were negligible compared to the Sr  
242 and U-Th-Ra amounts analyzed in the samples. The repeatability of the Sr, Th and U  
243 isotopic analyses was tested by repeated measurements of three solution standards,  
244 NBS 987, Th105 and HU1. The mean value of  $^{87}\text{Sr}/^{86}\text{Sr}_{\text{NBS987}}$  was  $0.71027 \pm 0.00002$   
245 ( $n=22$ , 2SD (Standard Deviation)), that of  $^{232}\text{Th}/^{230}\text{Th}_{\text{Th105}}$  was  $217080 \pm 2400$   
246 ( $n=37$ , 2SD) and  $(^{234}\text{U}/^{238}\text{U})_{\text{HU1}} = 0.999 \pm 0.004$  ( $n=72$ , 2SD). In addition, repeated  
247 analyses of the AThO rock standard yielded a mean U activity ratio value of  $1.000 \pm$   
248  $0.004$  ( $n=10$ , 2SD) and a  $^{232}\text{Th}/^{230}\text{Th}$  isotopic ratio of  $182840 \pm 1238$  ( $n=6$ , 2SD). All  
249 these data are consistent within errors with previously published data (Pelt et al.,  
250 2013 and references therein). The  $^{226}\text{Ra}$  concentration of the  $^{228}\text{Ra}$ -spike was  
251 regularly calibrated against the AThO rock standard assuming secular equilibrium  
252 for the  $^{226}\text{Ra}$ - $^{230}\text{Th}$  isotopes. The analysis of the  $(^{226}\text{Ra}/^{230}\text{Th})$  ratios of the BEN rock  
253 standard gives a value of  $1.002 \pm 0.017$  (2SD) that is entirely consistent with the  
254 assumed secular equilibrium value (Pelt et al., 2013).

### 255 **3.2. Vegetation samples**

256 Each sample was first washed with deionized ultrapure water in an ultrasonic  
257 tank/bath to remove soil and airborne particles. The samples were then dried at  
258  $60^\circ\text{C}$  until a constant mass was reached and finally crushed within a specific agate  
259 disk mill. Two aliquots of 2 to 10 g of plant material powder were digested on a  
260 hotplate in conventional PFA Teflon<sup>®</sup> beakers successively using a  $\text{HNO}_3$ - $\text{H}_2\text{O}_2$   
261 mixture and  $\text{HNO}_3$ -HF (a) to determine  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopic ratios, U-Th  
262 concentrations and U-Th activity ratios using the same protocol as described above  
263 for the soil samples and (b) to determine  $^{226}\text{Ra}$  concentrations. To avoid  
264 interference by Ca during TIMS measurements, excess Ca was removed from the

265 samples using a pretreatment based on manganese complexation according to a  
266 protocol adapted from Ghaleb et al. (2004). After complete sample mineralization,  
267 the residue was dissolved in 1 to 2 ml of 6N HCl bidistilled and 150 ml of ultrapure  
268 water. Approximately 150  $\mu$ l of 0.5 N  $\text{KMnO}_4$  was added to oxidize the residual  
269 organic matter. The solution was heated for 10 min at 80°C before adjusting the pH  
270 to 10-11 with 1 M NaOH. Next, 200  $\mu$ l of 0.5 N  $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$  was added to initiate Mn-  
271 oxide precipitation, onto which Ra sorbed, while most Ca remained in solution. The  
272 mixture was heated at 110°C for 15 min, cooled and centrifuged at 4000 rpm for 10  
273 min. The precipitate was washed with hot ultrapure water, centrifuged and  
274 dissolved in 5 to 10 ml of 6N HCl. After evaporation, the residue was dissolved with  
275 2 N HCl to separate and purify the Ra fraction according to the protocol detailed  
276 above for rocks. All blank procedures ranged between 7 and 41 pg for U, 0.7 and 162  
277 pg for Th, <0.04 fg for Ra and < 1 ng for Sr, which are negligible compared to the Sr  
278 and U-Th-Ra amounts analyzed in the samples.

279

### 280 **3.3. Soil solutions, rainwaters and throughfalls**

281 Water samples, i.e., soil solutions, rainwater and throughfalls, were filtered through  
282 a 0.45  $\mu$ m cellulose acetate membrane filters in the laboratory a few hours after  
283 sampling. Each water sample was subdivided into two aliquots: one acidified with  
284 bidistilled 13.5 N  $\text{HNO}_3$  to  $\text{pH} \approx 1$  for trace element and isotopic analyses; another  
285 one, not acidified, for measurement of pH, conductivity, and for analysis of major  
286 element and dissolved organic carbon (DOC) concentrations following the standard  
287 procedures used in the laboratory (e.g., Lucas et al., 2010; Schaffhauser et al., 2014;  
288 Gangloff et al., 2014) and detailed in Prunier et al. (2015). Trace element  
289 concentrations were determined by ICP-MS with an uncertainty better than 10%.  
290 The precision and accuracy of the results were checked by regular analyses of the  
291 SLRS-4 riverine standard. For Sr isotopic analyses and U-Th-Ra disequilibria  
292 determination, between 10 and 2000 ml of water samples were used to reach 5 to  
293 20 ng of U, 300 to 400 ng of Th, 100 ng of Sr and 2 to 40 fg of Ra, which are  
294 necessary for precise isotope determinations. Samples poor in U and Th were  
295 preconcentrated by coprecipitation with Fe hydroxide (Chabaux et al., 1995; 1997)  
296 or by total evaporation if the DOC concentration was too high. Blanks ranged

297 between 12 and 55 pg for U, 150 pg for Th, < 0.07 fg for Ra and < 1 ng for Sr. These  
298 quantities are negligible compared to those in the samples.

299

## 300 **4. RESULTS**

301 Major and trace element concentrations and the U and Sr isotope ratios were  
302 presented and discussed in Prunier et al. (2015). Therefore, the present work  
303 focuses on the U-Th-Ra isotope data, which, combined with Sr isotope ratios and  
304 major and trace element concentrations, allow for emphasizing the potential of  
305 using U-Th-Ra systematics in soils, soil solutions and trees to better constrain the  
306 sources and pathways of element transfers involved in the biogeochemical cycles in  
307 forest ecosystems. The main data used and discussed in this study are given in Table  
308 1a-d. The complete dataset of the major and trace element concentrations, including  
309 REE concentrations, is provided in Supplementary Material Tables EA1-2-3.

310

### 311 **4.1. Mineralogy**

312 In line with previous works on the soils in the Strengbach catchment (Ficher et al.,  
313 1998a, 1998b; Aubert et al., 2001; Stille et al., 2009), Prunier et al. (2015) showed  
314 that the main minerals of bulk soil samples are quartz, feldspars (orthoclase and  
315 albite), muscovite and clay minerals. Biotite and traces of apatite were observed in  
316 both soil profiles, while hematite (< a few %) was detected by XRD in only the  
317 spruce soil profile. The 2 µm grain size fractions of the samples from the spruce and  
318 beech profiles were composed of kaolinite and illite, with interstratified illite-  
319 vermiculite and/or illite-smectite and traces of goethite, which were more abundant  
320 in the spruce samples than in the beech samples. The minor minerals detected by  
321 SEM were zircons, monazites and apatites.

322 The new SEM observations of the grain size fractions in the present study  
323 emphasized that some zircons have blunted or fractured surfaces, which could be  
324 evidence of weak surface weathering of zircons (Fig. EA1a). In addition, some Ba  
325 and Sr sulfates were observed in the 2-50 µm and 50-100 µm fractions of the VP 90-  
326 100 horizon (Fig. EA1b). SEM observations have also shown that the “so-called” <2  
327 µm fraction of the HP90-100 horizon, used in Prunier et al. (2015), clearly  
328 encompasses much larger particles than expected, most likely due to separation  
329 problems. This fraction was therefore not considered in the present study.

330

331 **4-2: U and Th concentrations in grain size fractions**

332 As recognized by Prunier et al. (2015), the comparison of U concentrations with  
333 major and trace elements in the different grain size fractions showed that the U  
334 budget in these soils is strongly controlled by secondary minerals and minor  
335 primary minerals such as phosphates. A more thorough comparison of the  
336 variations in U and Th concentrations with major and trace element concentrations  
337 in the different soil samples and grain size fractions allows for a better constraint of  
338 the nature of the minor mineral phases controlling the U and Th budget in these  
339 soils and their varied influences in the two plots and the different fractions. The  
340 covariations between the U-Th concentrations and Zr concentrations (Fig. 2)  
341 confirm that the U and Th budgets in the 2-50  $\mu\text{m}$  and 50-100  $\mu\text{m}$  grain size  
342 fractions are at least partly controlled by zircons. In the beech (HP) plot samples, the  
343 correlations between U, Th and  $\text{Fe}_2\text{O}_3$  and  $\text{P}_2\text{O}_5$  concentrations for the coarse grain  
344 size fractions (Fig. 2) indicate that U and Th in the HP soils are also tightly  
345 associated with phosphate and Fe-bearing phases. However, in the spruce (VP) plot  
346 samples, U and Th concentrations were better correlated with Zr than with P  
347 concentrations, suggesting that zircon is likely one of the main carriers of U and Th  
348 in spruce plots but not in beech plots. The comparison of the Ba concentration with  
349 the U and Th concentrations in the grain size fractions extracted from the different  
350 soil horizons (Fig. EA2) indicates that some Ba-rich mineral phases also control the  
351 U and Th budgets in the spruce soil horizons, especially in the 2-50  $\mu\text{m}$  and 50-100  
352  $\mu\text{m}$  grain size fractions, while this control is much less present in the beech soil  
353 horizons. Sulfate minerals, observed by SEM, and Ba-rich K-feldspars also observed  
354 in Strengbach granitic rocks are among the possible Ba-carrying minerals, as well as  
355 Mn oxyhydroxides (Palumbo et al., 2001, Vaniman et al., 2002, Ghaleb et al., 2004).  
356 The VP spruce soil horizons had higher Ba levels than the HP soil horizons, implying  
357 that the abundance of these Ba-rich minerals was low in the HP sites. This difference  
358 can be related to the weak hydrothermal overprint of the bedrock from the southern  
359 slope where the beech plot stands, which is thus likely less marked by hydrothermal  
360 mineralizations that contain barites and oxyhydroxide minerals.

361 Together, these data emphasize the importance of secondary minerals as well as  
362 minor primary minerals (zircon, sulfates and phosphates minerals) in the U and Th  
363 budget in the soil of the two experimental plots in the Strengbach catchment.

364

#### 365 **4.3. Th isotopic ratios and U-Th-Ra disequilibrium in grain size fractions**

366 The present data show important variations between the ( $^{230}\text{Th}/^{232}\text{Th}$ ) ratios and  
367 U/Th chemical ratios in the different grain size fractions and between the different  
368 plots (Table 1a) with systematically lower values in the spruce (VP) than in the  
369 beech (HP) plots. The <2  $\mu\text{m}$  fraction of the HP (30-40 cm) soil horizon shows the  
370 highest ( $^{230}\text{Th}/^{232}\text{Th}$ ) ratio [ $(^{230}\text{Th}/^{232}\text{Th}) = 4$ ] of all the grain size fractions analyzed  
371 in this study, with a value close to that of apatite ( $\approx 5$  from U/Th ratios given in  
372 Aubert et al., 2004; 2001) (Fig. 3). The 2-50  $\mu\text{m}$  and 50-100  $\mu\text{m}$  grain size fractions  
373 from the spruce site exhibit the lowest ( $^{230}\text{Th}/^{232}\text{Th}$ ) ratio (0.71-0.75). The  
374 correlation between ( $^{230}\text{Th}/^{232}\text{Th}$ ) and ( $^{238}\text{U}/^{232}\text{Th}$ ) ratios and Zr concentrations  
375 observed for the VP grain size fractions (Fig. 4), as well as with Ba concentrations  
376 (Fig. 5), highlights the low U/Th and Th activity ratios of the zircons and the Ba-  
377 bearing minerals, which are much lower than the Th activity ratios of the other  
378 primary granite minerals (apatite, biotite, muscovite and albite) as estimated from  
379 the U/Th ratio given in Aubert et al. (2001; 2004). For the HP plot, all the grain size  
380 fractions, except the two 1.6-2 mm fractions, show a very good covariation between  
381 ( $^{230}\text{Th}/^{232}\text{Th}$ ) and  $\text{P}_2\text{O}_5$  contents ( $R=0.972$ ) (Fig. 6).

382 The  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$ - $^{226}\text{Ra}$  data (Tab. 1a) show that all grain size fractions are  
383 marked by systematic  $^{238}\text{U}$ - $^{230}\text{Th}$  disequilibrium with ( $^{238}\text{U}/^{230}\text{Th}$ ) <1. The  
384 comparison of the  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$ - $^{226}\text{Ra}$  disequilibria in the different grain size  
385 fractions indicates the higher ( $^{234}\text{U}/^{238}\text{U}$ ) and ( $^{230}\text{Th}/^{234}\text{U}$ ) ratios in the beech plot  
386 grain size fractions than in the spruce plot as well as the higher ratios for a given  
387 plot in the < 2  $\mu\text{m}$  fractions than in the other fractions (Fig. 7a,b). This systematic  
388 disequilibrium is, however, not observed for the  $^{226}\text{Ra}$ - $^{230}\text{Th}$  disequilibria. With the  
389 exception of the two <2  $\mu\text{m}$  fractions from the VP plot, which are marked by  
390 relatively high ( $^{226}\text{Ra}/^{230}\text{Th}$ ) ratios (1.42, 1.6), all other grain size fractions show  
391 rather similar ( $^{226}\text{Ra}/^{230}\text{Th}$ ) ratios scattering between 0.88 and 1.13 (Fig. 7b) that  
392 are unrelated to the size of the fractions or the depth of the analyzed horizons. At  
393 the scale of the spruce plot, however, the ( $^{226}\text{Ra}/^{230}\text{Th}$ ) and ( $^{230}\text{Th}/^{234}\text{U}$ ) ratios

394 decrease in the following order: <2  $\mu\text{m}$  fraction, 2-50  $\mu\text{m}$  fraction and other  
395 fractions. For the beech plots, such a systematic disequilibrium is not apparent for  
396 the ( $^{226}\text{Ra}/^{230}\text{Th}$ ) ratio, but it is still observed for the ( $^{230}\text{Th}/^{234}\text{U}$ ) ratio.

397

#### 398 **4.4. U-Th-Ra and Ba in soil solutions**

399 As for the grain size fractions, and as already noted in Prunier et al. (2015), the soil  
400 solution data point to significant geochemical differences between the soil solutions  
401 collected at the two experimental plots in both major and trace element  
402 concentrations. The soil solutions from the VP spruce plot have higher TDS and  
403 conductivities and lower pH values than those from the HP beech plot. The soil  
404 solutions from the VP spruce plot are also 5 to 10 times richer in Mg, K and Ca than  
405 those from the HP plot (data in supplementary materials Tab EA3). Our data show  
406 that such differences are also seen in the U-Th-Ra systematics and that Ba has a  
407 distinct compartment compared to Sr and Ca elements.

408

409 - Alkaline-earth elements

410 The trace element concentrations of the soil solutions show higher alkaline-earth  
411 (Sr, Ba) concentrations under spruces than under beeches (Fig. EA3). Within a plot,  
412 the Ca and Sr concentrations are higher in the surface soil solutions than in the deep  
413 layers, which is certainly related to root absorption of these elements by the trees,  
414 as evidenced by Ca isotopes (Cenki-Tock et al., 2009; Schmitt et al., 2017).  
415 Compared to Sr and Ca, Ba shows different behavior in the spruce plot (Fig. EA3),  
416 where the highest Ba concentrations are observed for soil solutions from 30 cm  
417 depth, with a negative correlation with the sulfate contents (Fig. EA3). A negative  
418 correlation is also observed for the -60 cm soil solution data but with a different  
419 slope (Fig. EA3). The observation that positive, linear correlations passing through  
420 the origin can be defined between the Ba and  $1/\text{SO}_4$  concentrations for these two  
421 soil solutions (Fig. EA3) likely indicates  $\text{BaSO}_4$  saturation, meaning that the Ba and  
422  $\text{SO}_4$  concentrations at depths of 30 cm and 60 cm are controlled by the precipitation  
423 of  $\text{BaSO}_4$ . The SEM observation of Ba sulfate precipitates in soil solutions collected at  
424 depths of 30 cm and 60 cm supports this interpretation (Fig. EA1c). The atypical Ba  
425 concentrations of the 30 cm soil solutions are clearly evidenced in a Ba vs Mg  
426 concentration diagram, which indicates a specific source of Ba at this depth, but not



427 at 60 cm. The positive trend between the K and Ba concentrations in 30 cm soil  
428 solutions likely suggests that the Ba input in these soil solutions results from the  
429 dissolution of Ba-rich K-feldspars, at a sufficiently high level to cause a BaSO<sub>4</sub>  
430 precipitation. For the 60 cm soil solutions, the correlation between Mn and Ba (Fig.  
431 EA3) suggests the dissolution of other minerals, such as Mn oxides and likely  
432 sulfates, which are often associated with Mn oxides in hydrothermal veins  
433 intersecting granitic rocks. The dissolution of sulfate minerals can thus control the  
434 BaSO<sub>4</sub> saturation of the 60 cm soil solutions. Such a dissolution at 60cm depth and  
435 not a 30cm depth can also account for the observation of a correlation between the  
436 Sr and 1/SO<sub>4</sub><sup>2-</sup> concentrations in only the 60 cm depth soil solutions (Fig. EA<sub>3</sub>),  
437 suggesting that the supply of sulfate is sufficient to also cause the saturation of  
438 SrSO<sub>4</sub> in these waters or also of (SrBa)SO<sub>4</sub>. Furthermore, dissolution of SO<sub>4</sub><sup>2-</sup> bearing  
439 mineral phases at 60 cm depth readily explains why the soil solutions from 60 cm  
440 depth at the spruce plot are the only water reservoir in the Strengbach catchment  
441 whose SO<sub>4</sub><sup>2-</sup> concentrations did not decrease from 1990-2010 (Fig. EA<sub>4</sub> and Ackerer  
442 et al., 2018).

443

444 - Th activity ratios and U-Th-Ra systematics

445 The (<sup>230</sup>Th/<sup>232</sup>Th) ratios of the (HP) beech plot soil solutions are significantly higher  
446 than those of the (VP) spruce plot and those of most of the corresponding grain size  
447 fractions (Fig. 3). Only the <2 μm grain size fraction of the HP (30-40 cm) soil layer  
448 and apatite had higher (<sup>230</sup>Th/<sup>232</sup>Th) ratios. Compared to the grain size fractions and  
449 the granite-derived primary minerals, the soil solutions of the beech plot exhibit  
450 relatively high Th isotope ratios, namely, (<sup>230</sup>Th/<sup>232</sup>Th) of 4 and 3.7 for the HP-10 cm  
451 and HP-70 cm soil solutions, respectively. These ratios are close to the (<sup>230</sup>Th/<sup>232</sup>Th)  
452 of the <2 μm fraction but with different U/Th ratios depending on their depth of  
453 collection. In the (<sup>230</sup>Th/<sup>232</sup>Th) vs. (<sup>238</sup>U/<sup>232</sup>Th) diagram (the so-called isochron  
454 diagram), the surface solution (-10 cm) plot is relatively close to the <2 μm grain  
455 size fraction, while the deep solution plot is much closer to the equiline (1:1 line in  
456 the isochron diagram) (Fig. 3). In the spruce plot, the Th activity ratios were  
457 analyzed in the soil solutions from the depths of only -5 cm and -10 cm due to the  
458 very low Th concentrations in the deeper soil solutions. As apparent in Fig. 3, these  
459 soil solutions have very similar (<sup>230</sup>Th/<sup>232</sup>Th) (1.6) but relatively scattered

460 ( $^{238}\text{U}/^{232}\text{Th}$ ) ratios (0.7-1.04). The Th activity ratios in these solutions are higher  
461 than those analyzed in the corresponding grain size fractions.

462 Based on the available ( $^{226}\text{Ra}/^{230}\text{Th}$ ) ratios in both the beech and spruce plots, the  
463 soil solutions have higher ( $^{226}\text{Ra}/^{230}\text{Th}$ ) ratios than the corresponding soil fractions  
464 (Table 1a-b). Furthermore, in the ( $^{226}\text{Ra}/^{238}\text{U}$ ) vs ( $^{234}\text{U}/^{238}\text{U}$ ) diagram (Fig. 8a), the  
465 (VP) spruce plot soil solutions from depths of 10 cm, 30 cm and 60 cm define a  
466 positive correlation with the lowest ( $^{226}\text{Ra}/^{238}\text{U}$ ) ratios in the 30 cm soil solutions.  
467 Moreover, the <2  $\mu\text{m}$  and 2-50  $\mu\text{m}$  grain size fractions from the VP 30-40 cm soil  
468 horizon are aligned together with the soil solution collected from a depth of 30 cm  
469 (Fig. 8b).

470

#### 471 **4.5. Geochemical and isotopic characteristics of the vegetation samples.**

472 The geochemical and isotopic data of the vegetation samples are given in Table 1c.  
473 These data show concentration variations, which vary from one tree to another and  
474 within a tree between its different compartments. Uranium and Th concentrations  
475 are higher in the roots than in the aerial parts of trees, which is not the case for Ba  
476 and  $^{226}\text{Ra}$ . This may indicate a possible fixation of U and Th on roots without real  
477 transport within the aerial parts of trees at the difference of Ba and Ra. Compared to  
478 soil solutions, soil samples and grain size fractions, trees are enriched in Ca, Sr, Rb  
479 and K, as well as in Ba (Table 1). The data also point to high variability in the relative  
480 concentrations of these elements between the different parts of the trees, even for  
481 the elements from the same chemical family, such as the alkaline-earth Ca, Sr, Ba.  
482 The Ca/Sr and Ba/Sr ratios vary by a factor of 5 or more in the beech trees and by a  
483 factor of 10 in spruce. Compared to U and Th, Ra is also highly enriched in the trees,  
484 with ( $^{226}\text{Ra}/^{230}\text{Th}$ ) ratios as high as 5 and ( $^{226}\text{Ra}/^{238}\text{U}$ ) ratios ranging from 1.12 up  
485 to 79 in spruce. In beech, ( $^{226}\text{Ra}/^{238}\text{U}$ ) ratios range from 21.5 to 1413, and  
486 ( $^{226}\text{Ra}/^{230}\text{Th}$ ) ratios range from 19.8 to 164.4.

487 The vegetation samples show  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope ratios similar to those of the  
488 corresponding soil solutions (Fig. 9). As noted in Prunier et al. (2015), the  
489 ( $^{234}\text{U}/^{238}\text{U}$ ) ratios of the beech samples are similar to those of the corresponding soil  
490 solutions and soil samples, while they are systematically higher in the vegetation  
491 samples from the spruce plot, with ( $^{234}\text{U}/^{238}\text{U}$ ) ratios  $\geq 1$  in spruce samples for  
492 ( $^{234}\text{U}/^{238}\text{U}$ ) ratios  $\leq 1$  in the soil solution samples (Fig. 10, and Prunier et al., 2015).

493 The beech and spruce samples have ( $^{238}\text{U}/^{230}\text{Th}$ ) ratios close to equilibrium  
494 [ $(^{230}\text{Th}/^{238}\text{U})\approx 1$ ] and hence plot along the equiline in the isochron diagram, with  
495 ( $^{230}\text{Th}/^{232}\text{Th}$ ) ratios ranging between 1 and 1.4 for beech and close to 1 for spruce,  
496 which is very different from those of the corresponding soil solutions (Fig. 3).

497

## 498 **5. DISCUSSION**

499

### 500 ***5-1 U-Th-Ra fractionation by vegetation***

501 The comparison of the vegetation chemical data with the soil and soil solution data  
502 points to an important enrichment of Ba and  $^{226}\text{Ra}$  relative to U and Th in trees,  
503 which suggests that trees can have a much greater impact on the Ra (Ba) budget  
504 than the U and Th budgets in forest ecosystems. This impact is made clear when the  
505 uptake of U, Th, Ba, Ra by tree roots and their respective recycling through litter  
506 degradation are compared with their drainage by soil solutions (Tab. 2a,b). The  
507 uptake fluxes can be estimated using the Ca uptake fluxes given in Poszwa et al.  
508 (2000) for the Strengbach beeches and spruces and the U/Ca, Th/Ca, Ba/Ca and  
509  $^{226}\text{Ra}/\text{Ca}$  ratios measured in the present study in the different tree organs (Tab.2a).  
510 These chemical ratios can vary within a tree, such as Ca/Sr ratios (e.g., Poszwa et al.  
511 2000; 2003; Wiegand et al., 2005; Blum et al., 2008; Drouet et Herbauts 2008),  
512 leading to a relatively large uncertainty in the calculated uptake fluxes. However, the  
513 data clearly indicate that the U and Th uptake fluxes are low compared to the  
514 drainage by soil solutions (Tab. 2b), while they are comparable for Ba and Ra.  
515 Similarly, the comparison of the maximum calculated U and Th fluxes coming from  
516 litter degradation with those drained by the soil solutions demonstrates the very  
517 low contribution of litter degradation on the U and Th budgets of soil solutions,  
518 which is not the case for Ba and Ra (Tab. 2b). These results demonstrate that Ra and  
519 Ba are highly cycled by vegetation, which is the opposite for U and Th, and that root  
520 uptake and litter degradation can be important actors in Ra-Th and Ra-U  
521 fractionation in soils and soil solutions (see also Rihs et al., 2011). This result is  
522 clearly illustrated by the U-Th-Ra disequilibria variations in the soil solutions of the  
523 beech plot at 10 cm depth (Fig. 11). The distribution of the data points in the  
524 ( $^{230}\text{Th}/^{234}\text{U}$ ) vs ( $^{226}\text{Ra}/^{230}\text{Th}$ ) diagram indicates a more important Ra contribution  
525 from litter decay to the soil solution in March 2005 than in May 2006, which mainly

526 impacts the ( $^{226}\text{Ra}/^{230}\text{Th}$ ) ratios of the soil solutions and has much less of an impact  
527 on the ( $^{230}\text{Th}/^{234}\text{U}$ ) ratios. The data also show that this type of vegetation impact is  
528 visible at 10 cm depth but is not visible at 70 cm depth, which indicates that tree-  
529 related fractionation is confined to superficial soil and soil solutions. The  $^{238}\text{U}$ -Ba-  
530  $^{226}\text{Ra}$  data of soil solutions under spruces supports this conclusion. For the spruce  
531 plot, the soil solution data collected at 10, 30 and 60 cm and the data from the  $<2\ \mu\text{m}$   
532 and  $2\text{-}50\ \mu\text{m}$  grain size fractions of the 30-40 cm soil horizon define two linear  
533 trends that converge towards the values of the 30 cm soil solutions in the  
534 ( $^{238}\text{U}/^{226}\text{Ra}$ ) vs ( $^{234}\text{U}/^{238}\text{U}$ ) diagram (Fig. 7a). The latter soil solutions have the  
535 lowest ( $^{234}\text{U}/^{238}\text{U}$ ) and ( $^{226}\text{Ra}/^{238}\text{U}$ ) ratios measured at the site ( $<1$ ), which cannot  
536 be explained by the contributions of U and Ra fluxes from vegetation recycling, as all  
537 vegetation samples are marked by ( $^{226}\text{Ra}/^{238}\text{U}$ )  $\gg 1$ . Based on the  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{226}\text{Ra}$ -Ba  
538 systematics, it is also difficult to invoke a variable vegetation contribution from one  
539 soil solution sample to another to explain the ( $^{226}\text{Ra}/^{238}\text{U}$ ) and ( $^{234}\text{U}/^{238}\text{U}$ )  
540 differences among the soil solutions from depths of 30 cm and 60 cm. If this would  
541 have been the case, a correlation between the Ba/U and ( $^{226}\text{Ra}/^{238}\text{U}$ ) ratios of these  
542 soil solutions should have been observed, which is not the case (Fig. 7b). Thus, the  
543 geochemical end-member with ( $^{234}\text{U}/^{238}\text{U}$ ) and ( $^{226}\text{Ra}/^{238}\text{U}$ ) ratios  $<1$  likely  
544 represents a weathering end-member resulting from the destabilization of  
545 secondary minerals contained in the finest grain size fractions of the 30-40 cm soil  
546 horizon. The covariations observed in the ( $^{226}\text{Ra}/^{238}\text{U}$ ) vs ( $^{234}\text{U}/^{238}\text{U}$ ) and  
547 ( $^{226}\text{Ra}/^{238}\text{U}$ ) vs Ba/U diagrams between the 30 and 60 cm soil solutions (Fig. 7a, b)  
548 likely reflect the control by different mineral fractions in each of these soil solutions.  
549 For the 30 cm soil solution, a high contribution of a mineral fraction with high Ba/U  
550 ratios but depleted in  $^{234}\text{U}$  and  $^{226}\text{Ra}$  relative to  $^{238}\text{U}$  was observed. This mineral  
551 fraction likely explains the low ( $^{234}\text{U}/^{238}\text{U}$ ) and ( $^{226}\text{Ra}/^{238}\text{U}$ ) ratios of the  $2\text{-}50\ \mu\text{m}$   
552 fractions of the 30-40 cm soil horizon. The  $2\text{-}50\ \mu\text{m}$  fractions of the 30-40 cm soil  
553 horizon are the most Ba enriched. Thus, mobilization of weathering products of Ba-  
554 rich phases, such as Ba-rich K-feldspar evidenced in § 4-4, likely controls the U-Ba-  
555 Ra characteristics of the 30 cm deep soil solutions. For the 60 cm deep soil solutions,  
556 other minerals or less contribution of these Ba-rich minerals must be invoked to  
557 explain their U-Ra-Ba characteristics, which is consistent with the proposition for

558 these soil solutions of a specific weathering flux from oxides and sulfate minerals  
559 (see section 4-4).

560

561 However, regardless of the precise origin of weathering fluxes explaining the U, Ba,  
562 Ra systematics within the deep soil solutions of the spruce plots, the results clearly  
563 show that the impact of vegetation on U-(Th)-Ba and -Ra fractionations is visible  
564 mainly in the surface soil horizons and soil solutions and much less in the deeper  
565 ones. This conclusion is consistent with the demonstration that the ( $^{226}\text{Ra}/^{230}\text{Th}$ )  
566 ratios in the shallowest soil layers can be affected by vegetation changes/types over  
567 short timescales (Rihs et al., 2016). Moreover, this conclusion supports the  
568 assumption of Ackerer et al. (2016) and the suggestions of Gontier et al. (2015) and  
569 Rihs et al. (2016) that the deeper part of the weathering profiles below the zone of  
570 vegetation influence is certainly the most adapted zone to apply the U-series  
571 nuclides methodology classically developed for recovering regolith production rates  
572 (e.g., Dequincey et al., 2002; Dosseto et al., 2008; Chabaux et al., 2013). The highly  
573 contrasted behaviors of Ra and U-Th regarding vegetation cycling also has  
574 implications for the interest in these elements and their isotopic ratios for tracing  
575 biogeochemical cycles and water-rock interactions in forest ecosystems. Thus, being  
576 highly absorbed by trees, Ra and its isotopic ratio ( $^{228}\text{Ra}/^{226}\text{Ra}$ ) should become a  
577 useful tracer of the impacts of vegetation on the geochemical cycles in the  
578 biosphere. Moreover, the very different half-lives of  $^{228}\text{Ra}$  (5.75 a) and  $^{226}\text{Ra}$  (1600  
579 a) should make Ra also a potential chronometer of the litter degradation rate, in  
580 addition to being relevant for constraining the chemical element residence time in  
581 the vegetation (e.g., Baeza et al., 1999). The second important implication of the  
582 results is linked to the small impact of vegetation cycling on the U and Th budgets in  
583 soils and soil solutions. These elements are therefore mostly controlled by water-  
584 rock interactions. This finding is certainly the main difference between these  
585 isotopic ratios and  $^{87}\text{Sr}/^{86}\text{Sr}$  or  $^{143}\text{Nd}/^{144}\text{Nd}$ , as Sr and Nd are two significantly  
586 biocycled chemical elements (e.g., Stille et al., 2006; 2009). The Sr and Nd isotopic  
587 ratios in soils and soil solutions thus represent an integration of lithogenic fluxes  
588 directly derived from water-rock interactions with recycled and hence “delayed”  
589 fluxes due to Sr and Nd vegetation cycling. Uranium and thorium are probably  
590 among the few geochemical elements to be controlled by only direct water-rock

591 interactions and therefore to be specific tracers of these interactions. The  
592 combination of this property with (a) the large range of the variations in the  
593 ( $^{230}\text{Th}/^{232}\text{Th}$ ) ratios in the soil minerals, especially in secondary and minor minerals  
594 (this study; Bosia et al., 2016; 2018) and (b) the low contributions of rainwater and  
595 atmospheric deposits on U and Th soil and soil solution budgets on granitic lithology  
596 (e.g., Chabaux et al., 2005; 2013) indicates that the Th activity ratio has the potential  
597 to become a powerful tracer of the sources of the chemical fluxes in the soils, soil  
598 solutions and vegetation. Such an interest is illustrated in the following two sections.  
599

### 600 **5-2 U-Th tracing weathering fluxes in soil solutions**

601 Previous studies have shown that Sr and Nd isotopes in soil solutions and streamlets  
602 in the Strengbach watershed principally result from apatite and feldspar dissolution  
603 (Aubert et al., 2001, Stille et al., 2006, 2009). The proximity of the soil solution HP-  
604 70 (beech plot) to the ( $^{230}\text{Th}/^{232}\text{Th}$ - $^{238}\text{U}/^{232}\text{Th}$ ) equiline between the apatite and the  
605 feldspars data points (Fig. 3) is consistent with this interpretation. The soil solution  
606 HP-10, however, clearly suggests a contribution of a third flux in addition to the two  
607 previous fluxes with a U-Th signature close to that of the  $<2\ \mu\text{m}$  grain size fraction,  
608 which is also true when looking at the data in the ( $^{230}\text{Th}/^{232}\text{Th}$ ) vs  $^{87}\text{Sr}/^{86}\text{Sr}$  diagram  
609 (Fig. 12).

610 The covariation between ( $^{230}\text{Th}/^{232}\text{Th}$ ) and  $\text{P}_2\text{O}_5$  contents in the grain size fractions  
611 of the beech plot samples (Fig. 6) implies that Th isotopes are essentially controlled  
612 by the presence of phosphate minerals with high Th activity ratios. Therefore, the  
613 high Th activity ratios of the  $<2\ \mu\text{m}$  fraction are imposed by phosphate minerals,  
614 which in turn are those that controlled the U-Th-Sr weathering fluxes from the  $<2$   
615  $\mu\text{m}$  fractions. As in the grain size fractions of the beech plot, the  $\text{P}_2\text{O}_5$  contents do  
616 not correlate with the corresponding Ca contents (not shown), it is not apatite but  
617 probably other phosphate-rich, apatite replacement phases that control the  
618 covariation between  $\text{P}_2\text{O}_5$  contents and the ( $^{230}\text{Th}/^{232}\text{Th}$ ) ratios in such a system.  
619 Furthermore, as the ( $^{238}\text{U}/^{232}\text{Th}$ ) ratio of the  $<2\ \mu\text{m}$  grain size fraction from the HP  
620 plot ( $<1.48$ ) is significantly lower than that of apatite (5.07) and has relatively low  
621 Sr concentrations relative to Fe, the formation of such secondary minerals from the  
622 dissolution of apatite during weathering caused mobilization of not only Ca (Stille et  
623 al., 2009) but also apparently apatite-derived-U and Sr (Fig. EA2). Such a difference

624 in the mobilization of U-Th-Sr during the weathering of apatite and formation of  
625 secondary phosphate phases readily explains why the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio (0.85) of the  
626  $<2\ \mu\text{m}$  grain size fraction from the HP plot (30-40 cm) is significantly higher than  
627 that of primary apatite (0.716), while the  $(^{230}\text{Th}/^{232}\text{Th})$  ratio of this fraction (4.085)  
628 remains close to that of apatite (5).

629 Altogether, these data indicate that in the beech plot, the dissolution of secondary  
630 phosphates in the  $<2\ \mu\text{m}$  fraction controls an important part of the U-Th-Sr chemical  
631 budget of the surface soil solutions. These secondary minerals and their U-Th-Sr  
632 isotopic signatures must therefore be inherited from a weathering process anterior  
633 to the process controlling the present-day U-Th-Sr isotopic signature of the surface  
634 soil solutions. Based on these data, a two-step weathering scenario can thus be  
635 proposed for the beech plot: (a) predominant dissolution of primary minerals in the  
636 deep soil horizons and the formation of secondary minerals partially maintain the  
637 isotopic signature of the weathered primary minerals; (b) dissolution of these  
638 secondary minerals, in particular those contained in the finest grain size fractions, in  
639 the surface soil horizons. Schmitt et al. (2017) showed that the Sr isotope ratios of  
640 the soil solutions increased from 2006 to 2011 in the beech plot at 10 cm depth but  
641 not at 70 cm depth, which indicates that the contribution of the secondary minerals  
642 to the chemical budget of the surface soil solution increased over this period and  
643 hence could be a relatively recent process. This result is consistent with the results  
644 of Rihs et al. (2011), who concluded based on short half-lived radionuclides of the  
645  $^{232}\text{Th}$ -series that the surface soils under the beech plot have been affected by recent  
646 ( $<30\text{a}$ ) weathering processes.

647 For the spruce (VP) plot, the scattering of the 5 cm and 10 cm deep soil solution data  
648 in the isochron diagram (Fig. 3), i.e., similar  $(^{230}\text{Th}/^{232}\text{Th})$  ratios but variable  
649  $(^{238}\text{U}/^{232}\text{Th})$  ratios, cannot be explained by the varying tree contributions to the U-  
650 Th budget of the different soil solutions, as tree samples are marked by  
651  $(^{230}\text{Th}/^{232}\text{Th})$  ratios lower than those measured in the surface soil solutions. For this  
652 reason, and in line with the low contribution of tree cycling to the U and Th budget,  
653 it is proposed that the U-Th budget of the spruce surface soil solutions (VP plot) is  
654 controlled, as occurs in the beech plot, by a mixture of U-Th coming from the  
655 dissolution of secondary minerals with  $(^{230}\text{Th}/^{238}\text{U}) < 1$  and high  $(^{230}\text{Th}/^{232}\text{Th})$  ratios  
656 and more “equilibrated” U-Th coming from the dissolution of primary minerals.

657 However, unlike the beech plot, none of the analyzed grain size fractions in the  
658 spruce plot show U-Th signatures similar to that of the surface soil solutions. In  
659 particular, all of the grain size fractions have much lower ( $^{230}\text{Th}/^{232}\text{Th}$ ) ratios than  
660 those in the solutions, which can be explained in two ways. First, the U-Th signature  
661 of the 30-40 cm grain size fractions are not representative of the 10 and 5 cm deep  
662 fractions because of the local lithological heterogeneities (cf section 4-4). Second,  
663 the weathering processes in the spruce plot were initially similar to those in the HP  
664 plot, but this plot is now in a much more advanced weathering stage. Thus, it can  
665 now be proposed that a large part of the minerals carrying the apatite signature has  
666 been leached much more intensively under spruce than under beech, causing an  
667 important loss of these minerals and hence a significant decrease in the  
668 ( $^{230}\text{Th}/^{232}\text{Th}$ ) ratios of the grain size fractions. This scenario, which is favored by the  
669 more acidic conditions under the spruce plot, is also supported by the observation  
670 of an earlier increase in the Sr isotopic ratios in the soil solutions of the VP spruce  
671 plot than that in the HP beech plot: between 1997 and 2006 for the spruce plot  
672 (Prunier et al., 2015) and between 2006 and 2011 for the beech plot (Schmitt et al.,  
673 2017) (Fig. 9).

674 Thus, based on these results, the weathering scenario retained for the spruce plot  
675 (VP) is similar to that invoked for the beech plot (HP) but with a slightly different  
676 mineralogical composition and a much more advanced degree of alteration of the  
677 fine grain size fractions of the VP surface soil horizons. This scenario, which is also  
678 consistent with the B isotope data in the Strengbach catchment (Lemarchand et al.  
679 2012), not only accounts for the earlier modification of the Sr isotope ratios in the  
680 soil solutions of the spruce plot but also explains why the  $<2\ \mu\text{m}$  and  $2\text{-}50\ \mu\text{m}$   
681 fractions are more depleted in Sr, Ca, U, Th and REE (Fig. EA2) for equivalent Fe  
682 contents in the spruce (VP) than in the beech (HP) plot. This scenario is also  
683 consistent with the weathering indexes calculated in Prunier (2008) following the  
684 approaches proposed in Kronberg and Nesbeitt (1981). Such a difference between  
685 the degree and timing of the destabilization of the beech and spruce plots is likely  
686 the consequence of a larger chemical export by soil solutions under the spruce than  
687 the beech plot. Climatic differences exist between the two slopes (e.g., Viville et al.,  
688 1993; 2012), with longer and more intense sunshine duration on the VP south-  
689 facing slope, which may explain part of this difference. But, this difference is also



690 certainly related to the difference in the pH of the soil solutions under these two  
691 plots, which is clearly linked to the differences in vegetation cover. The more acidic  
692 soil solutions under spruces allowed for stronger leaching of the soils in the spruce  
693 (VP) plot than allowed by the less acidic soils in the beech (HP) plot. The fast-  
694 growing spruces found in the VP plot were planted for forest exploitation. These  
695 trees generally induce both a strong acidification of soils and soil solutions via the  
696 decomposition of the needles and a high nutrient export flux that is much greater  
697 than that induced by trees naturally growing on the site (fir - beech) (e.g., Binkley  
698 and Valentine, 1991; Alriksson and Eriksson, 1998; Augusto et al., 2015; Berger et  
699 al., 2009; Cremer and Prietzel, 2017). The cause of soil depletion and irreversible  
700 modification of the tree nutrient carrier phases by vegetation have not been  
701 sufficiently considered until now. The vegetation could play an important role and  
702 may be equivalent or even more important than the effects of acid rain. For the  
703 Strengbach catchment, we propose that the artificial change in vegetation explains  
704 much of the differences in soil destabilization states between the beech and spruce  
705 plots.

706

### 707 **5-3 U-Th, tracing the source of elements in the water-tree system.**

708 The Sr-U-Th isotopic characteristics of soil solutions and trees are different. Soil  
709 solutions have Sr isotopic ratios that are relatively close to those of trees, which is  
710 consistent with the biorecycled behavior of Sr. Nevertheless, Sr isotopic ratios in  
711 trees are systematically slightly less radiogenic than those in soil solutions (Fig. 9).  
712 The difference between soil solutions and trees is more marked in the spruce plot  
713 than in the beech plot and increases with time (Fig. 9). As discussed in the previous  
714 section (§ 5.2), this difference might be related to the higher or lower degree of  
715 modifications of the water-rock-vegetation system in these two plots, as the  
716 alteration processes have been more intensively modified in the spruce (VP) plot  
717 than in the beech (HP) plot. This difference may also point to the occurrence of Sr  
718 fluxes in soil solutions, which are different from those taken up by the tree and,  
719 therefore, different from those recycled by vegetation. The observations that the U  
720 activity ratios are higher in trees than in soil solutions in the spruce (VP) plot and  
721 that the Th ratios are systematically different between trees and soil solutions in  
722 both plots support such an interpretation (Fig. 13). The beech plot soil solutions are

723 entirely consistent with the three-end-member mixing model proposed in the  
724 previous sections, between (1) the  $<2 \mu\text{m}$  grain size fractions marked by a high  
725  $(^{230}\text{Th}/^{232}\text{Th})$  ratio and a strong  $^{234}\text{U}$ - $^{238}\text{U}$  disequilibrium, (2) an apatite end-  
726 member with a high Th activity ratio and  $^{238}\text{U}$ - $^{234}\text{U}$  equilibrium and (3) a third end-  
727 member marked by a low  $(^{230}\text{Th}/^{232}\text{Th})$  ratio and a  $(^{234}\text{U}/^{238}\text{U})$  ratio close to  
728 equilibrium. However, the very contrasted values of soil solutions and tree samples  
729 indicate that beech trees absorb U and Th and probably also other nutrients not  
730 directly from the gravitational soil solutions collected in this study but from other  
731 reservoirs marked by different chemical and isotopic compositions, i.e. water-  
732 reservoir - like bounded waters, or possibly also directly from solids, as trees can  
733 uptake nutrients from solids without going through soil solutions (in Morgan and  
734 Connolly, 2013). The relatively low  $(^{230}\text{Th}/^{232}\text{Th})$  ratios of trees can be derived from  
735 primary minerals, most likely biotite but also possibly apatite or feldspar, to account  
736 for the scattering of the Th activity ratios in the beech trees. The  $^{234}\text{U}$ - $^{238}\text{U}$   
737 disequilibria in the tree samples are consistent with an uptake of U enriched in  $^{234}\text{U}$   
738 (by alpha recoil) from primary minerals. The absence of  $^{238}\text{U}$ - $^{230}\text{Th}$  fractionation  
739 suggests that during nutrient uptake, U and Th are not significantly fractionated.  
740 This conclusion of different U and Th sources for vegetation and soil solutions has  
741 also to be proposed for the spruce plot on the basis of the  $(^{230}\text{Th}/^{232}\text{Th})$  vs  
742  $(^{234}\text{U}/^{238}\text{U})$  and vs  $^{87}\text{Sr}/^{86}\text{Sr}$  diagrams (Fig. 13 and Fig. 12). In the  $(^{230}\text{Th}/^{232}\text{Th})$  vs  
743  $(^{234}\text{U}/^{238}\text{U})$  diagram, the spruce plot soil solutions confirm the suggestion (§ 5-2)  
744 that the U-Th budget of spruce soil solutions is controlled by minerals with  
745  $(^{234}\text{U}/^{238}\text{U}) < 1$  and low  $(^{230}\text{Th}/^{232}\text{Th})$  ratios, i.e., the U-Th characteristics of Ba-rich  
746 and Zr-rich minerals in the spruce soils. On the other hand, spruce data in the  
747  $(^{230}\text{Th}/^{232}\text{Th})$  vs  $(^{234}\text{U}/^{238}\text{U})$  diagram suggest that the U and Th sources for spruces  
748 might not be very different from those for beech, confirming that these trees absorb  
749 nutrients from a distinct reservoir to that controlling the U-Th budget in solutions  
750 collected by zero-tension lysimetric plates. The Strengbach results thus underscore  
751 an interest, certainly not anticipated so far, of the use of the U-Th systematics in the  
752 critical zone to constrain the nutrient source of the plants.

753

754 **CONCLUSIONS**

755  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$ - $^{226}\text{Ra}$  nuclide data and ( $^{230}\text{Th}/^{232}\text{Th}$ ) ratios of soil minerals, soil  
756 solutions and trees from the two instrumented spruce and beech plots of the  
757 Strengbach catchment, yield new constraints on the sources and transfer pathways  
758 of these elements within the plant-soil-water system. It has been demonstrated that  
759 these are clearly important geochemical parameters for tracing biogeochemical  
760 processes in the critical zone.

761 The results highlight the highly contrasting impact of trees on U-Th and Ra (Ba)  
762 budgets in forest ecosystems with Ra-Ba being highly and U-Th only slightly cycled  
763 by vegetation. Thus, tree uptake and litter decay can be a cause of Th-Ra(Ba)  
764 fractionations in soil solutions and soils, especially in the surface soil horizons. In  
765 contrast these processes have much less impact on U-Th fractionation, which is  
766 mainly controlled by water-rock interaction. Therefore, due to the strong cycling by  
767 trees, Ra together with its ( $^{228}\text{Ra}/^{226}\text{Ra}$ ) isotopic ratio might become a powerful  
768 tracer and chronometer of the biogeochemical cycles in forest ecosystems and the  
769 processes they involve. On the other hand, due to the small impact of vegetation on  
770 the U and Th budget in soils and soil solutions, U and Th isotopes are probably  
771 among the few tracers to be specific indicators of water-rock interactions in the CZ  
772 markedly contrasting with classical isotope systems such as Sr or Nd, routinely used  
773 in the study of the CZ and significantly affected by vegetation cycling. Therefore, the  
774 characteristics of Th along with its fairly large range of activity ratios in soil  
775 minerals, especially in secondary and minor mineral phases, makes it a powerful  
776 and specific tracer of the sources of chemical fluxes in soils, soil solutions and  
777 vegetation. The Strengbach data emphasize this point but also highlight the utility of  
778 combining analysis of U, Th activity and Sr isotope ratios to constrain the source of  
779 these elements in soils and soil solutions. This approach places new constraints on  
780 the weathering processes affecting the Strengbach bedrocks and the nature and  
781 evolution of the reservoirs involved in (nutrient) element transfer at the plant-soil-  
782 water interface. It has been shown that minor mineral phases such as zircons,  
783 sulfates and phosphates significantly control the U and Th chemical budget and Th  
784 activity ratios of the soil samples and also the U-Th fluxes transiting in the soil  
785 solutions. The comparison of the U-Th-Sr isotopic characteristics of soil solutions  
786 and soil grain size fractions also allows the recognition of two stages of weathering  
787 with (a) dissolution of primary minerals and formation of secondary ones in the

788 deep soil horizons and soil solutions and (b) dissolutions of both primary and  
789 secondary mineral phases in the finest soil grain size fractions of the nearest surface  
790 soil horizons. The latter process might be related to recent modifications of  
791 weathering in the catchment which is stronger and older under the spruce  
792 compared to the beech plot. We propose that the artificial change in vegetation over  
793 the past decades through planting of spruces significantly contributed to the current  
794 differences in soil weathering between the beech and spruce plots. Spruce  
795 plantation in the Strengbach catchment increased soil acidity, which accelerated  
796 weathering of some minerals and likely also increased Ca leaching and the depletion  
797 of the nutrient pool in the Ca-poor soil-vegetation system of the Strengbach  
798 catchment. The U-Th-Sr results of this study point to the occurrence of isotopically  
799 different reservoirs of these elements for trees and gravity soil solutions collected  
800 by lysimetric plates. This further suggests that, in the case of the Strengbach  
801 watershed, the gravity soil solutions cannot be the main, or even an important, tree  
802 nutrient reservoir, which emphasizes that the U-Th systematics in the critical zone  
803 can offer useful constraints on the nutrient source of the plants.

804

805

806 **Acknowledgments:** The study benefited from funding from the “Région Alsace”  
807 (France), the CPER 2003-2013 “REALISE”, and the “PPF REALISE” (University of  
808 Strasbourg, France). During the course of the study J. Prunier benefited from the  
809 funding of a Ph.D. scholarship from the University of Strasbourg. D. Million and R.  
810 Boutin are thanked for the analysis of the major and trace element concentrations.  
811 The corresponding author thanks very much the Associate Editor Frank McDermott  
812 and two anonymous reviewers for their very constructive comments that have  
813 helped us to highlight much better the main results and conclusions of this study. He  
814 also thanks Robert Ellam for the discussions on the last version of the manuscript.

815

816 **References:**

- 817 Ackerer J., Chabaux F., Van der Woerd J., Viville D., Pelt E., Kali E., Lerouge C., Ackerer  
818 P., Di Chiara R., Négrel P. (2016). Regolith evolution on the millennial timescale  
819 from combined U-Th-Ra isotopes and in situ cosmogenic <sup>10</sup>Be analysis in a  
820 weathering profile (Strengbach catchment, France). *Earth and Planetary  
821 Science Letters*, 453, 33–43
- 822 Ackerer J., Chabaux F., Lucas Y., Clément A., Fritz B., Beaulieu E., Viville D., Pierret  
823 M.C., Gangloff S., Négrel Ph. (2018). Monitoring and reactive-transport  
824 modeling of the spatial and temporal variations of the Strengbach spring  
825 hydrochemistry. *Geochimica Cosmochimica Acta*, 225, 17-35.
- 826 Akerman, A., Poitrasson, F., Oliva, P., Audry, S., Prunier, J., 2014. Isotopic fingerprint  
827 of Fe cycling in an equatorial soil-plant-water system: The Nsimi watershed,  
828 South Cameroon. *Chem. Geol.* 385, 104–116.
- 829 Alriksson A. and Eriksson H.M., 1998. Variations in mineral nutrient and C  
830 distribution in the soil and vegetation compartments of five temperate tree  
831 species in NE Sweden. *Forest Ecology and Management* 108, 261-273.
- 832 Aubert D., Probst A., Stille P., and Viville D. (2002) Evidence of hydrological control  
833 of Sr behavior in stream water (Strengbach catchment, Vosges mountains,  
834 France. *Appl. Geochem.* 17, 285-300.
- 835 Aubert D., Stille P., and Probst A. (2001) REE fractionation during granite  
836 weathering and removal by waters and suspended loads: Sr and Nd isotopic  
837 evidence. *Geochim. Cosmochim. Acta* 65, 387-406.
- 838 Aubert D., Probst A., Stille P. (2004) Distribution and origin of major and trace  
839 elements (particular REE, U and Th) into labile and residual phases in an acid  
840 soil profile (Vosges Mountains, France). *Applied Geochem.*, 2004, 19, 6, p. 899-  
841 916. doi:10.1016/j.apgeochem.2003.11.005
- 842 Augusto L., De Schrijver A., Vesterdal L., Smolander A., Prescott C., Ranger J. 2015.  
843 Influences of evergreen gymnosperm and deciduous angiosperm tree species  
844 on the functioning of temperate and boreal forests. *Biological Reviews*, 90 (2)  
845 444-466
- 846 Babcsányi, I., Imfeld, G., Granet, M., Chabaux, F. (2014) Copper stable isotopes to  
847 trace copper behavior in wetland systems *Environmental Science and  
848 Technology*, 48, 5520-5529.
- 849 Babcsányi, I., Chabaux, F., Granet, M., Meite, F., Payraudeau, S., Duplay, J., Imfeld, I.  
850 (2016) Copper in soil fractions and runoff in a vineyard catchment: Insights  
851 from copper stable isotopes. *Science of the Total Environment* 557–558, 154–  
852 162.
- 853 Baeza A., Barandica J., Paniagua J.M., Rufo M., Sterling A., 1999. Using (<sup>226</sup>Ra/<sup>228</sup>Ra)  
854 disequilibrium to determine the residence half-lives of radium in vegetation  
855 compartments. *Journal of Environmental Radioactivity* 43 (3): 291-304
- 856 Bagard M-L, Chabaux F, Pokrovsky O. S., Viers J., Prokushkin A. S., Stille P., Rihs S.,  
857 Schmitt A.-D., Dupré B. (2011). Seasonal variability of element fluxes in two

858 Central Siberian rivers draining high latitude permafrost dominated areas  
859 *Geochimica Cosmochimica Acta*, 75, 3335-3357.

860 Banwart, S.A., Bernasconi, S.M., Blum, W.E.H., de Souza, D.M., Chabaux, F., Duffy, C.,  
861 Kercheva, M., Krám, P., Lair, G.J., Lundin, L., Menon, M., Nikolaidis, N., Novak, M.,  
862 Panagos, P., Ragnarsdottir, K.V., Robinson, D.A., Rousseva, S., de Ruiter, P., van  
863 Gaans, P., Weng, L., White, T., Zhang, B. (2017) Soil Functions in Earth's Critical  
864 Zone: Key Results and Conclusions. *Advances in Agronomy* 142, 1-27 DOI:  
865 10.1016/bs.agron.2016.11.001

866 Banwart S.A., Nikolaos P. Nikolaidis N.P., Zhu Y-G, Peacock C.L., Sparks D.L. (2019)  
867 Soil Functions: Connecting Earth's Critical Zone. *Annu. Rev. Earth Planet. Sci.*  
868 47:333–59.

869 Beaulieu E., Lucas Y., Viville D., Chabaux F., Ackerer P., Goddérís Y., Pierret M.C.,  
870 Hydrological and vegetation response to climate change in a forested  
871 mountainous catchment (2016) *Modeling Earth Systems and Environment*, 2,  
872 191 (DOI: 10.1007/s40808-016-0244-1).

873 Berger, T.W., Untersteiner, H., Topfitzer, M. et Neubauer C. (2009) Nutrient fluxes in  
874 pure and mixed stands of spruce (*Picea abies*) and beech (*Fagus sylvatica*)  
875 *Plant Soil* 322, 317-342.

876 Binkley D. Valentine D., 1991. Fifty-year biogeochemical effects of green ash, white  
877 pine, and Norway spruce in a replicated experiment. *Forest Ecology and*  
878 *Management* 40, 13-25.

879 Blum J.L., Erel Y., (2005). Radiogenic isotopes in weathering and hydrology In  
880 *Surface and Ground Water, Weathering and Soils* (ed. J.I. Drever) 5 *Traitise on*  
881 *Geochemistry* (eds. H.D. Holland and K.K. Turekian). Elsevier-Pergamon,  
882 Oxford. pp.365–392.

883 Blum J.D., Dasch A.A., Hamburg S.P., Yanai R.D., Arthur M.A. (2008) Use of foliar  
884 Ca/Sr discrimination and  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios to determine soil Ca sources to  
885 sugar maple foliage in a northern hardwood forest. *Biogeochem.* 87, 287-296.

886 Bosia C., Chabaux F., Pelt E., France-Lanord C., Morin G., Lavé J., Stille P. (2016) U-Th-  
887 Ra variations in the Himalayan River sediments (Gandak river, India):  
888 weathering fractionation and/or grain-size sorting? *Geochimica et*  
889 *Cosmochimica Acta* 193, 176–196.

890 Bosia C., Chabaux F., Pelt E., Coge A., Stille P., Deloule E., France-Lanord C (2018). U-  
891 series disequilibria in minerals from Gandak River sediments (Himalaya),  
892 *Chemical Geology*, 477, 22–34.

893 Bouchez J., von Blanckenburg F., Schuessler J.A. (2013). Modeling novel stable  
894 isotope ratios in the weathering zone. *Am. J. Sci.* 313, 267–308.

895 Bourdon B., Bureau S., Andersen M.B., Pili E., and Hubert E. (2009) Weathering rates  
896 from up to bottom in carbonate environment, *Chem. Geol.* 258, 275-287.

897 Brantley S.L., Goldhaber M.B., and Ragnarsdottir V.K. (2008) Crossing disciplines  
898 and scales to understand the Critical Zone, *Elements* 3, 307-314.

899 Braun J.J., Viers J., Dupré B., Polvé M., Ndam J., and Muller J.P. (1998) Solid/liquid  
900 REE fractionation in the lateritic system of Goyoum, East Cameroon: The

901           implication for the present dynamics of the soil covers of the humid tropical  
902           regions. *Geochim. Cosmochim. Acta* 62, 273-299.

903 Bullen, T.D., Kendall, C., 1998. Tracing weathering reactions and water flowpaths: a  
904           multi- isotope approach. In: Kendall, C., McDonnell, J.J. (Eds.), *Isotope Tracers*  
905           in Catchment Hydrology. Elsevier, Amsterdam, pp. 611-646.

906 Cenki-Tok B., Chabaux F., Lemarchand D., Schmitt A.-D., Pierret M.-C., Viville D.,  
907           Bagard M.-L., Stille P., 2009. The impact of water-rock interaction and  
908           vegetation on calcium isotope fractionation in soil- and stream waters of a  
909           small, forested catchment (the Strengbach case). *Geochim. Cosmochim. Acta*  
910           73, 2215-2228.

911 Cerne M., Smodis B., Strok M., Jacimovic R. (2010) Accumulation of  $^{226}\text{Ra}$ ,  $^{238}\text{U}$  and  
912            $^{230}\text{Th}$  by wetland plants in a vicinity of U-mill tailings at Zirovski vrh  
913           (Slovenia). *J Radioanal. Nucl. Chem.* 286, 323-327.

914 Chabaux F., Ben Othman D., J.L. Birck (1994) A new Ra-Ba chromatographic  
915           separation and its application for the Ra mass spectrometric measurement in  
916           recent volcanic rocks. *Chem. Geol.* 114, 191-197. Erratum (1994)*Chem. Geol.*  
917           116, 301.

918 Chabaux F., Cohen A.S., O'Nions R.K., Hein J.R. (1995)  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$  chronometry of  
919           Fe-Mn crusts: Growth processes and recovery of thorium isotopic ratios of  
920           seawater. *Geochim. Cosmoch. Acta* 59, 633-638.

921 Chabaux F., O'Nions R.K., Cohen A.S., Hein J.R. (1997).  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$  disequilibrium  
922           in hydrogenous oceanic FeMn crusts: palaeoceanographic record or  
923           diagenetic alteration? *Geochim. Cosmochim. Acta* 61, 3619-3632.

924 Chabaux F., Hémond C., Allègre C.J. (1999). Timing of magmatic processes in  
925           subduction zones: the Lesser Antilles case. *Chem. Geol.* 153, 171-185

926 Chabaux F., Riotte J., Schmitt A.-D., Carignan J., Herckès P., Pierret M.-C., Wortham H.  
927           (2005) Variations of U and Sr ratios in Alsace and Luxembourg rain waters:  
928           origin and hydrogeochemical implications, *Comptes Rendus Geoscience* 337,  
929           1447-1456.

930 Chabaux F., Riotte J., and Dequincey O. (2003a) U-Th-Ra fractionation during  
931           weathering and river transport. *Rev Mineral. Geochem.* 52, 533-576.

932 Chabaux F., Dequincey O., Lévèque J.-J., Leprun J.-C., Clauer N., Riotte J., and Paquet  
933           H. (2003b) Tracing and dating recent chemical transfers in weathering profiles  
934           by trace element geochemistry and  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$  disequilibria: the exemple  
935           of the Kaya lateritic toposequence (Burkina-Faso). *C. R. Geoscience* 335, 1219-  
936           1231.

937 Chabaux F., Bourdon B., and Riotte J. (2008). U-Series Geochemistry in Weathering  
938           Profiles, River Waters and Lakes. *Radioactivity in the Environment*, 13, 49-104.

939 Chabaux F., Blaes E., Granet M., di Chiara Roupert R., Stille P. (2012) Determination  
940           of transfer time for sediments in alluvial plains using  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$   
941           disequilibria: The case of the Ganges river system. *CR Geoscience* 344, 688-703

942 Chabaux F., Blaes E., Stille P., di Chiara Roupert R., Pelt E., Dosseto A., Ma L., Buss H.,  
943           Brantley S.L. (2013). Regolith formation rate from U-series nuclides:

944 Implications from the study of a spheroidal weathering profile in the Rio  
945 Icacos watershed (Puerto Rico) *Geochimica et Cosmochimica Acta*, 100, 73-95  
946 Chabaux F., Sonke, J.E., Négrel, P., Cloquet C. (2015a,b) Geochemical and isotopic  
947 record of anthropogenic activities – Thematic issue dedicated to Jean Carignan  
948 (1965–2012). Part 1 : Radiogenic isotopes and elemental geochemistry.  
949 *Compte Rendus Geoscience*, 347, 213-214 - Part 2: Traditional and non-  
950 traditional stable isotopes - *Compte-Rendus Geoscience*, 347, 315-316  
951 Cividini D., Lemarchand D., Chabaux F., Boutin R., Pierret M.-C., 2010. From  
952 biological to lithological control of the B geochemical cycle in a forest  
953 watershed (Strengbach, Vosges). *Geochim. Cosmochim. Acta* 74, 3143–3163.  
954 Cremer, M., Prietzel, J. (2017) Soil acidity and exchangeable base cation stocks under  
955 pure and mixed stands of European beech, Douglas fir and Norway spruce.  
956 *Plant Soil* 415, 393-405.  
957 DePaolo D., Lee V.E., Christensen J.N., Maher K. (2012) Uranium comminution ages:  
958 sediment transport and deposition time scales. *C.R. Geosci.* 344, 678-687.  
959 DePaolo D., Maher K., Christensen J.N., and McManus J. (2006) Sediment transport  
960 time measured with U-series isotopes: Results from ODP North Atlantic drift  
961 site 984. *Earth Planet. Sci. Lett.* 248, 394-410.  
962 Dequincey O., Chabaux F., Clauer N., Sigmarsson O., Liewig N., and Leprun J.-C.  
963 (2002) Chemical mobilizations in laterites: Evidence from trace elements and  
964  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$  disequilibria. *Geochim. Cosmochim. Acta* 66, 1197-1210.  
965 Dequincey O., Chabaux F., Leprun J.-C., H. Paquet, Clauer N., Ph. Larqué (2005)  
966 Lanthanide and trace elements mobilisation along a toposequence : clues from  
967 Kaya laterite (Burkina Faso) *European Journal of Soil Sciences*, 57, 816-830  
968 Dewandel, B., Lachassagne, P., Wyns, R., Maréchal, J.C., Krishnamurthy, N.S., 2006. A  
969 gen-eralized 3-D geological and hydrogeological conceptual model of granite  
970 aquifers controlled by single or multiphase weathering. *J. Hydrol.* 330, 260–  
971 284.  
972 Dosseto, A., Turner, S.P., Chappell, J., 2008. The evolution of weathering profiles  
973 through time: new insights from uranium-series isotopes. *Earth Planet. Sci.*  
974 *Lett.* 274 (3), 359–371.  
975 Dosseto A., Buss H., Chabaux F. (2014) Age and weathering rate of sediments in  
976 small-catchments : the role of hillslope erosion. *Geochimica et Cosmochimica*  
977 *Acta*,132, 238-258.  
978 Dosseto, A., Schaller, M., 2016. The erosion response to Quaternary climate change  
979 quantified using uranium isotopes and in situ-produced cosmogenic nuclides.  
980 *Earth-Sci. Rev.* 155, 60–81.  
981 Drouet T., Herbauts J. (2008) Evaluation of the mobility and discrimination of Ca, Sr  
982 and Ba in forest ecosystems: consequence on the use of alkaline-earth element  
983 ratios as tracers of Ca. *Plant Soil* 302, 105-124.  
984 Durand S., Chabaux F., Rihs S., Düringer P., Elsass P. (2005) U isotope ratios as  
985 tracers of groundwater inputs into surface waters: Example of the Upper  
986 Rhine hydrosystem *Chemical Geology*, 220, 1-19.



- 987 Fichter J., Turpault M-P., Dambrine E., and Ranger J. (1998a) Localization of base  
 988 cations in particle size fractions of acid forest soils \_Vosges Mountains, N-E  
 989 France. *Geoderma* 82, 295–314.
- 990 Fichter J., Turpault M-P., Dambrine E., and Ranger J. (1998b) Mineral evolution of  
 991 acid forest soils in the Strengbach catchment (Vosges mountains, N-E France).  
 992 *Geoderma* 82, 315-340.
- 993 Ghaleb, B., Pons-Branchu, E., Deschamps, P., 2004. Improved method for radium  
 994 extraction from environmental samples and its analysis by thermal ionization  
 995 mass spectrometry. *J. Anal. At. Spectrom.* 7, 906–910.
- 996 Gangloff S., Stille P., Pierret M-C., Weber T., and Chabaux F. (2014). Characterization  
 997 and evolution of dissolved organic matter in acidic forest soil and its impact on  
 998 the mobility of major and trace elements (case of the Strengbach watershed).  
 999 *Geochim. Cosmochim. Acta* 130, 21–41.
- 1000 Gerzabek M.H., Strebl F., and Temmel B. (1998). Plant uptake of radionuclides in  
 1001 lysimeter experiments. *Environ. Pollut.* 99, 93-103.
- 1002 Gontier, A., Rihs, S., Chabaux, F., Lemarchand, D., Pelt, E., Turpault, M.-P. (2015)  
 1003 Lack of bedrock grain size influence on the soil production rate, *Geochimica et*  
 1004 *Cosmochimica Acta*, 166, 146-164.
- 1005 Granet M., Chabaux F., Stille P., Dosseto A., France-Lanord C., Blaes E. (2010) U-  
 1006 series disequilibria in suspended river sediments and implication for sediment  
 1007 transfer time in alluvial plains : the case of the Himalayan rivers *Geochim.*  
 1008 *Cosmochim. Acta*, 74, 2851-2865
- 1009 Granier A., Bréda N., Biron P., Villette S. (1999) A lumped water balance model to  
 1010 evaluate duration and intensity of drought constraints in forest stands. *Ecol.*  
 1011 *Model.* 116(2–3), 269–283.
- 1012 Greeman, D.J., Rose, A.W., Washington, J.W., Dobos, R.R., Ciolkosz, E.J., 1999.  
 1013 Geochemistry of radium in soils of the Eastern United States. *Appl. Geochem.*  
 1014 14, 365–385.
- 1015 Hasalová, P., Schulmann K., Tabaud A.-S., Oliot E. (2015) Microstructural evidences  
 1016 for mineralogical inheritance in partially molten rocks: example from the  
 1017 Vosges Mts. *Bull. Soc. Géol. France*, 186, 131-143.
- 1018 Ignatova N., Dambrine E. (2000) Canopy uptake of N deposition in spruce (*Picea*  
 1019 *abies* L. Karst) stands. *Annals of Forest Science*, Springer Verlag/EDP Sciences,  
 1020 57, 113-120.
- 1021 Ivanovich, M. and Harmon, R. S. (eds.) (1992) Uranium-Series Disequilibrium:  
 1022 Application to Earth, Marine, and Environmental Sciences. Clarendon Press,  
 1023 Oxford.
- 1024 Jeambrun, M., Pourcelot, L., Mercat, C.; Boulet, B., Pelt, E., Chabaux, F., Cagnat X.,  
 1025 Gauthier-Lafaye F. (2012) Potential sources affecting the activity  
 1026 concentrations of <sup>238</sup>U, <sup>235</sup>U, <sup>232</sup>Th and some decay products in lettuce and  
 1027 wheat samples. *J. Environ. Monit.*, 14, 2902
- 1028 Kendal C., Doctor D.H., 2005. Stable isotope applications in hydrologic studies pp.  
 1029 319– 364. In *Surface and Ground Water, Weathering and Soils* (ed. J.I. Drever)

- 1030 5 Traitise on Geochemistry (eds. H.D. Holland and K.K. Turekian). Elsevier-  
1031 Pergamon, Oxford.
- 1032 Kronberg B.I., Nesbitt H.W. (1981) Quantification of weathering, soil geochemistry  
1033 and soil fertility. *J. Soil Sci.*, 32, 453-459.
- 1034 Ladouche B., Probst A., Viville D., Idir S., Baqué D., Loubet M., Probst J.-L., and Bariac  
1035 T. (2001) Hydrograph separation using isotopic, chemical and hydrological  
1036 approaches (Strengbach catchment France). *J. Hydrol.* 242, 255-274.
- 1037 Lahd Geagea M., Stille P., Millet M. and Perrone T. (2007) REE characteristics and Pb,  
1038 Sr and Nd isotopic compositions of steel plant emissions. *Sci. Total Environ.*  
1039 373, 404–419.
- 1040 Laveuf C. and Cornu S. (2009) A review on the potentiality of Rare Earth Elements to  
1041 trace pedogenetic processes. *Geoderma* 154, 1-12.
- 1042 Lemarchand, D., Cividini, D., Turpault, M.-P. and Chabaux, F. Boron isotopes in  
1043 different grain size fractions: Exploring past and present water-rock  
1044 interactions from two soil profiles (Strengbach, Vosges Mountains). *Geochim  
1045 Cosmochim Acta* **98**, 78–93 (2012).
- 1046 Lemarchand E., Chabaux F., Vigier N., Millot R., Pierret M-C., 2010. Lithium isotope  
1047 systematics in a forested granitic catchment (Strengbach, Vosges Mountains,  
1048 France). *Geochim. Cosmochim. Acta* 74, 4612-4628.
- 1049 Li L., Maher K., Navarre-Sitchler A., Druhan J., Meile C., Lawrence C., Moore J.,  
1050 Perdrial J., Sullivan P., Thompson A., Jin L., Bolton E. W., Brantley S. L., Dietrich  
1051 W.E., Mayer K.U., Steefel C.I., Valocchi A., Zachara J., Kocar B., Mcintosh J.,  
1052 Tutolo B.M., Kumar M., Sonnenthal E., Bao C., Beisman J. (2017) Expanding the  
1053 role of reactive transport models in critical zone processes. *Earth-Science  
1054 Reviews* 165, 280–301.
- 1055 Lu P., Biron P., Breda N., and Granier A. (1995) Water relations of adult Norway  
1056 spruce (*Picea abies L.*) under soil drought in the Vosges mountains : water  
1057 potential, stomatal conductance and transpiration. *Ann. Sci. For.* 52, 117-129.
- 1058 Lucas Y., Schmidt A.D., Chabaux F., Clément A., Fritz B., Elsass Ph., Durand S. (2010)  
1059 Geochemical tracing and hydrogeochemical modelling of water-rock  
1060 interactions during salinization of alluvial groundwater (Upper Rhine valley,  
1061 France) *Applied Geochemistry* 25, 1644-1663.
- 1062 Lucas Y., Chabaux F., Schaffhauser T., Fritz B., Ambroise B., Ackerer J., Clément A.  
1063 (2017) Hydrogeochemical modeling (KIRMAT) of spring and deep borehole  
1064 water compositions in the small granitic Ringelbach catchment (Vosges  
1065 Mountains, France). *Applied Geochemistry* 87, 1–21.
- 1066 Ma L., Chabaux F., Pelt E., Blaes E., Jin L., Brantley S. (2010) Regolith production  
1067 rates calculated with uranium-series isotopes at Susquehanna/Shale Hills  
1068 critical Zone Observatory *Earth and Planet Sci. Lett.*, 297, 211-225
- 1069 Ma L., Chabaux F., Pelt E., Granet M., Sak P., Gaillardet J., Lebedeva M., Brantley S.B.  
1070 (2012) The effect of curvature on weathering rind formation: evidence from U-  
1071 series isotopes in basaltic andesite weathering clasts in Guadeloupe  
1072 *Geochimica et Cosmochimica Acta*, 80, 92-107.

1073 Ma L., Chabaux F., West N., Kirby E., Jin L., Brantley S. (2013). Regolith production  
1074 and transport in the Susquehanna Shale Hills Critical Zone Observatory, Part 1:  
1075 Insights from U-series isotopes. *Journal of Geophysical Research. Earth Surface*  
1076 118, 722-740

1077 Maher K., DePaolo D.J., Christensen J.N. (2006) U–Sr isotopic speedometer: Fluid  
1078 flow and chemical weathering rates in aquifers. *Geochim. Cosmochim. Acta* 70;  
1079 4417–4435.

1080 Million J.B., Sartain J.B., Gonzales R.X., Carrier W.D. (1994) Radium-226 and calcium  
1081 uptake by crops grown in mixtures of sand and clay tailings from phosphate  
1082 mining. *J Environ. Qual.* 23, 671-676.

1083 Morgan J.B., Connolly E.L. (2013). Plant-soil interactions: nutrient uptake. *Nature*  
1084 *Education Knowledge* 4 (8), 2.

1085 Négrel Ph., Pauwels H., Chabaux F. (2018) Characterizing Multiple water-rock  
1086 interactions in the critical zone through Sr-Isotope tracing of surface and  
1087 groundwater. *Applied Geochemistry* 93, 102-112.

1088 Opfergelt, S., Delmelle, P., 2012. Silicon isotopes and continental weathering  
1089 processes: assessing controls on Si transfer to the ocean. *CR Geoscience* 344,  
1090 723–738.

1091 Opfergelt, S., Burton, K.W., Georg, R.B., West, A.J., Guicharnaud, R.A., Sigfusson, B.,  
1092 Siebert, C., Gislason, S.R., Halliday, A.N., 2014. Magnesium retention on the soil  
1093 exchange complex controlling Mg isotope variations in soils, soil solutions and  
1094 vegetation in volcanic soils, Iceland. *Geochim. Cosmochim. Acta* 125, 110–130.

1095 Osmond J.K. and Ivanovich M. (1992) Uranium-series mobilization and surface  
1096 hydrology. In *Uranium series disequilibrium: Application to the earth, marine*  
1097 *and environmental Sciences* (Eds. M. Ivanovich and R.S. Harmon), Oxford  
1098 University Press, New York, pp. 259-288.

1099 Palumbo, B., Bellanca, A., Neri, R., Roe, M.J., 2001. Trace metal partitioning in Fe–Mn  
1100 nodules from Sicilian soils, Italy. *Chem. Geol.* 173, 257–269.

1101 Pelt, E., Chabaux, F., Innocent, C., Navarre-Sitchler, A.K., Sak, P.B., Brantley, S.L., 2008.  
1102 Uranium–thorium chronometry of weathering rinds: rock alteration rate and  
1103 paleo-isotopic record of weathering fluids. *Earth Planet. Sci. Lett.* 276, 98–105.

1104 Pelt E., Chabaux F., Stille P., Innocent C., Ghaleb B., Gérard M., Guntzer F., 2013.  
1105 Atmospheric dust contribution to the budget of U-series nuclides in soils from  
1106 the Mount Cameroon volcano. *Chem. Geol.*, 341, 147-157

1107 Pierret M.C., Stille P., Prunier J., Viville D., Chabaux F. (2014) Chemical and U-Sr  
1108 isotopic variations in stream and source waters of the Strengbach watershed  
1109 (Vosges mountains, France. *Hydrol. Earth Syst.* 18, 3969-3985.

1110 Pierret M.C., Cotel S., Ackerer P., Beaulieu E., Benarioumlil S., Boucher M., Boutin R.,  
1111 Chabaux F., Dambrine E., Delay F., Fournet C., Friedmann P., Fritz B., Gangloff S.,  
1112 Girard J.F., Legtchenko A., Viville D., Weill S. and Probst A., 2018. The  
1113 Strengbach Catchment: a multidisciplinary environmental sentry for 30 years.  
1114 *Vadose Zone Journal* 17 (1) DOI: 10.2136/vzj2018.04.0090

- 1115 Poszwa A., Dambrine E., Pollier B., Atteia O. (2000) A comparison between Ca and Sr  
1116 cycling in forest ecosystems. *Plant Soil* 225, 299–310.
- 1117 Poszwa, A., Wickman, T., Dambrine, E., Ferry, B., Dupouey, J. L., Helle, G., and Breda,  
1118 N. (2003). A retrospective isotopic study of Spruce decline in the Vosges  
1119 mountains (France). *Water, Air and Soil Pollution: Focus*, 3(1), 201-222.
- 1120 Pourcelot L., Calmon P., Chabaux F., Conil S., Galy C., Granet M., Lascar E., Leclerc E.,  
1121 Perrone T., Redon P.-O., Rihs S. (2017) Comparative repartition of  $^{226}\text{Ra}$ ,  $^{238}\text{U}$ ,  
1122  $^{234}\text{U}$ ,  $^{230}\text{Th}$  and  $^{232}\text{Th}$  in a variety of soils sampled from geological formations in  
1123 the NE of the Basin of Paris. *Applied Geochemistry*, 84, 314-324.
- 1124 Prunier J., (2008). Etude du fonctionnement d'un écosystème forestier en climat  
1125 tempéré, par l'approt de la géochimie élémentaire et isotopique (Sr, U-Th-  
1126 Ra). Cas du bassin versant du Strengbach (Vosges, France). PhD Thesis.  
1127 Université Louis Pasteur de Strasbourg, France pp.303.
- 1128 Prunier J., Chabaux F., Stille P., Gangloff S., Pierret M.C., Viville, D., A. Aubert (2015).  
1129 Geochemical and isotopic (Sr,U) monitoring of soil solutions from the  
1130 Strengbach catchment (Vosges mountains, France) : Evidence for recent  
1131 weathering evolution. *Chem. Geol.*, 417, 289-305
- 1132 Rihs S., Prunier J., Thien B., Lemarchand D., Pierret M.-C., Chabaux F. (2011) Using  
1133 short-lived nuclides of the U- and Th-series to probe the kinetics of colloid  
1134 migration in forested soils. *Geochim. Cosmochim. Acta* 75, 7707-7724.
- 1135 Rihs S., Gontier A., Pelt E., Fries D., Turpault M-P, Chabaux F. (2016) Behavior of U,  
1136 Th and Ra isotopes in soils during a land cover change *Chemical Geology* 441  
1137 106–123.
- 1138 Riotte J. and Chabaux F. (1999) ( $^{234}\text{U}/^{238}\text{U}$ ) Activity ratios in freshwaters as tracers  
1139 of hydrological proceses: The Strengbach watershed (Vosges, France).  
1140 *Geochim. Cosmochim. Acta* 63, 1263-1275.
- 1141 Riotte, F. Chabaux, M. Benedetti, A. Dia, J. Boulègue, M. Gérard, J. Etamé (2003)  
1142  $^{234}\text{U}$ - $^{238}\text{U}$  fractionations in surface waters: the Mount Cameroun case, *Chem.*  
1143 *Geol.*, 202, 365-381.
- 1144 Schaffhauser T., Chabaux F., Ambroise B., Lucas Y., Stille P., Reuschlé T., Perrone T.,  
1145 Fritz B. (2014) Geochemical and isotopic (U, Sr) tracing of water pathways in  
1146 the granitic Ringelbach catchment (Vosges Mountains, France) *Chemical*  
1147 *Geology*, 374-375, 117-127.
- 1148 Schmitt A.-D., Chabaux F., Stille P. (2003). The calcium riverine and hydrothermal  
1149 isotopic fluxes and the oceanic calcium mass balance. *Earth Planet. Sci. Lett.*  
1150 213, 503–518.
- 1151 Schmitt A.-D., Vigier N., Lemarchand D., Stille P., Millot R., Chabaux F. (2012).  
1152 Processes controlling the stable isotope compositions of Li, B, Mg and Ca in  
1153 plants, soils and waters: a review. *C. R. Geoscience* 344, 704–722.
- 1154 Schmitt A.-D., Cobert F., Bourgeade P., Ertlin D., Labolle F., Gangloff S., Badot P.-M.,  
1155 Chabaux F., Stille P. (2013) Calcium isotope fractionation during plant growth  
1156 under a limiting nutrient supply, *Geochim. Cosmochim. Acta*, 100, 73-95.

- 1157 Schmitt A.D., Gangloff S., Labolle F., Chabaux F., Stille P. (2017). Ca biogeochemical  
 1158 cycle at the beech tree - soil solution interface from the Strengbach CZO (NE  
 1159 France): insights from stable Ca and radiogenic Sr isotopes *Geochimica et*  
 1160 *Cosmochimica Acta* 213, 91-109
- 1161 Schmitt AD, Borrelli N., Ertlen D., Gangloff S., Chabaux F., Osterrieth M. (2018).  
 1162 Stable calcium isotope speciation and calcium oxalate production within beech  
 1163 tree (*Fagus sylvatica* L.) organs. *Biogeochemistry*, 137,197-217 DOI  
 1164 10.1007/s10533-017-0411-0
- 1165 Solovitch-Vella N., Pourcelot L., Chen V.T., Froidevaux P., Gauthier-Lafaye F., Stille P.,  
 1166 Aubert D. (2007) Comparative migration behaviour of  $^{90}\text{Sr}$ ,  $^{239+240}\text{Pu}$  and  $^{241}\text{Am}$   
 1167 in mineral and organic soils of France. *Appl. Geochem.* 22, 2526-2535.
- 1168 Soudek P., Podracka E., Vagner M., Vanek T., Petrik P., Tykva R. (2004)  $^{226}\text{Ra}$  uptake  
 1169 from soils into different plant species. *J. Radioanal. Nucl. Chem.* 282, 187-189.
- 1170 Steinmann M., Stille P. (1997) Rare earth element behavior and Pb, Sr, Nd isotope  
 1171 systematics in a heavy metal contaminated soil. *Applied Geochemistry*, 12,  
 1172 607-623.
- 1173 Steinmann M. Stille P. (2009) Controls on transport and fractionation of the rare  
 1174 earth elements in stream water of a mixed basaltic-granitic catchment basin  
 1175 (Massif Central, France). *Chem. Geol.*, 254, 1-18.
- 1176 Stille P., Pourcelot L., Granet M., Pierret M.C., Gueguen F., Perrone T., Morvan G.,  
 1177 Chabaux F. (2011) Deposition and migration of atmospheric Pb in soils from a  
 1178 forested silicate catchment today and in the past (Strengbach Case): Evidence  
 1179 from  $^{210}\text{Pb}$  activities and Pb isotope ratios. *Chem. Geol.*, 289, 140-153.
- 1180 Stille P., Pierret M.-C., Steinmann M., Chabaux F., Boutin R., Aubert D., Pourcelot L.,  
 1181 Morvan G. (2009) Impact of atmospheric deposition, biogeochemical cycling  
 1182 and water-mineral interaction on REE fractionation in acidic surface soils and  
 1183 soil water (the Strengbach case). *Chem. Geol.* 264, 173-186.
- 1184 Stille P., Steinmann M., Pierret M.-C., Gauthier-Lafaye F., Chabaux F., Viville D.,  
 1185 Pourcelot L., Matera V., Aouad G., Aubert D. (2006) The impact of vegetation  
 1186 on REE fractionation in stream waters of a small forested catchment (the  
 1187 Strengbach case). *Geochim. Cosmochim. Acta* 70, 3217-3230.
- 1188 Stille P, Schmitt AD, Labolle F, Pierret MC, Gangloff S, Cobert F, Lucot E, Gueguen F,  
 1189 Brioschi L, Steinmann M, Chabaux F (2012). The suitability of annual tree  
 1190 growth rings as environmental archives: Evidence from Sr, Nd, Pb and Ca  
 1191 isotopes in spruce growth rings from the Strengbach watershed *CR*  
 1192 *Geoscience*, 344, 297-311.
- 1193 Sullivan P. L, Ma L, West J., Jin N. L., Karwan D.L., Noireaux J., Steinhofel G., Gaines  
 1194 K.P., Eissenstat D.M., Gaillardet J., Derry L.A., Meek K., Hynek S., Brantley S.L. CZ-  
 1195 tope at Susquehanna Shale Hills CZO: Synthesizing multiple isotope proxies to  
 1196 elucidate Critical Zone processes across timescales in a temperate forested  
 1197 landscape. *Chem Geol* 445, 103–119 (2016).
- 1198 Tabaud A.-S., Janoušek V., Skrzypek E., Schulmann K., Rossi P., Whitechurch H.,  
 1199 Guerrot C., Paquette J.-L. (2015) Chronology, petrogenesis and heat sources for

1200 successive Carboniferous magmatic events in the Southern–Central Variscan  
 1201 Vosges Mts (NE France). *Journal of the Geological Society*, 172, 87-102.  
 1202 Tricca A., Wasserburg G.J., Porcelli D. and Baskaran M. (2001) The transport of U-  
 1203 and Th-series nuclides in a sandy unconfined aquifer. *Geochim. Cosmochim.*  
 1204 *Acta* 65, 1187-1210.  
 1205 Tricca A., Stille P., Steinmann M., Kiefel B., Samuel J., Eikenberg J. (1999) Rare earth  
 1206 elements and Sr and Nd isotopic compositions of dissolved and suspended  
 1207 loads from small river systems in the Vosges mountains (France), the river  
 1208 Rhine and the groundwater. *Chem. Geol.* 160, 139-158.  
 1209 Vaniman D.T., Chipera S.J., Bish D.L., Duff M.C., Hunter D.B. (2002). Crystal chemistry  
 1210 of clay-Mn oxide association in soils, fractures and matrix of the Bandelier tuff,  
 1211 Pajarito Mesa, New Mexico. *Geochim. Cosmochim. Acta* 66, 1349–1374  
 1212 Viers J., Prokushkin A.S., Pokrovsky O.S., Kirilyanov A.V., Zouiten C., Chmeleff J.,  
 1213 Meheut M., Chabaux F., Oliva P., Dupré B. (2015) Zn isotope fractionation in a  
 1214 pristine larch forest on permafrost-dominated soils in Central Siberia.  
 1215 *Geochemical Transactions* 16, Article number 3  
 1216 Vigier N., Bourdon B., Turner S., Allègre C.J. (2001). Erosion timescales derived from  
 1217 U-decay series measurements in rivers *Earth Planet. Sci. Lett.* 193, 546–563.  
 1218 Viville D., Chabaux F., Stille P., Pierret M.-C., Gangloff S., 2012. Erosion and  
 1219 weathering fluxes in granitic basins: The example of the Strengbach catchment  
 1220 (Vosges massif, eastern France). *Catena* 92, 122–129.  
 1221 Viville D., Biron P., Granier A., Dambrine E., and Probst A. (1993) Interception in a  
 1222 mountainous declining spruce stand in the Strengbach catchment (Vosges,  
 1223 France). *J. Hydrol.* 144, 273-282.  
 1224 Voinot A., Lemarchand D., Collignon C., Granet M., Chabaux F., Turpault MP (2013)  
 1225 Experimental dissolution vs. Transformation of micas in acid soil conditions :  
 1226 clues from boron isotopes *Geochimica et Cosmochimica Acta*, 117, 144-160.  
 1227 Wiegand B.A., Chadwick O.A., Vitousek P.M., Wooden J.L. (2005) Ca cycling and  
 1228 isotopic fluxes in forested exosystems in Hawaii. *Geophys. Res. Lett.* 32,  
 1229 L11404.  
 1230 Wild B., Daval D., Beaulieu E., Pierret M.P., Viville D., Imfeld G. (2019) In-situ  
 1231 dissolution rates of silicate minerals and associated bacterial communities in  
 1232 the critical zone (Strengbach catchment, France). *Geochim. Cosmochim. Acta*  
 1233 249, 95–120.  
 1234 WRB (2014) World reference base for soil resources 2014. International soil  
 1235 classification system for naming soils and creating legends for soil maps.  
 1236 Update 2015. [www.fao.org/3/a-i3794e.pdf](http://www.fao.org/3/a-i3794e.pdf)  
 1237 Wyns R., Baltassat J.-M., Lachassagne P., Legchenko A., Vairon J., Mathieu F. (2004).  
 1238 Application of proton magnetic resonance soundings to groundwater reserve  
 1239 mapping in weathered basement rocks (Brittany, France). *Bull. Soc. Geol. Fr.*  
 1240 175, 21–34.  
 1241

1242 **Table Captions**

1243 Table 1 a-c: Major and trace element concentrations,  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $(^{238}\text{U}/^{234}\text{U})$   
1244 isotopic ratios, and U-Th-Ra activity ratios in soil grain size fractions (1a); soil  
1245 solutions, rainwaters and throughfalls (1b); and litter and tree samples (1c).

1246 Table 2a: Mean annual (2004-2006) Ba, U, Th, Ra uptake fluxes by trees for the two  
1247 experimental plots of the catchment.

1248 Table 2b: Mean annual (2004-2006) Ba, U, Th, Ra fluxes brought by litter deposition  
1249 and throughfall and circulating in the soil solutions for the two experimental  
1250 plots of the catchment.

1251

1252 **Figure Captions:**

1253 Figure 1: Left side: geological map of the Strengbach catchment (from El Gh'Mari,  
1254 1995) showing the locations of the spruce (VP) and beech (HP) plots and the  
1255 precipitation sampling sites (PPT). Right side: schematic presentation of the  
1256 beech and spruce soil profiles, with the locations of the soil horizons analyzed  
1257 in this study and the position of the lysimeter plates used to collect the soil  
1258 solution samples. The surface lysimeter plates allow for sampling soil  
1259 solutions in zones of high root density (0-30cm) and the deepest lysimeter  
1260 plates the soil solution below the root zone as in both plots nearly all the fine  
1261 root biomass resides in the organic layer and upper 0–70 cm of mineral soil.  
1262 Descriptions of the beech (HP) and spruce (VP) soil profiles can be found in  
1263 Aubert et al. (2001, 2004), Fichter et al. (1998a, 1998b) and Prunier et al.  
1264 (2015): the beech soil profile is composed of a  $\approx 2$  cm thick “O” horizon, a  $\approx$   
1265 20–30 cm thick “A” horizon, which recovers a “B” horizon, whose transition  
1266 with the saprolite is at  $\approx 90$ –100 cm depth; the spruce soil profile is marked by  
1267 a  $\approx 2$  cm thick “O” horizon, a  $\approx 30$ –40 cm thick “A” topsoil horizon, and a B  
1268 horizon, which reaches the granitic saprock at  $\approx 1$ –1.2 m depth.

1269 Figure 2: Variations in the U concentration as a function of  $\text{Fe}_2\text{O}_3$  (A),  $\text{P}_2\text{O}_5$  (B) and  
1270 variations in the U (C) and Th (D) concentrations as a function of Zr  
1271 concentrations for the soil size fractions from the spruce and beech soil  
1272 samples.

1273 Figure 3: Plot of the data in the isochron diagram,  $(^{230}\text{Th}/^{232}\text{Th})$  vs  $(^{238}\text{U}/^{232}\text{Th})$ ,  
1274 with the different mixing lines discussed in the text. The Th activity ratios of  
1275 the primary minerals are calculated by assuming they are at secular  
1276 equilibrium [ $(^{230}\text{Th}/^{232}\text{Th}) = (^{238}\text{U}/^{232}\text{Th})$ ].

1277 Figure 4: Variations in the  $(^{230}\text{Th}/^{232}\text{Th})$  and  $(^{238}\text{U}/^{232}\text{Th})$  ratios as a function of Zr  
1278 concentrations for the soil size fractions from the spruce and beech soil  
1279 samples.

1280 Figure 5: Variations in the  $(^{234}\text{U}/^{238}\text{U})$  and  $(^{230}\text{Th}/^{232}\text{Th})$  ratios as a function of Zr  
1281 concentrations for the soil size fractions from the spruce and beech soil  
1282 samples.

1283 Figure 6: Variation in the  $(^{230}\text{Th}/^{232}\text{Th})$  ratio as a function of  $\text{P}_2\text{O}_5$  concentrations for  
1284 the soil size fractions from the spruce and beech soil samples.

1285 Figure 7: Variations in the ( $^{234}\text{U}/^{238}\text{U}$ ) (7a) and ( $^{226}\text{Ra}/^{230}\text{Th}$ ) (7b) ratios as a  
1286 function of ( $^{230}\text{Th}/^{234}\text{U}$ ) ratios for the soil size fractions from the spruce and  
1287 beech soil samples. Nota Bene: ( $^{234}\text{U}/^{238}\text{U}$ ) ratios of 3 dusts analyses on the site  
1288 are given in Prunier et al. (2015). Their U activity ratios range between 0.988  
1289 and 1.04, and cannot explain the atypical U activity ratios (i.e.  $\approx 0.9$ ) of the  
1290 deepest soil solutions.

1291 Figure 8a: Plot of the spruce site data in the ( $^{226}\text{Ra}/^{238}\text{U}$ ) vs ( $^{234}\text{U}/^{238}\text{U}$ ) diagram. As  
1292 detailed in the text, the soil solution data collected at 10, 30 and 60 cm and  
1293 those of the  $<2\ \mu\text{m}$  and 2-50  $\mu\text{m}$  grain size fractions of the 30-40 cm soil  
1294 horizon define two linear trends that converge towards the values of the 30  
1295 cm soil solutions.

1296 Figure 8b: Plot of the spruce site data in the ( $^{226}\text{Ra}/^{238}\text{U}$ ) vs Ba/U diagram.

1297 Figure 9: Depth variations in the Sr isotope ratios of the soil solutions from the  
1298 spruce (VP) and beech (HP) sites. The 0 cm sample points correspond to the  
1299 throughfall values. The ranges of the vegetation and atmospheric dust values  
1300 for Sr (data from Guéguen et al., 2012) are also shown. The apatite data are  
1301 from Aubert et al. (2001). The Sr isotope data for the soil solutions for 1998-  
1302 1998 are from Aubert et al. (2001), the data from 2004-2006 are from this  
1303 study; and the data from 2011-2012 are from Schmitt et al. (2017).

1304 Figure 10: ( $^{234}\text{U}/^{238}\text{U}$ ) vs  $^{87}\text{Sr}/^{86}\text{Sr}$  diagram for the soil solutions, soil grain size  
1305 fractions, vegetation samples and atmospheric deposits from the beech (HP)  
1306 and spruce (VP) sites. The albite and apatite Sr data are from Probst et al.  
1307 (2000) and Aubert et al. (2001), respectively. The curves are the theoretical  
1308 mixing curves between end-members with U–Sr characteristics similar to  
1309 those of the 2  $\mu\text{m}$  fractions of the HP beech 30-40 cm soil horizon and the  
1310 apatite and the albite end-members (see text for details).

1311 Figure 11: Plot of the data in the ( $^{230}\text{Th}/^{234}\text{U}$ ) vs ( $^{226}\text{Ra}/^{230}\text{Th}$ ) diagram. The  
1312 ( $^{230}\text{Th}/^{234}\text{U}$ ) ratio variations between depths of 10 cm and 70 cm cannot result  
1313 from the variable contributions of U and Th from litter decay.

1314 Figure 12: Plot of the data in a diagram of the ( $^{230}\text{Th}/^{232}\text{Th}$ ) ratios against  
1315 ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) isotopic ratios with the different mixing lines discussed in the  
1316 text.

1317 Figure 13: Plot of the data in the ( $^{230}\text{Th}/^{232}\text{Th}$ ) vs ( $^{234}\text{U}/^{238}\text{U}$ ) diagram. The lines in  
1318 the figure represent possible mixing lines between the different end-members  
1319 invoked to account for the dispersion of the (HP) beech plot data points in the  
1320 diagram (see text).

1321

### 1322 **Supplementary Materials**

1323 Table EA1a-d: Major and trace element concentrations in the soil solutions from the  
1324 spruce (1a) and beech (1b) plots, throughfall (1c) and rainwater (1d) for  
1325 2003-2006.

1326 Table EA2a: Major (oxide %) and trace element concentrations (mg/kg) in the  
1327 bedrock (granite), in soil ( $< 2\ \text{mm}$ ) and the soil grain size fractions from the



1328 spruce and beech plots.  
1329 Table EA2b: Major and trace element concentrations in the litter and different parts  
1330 of tree samples.  
1331 Table EA3a-e: REE concentrations in soil solutions from the spruce plot (a), from the  
1332 beech plot (b), in throughfalls (c), in the granitic bedrock, in soil (< 2 mm)  
1333 and soil grain size fractions (d) and in vegetation samples (e).  
1334  
1335 Figure EA1: SEM observations of zircons with evidence of blunted or fractured  
1336 surfaces (1a), sulfate minerals in VP spruce soils (1b) and soil solutions (1c)  
1337 Figure EA2: Variations in some major and trace element concentrations as a  
1338 function of Fe<sub>2</sub>O<sub>3</sub> concentrations for the soil size fractions from the spruce and  
1339 beech soil samples. Fe<sub>2</sub>O<sub>3</sub> concentrations increase with the decrease in the  
1340 grain size fraction.  
1341 Figure EA3: Plot of soil solution data in binary concentration diagrams (Mn, K vs. Ba;  
1342 Ba, Ca vs. Mg; Sr, Ba vs. 1/SO<sub>4</sub><sup>2-</sup>)  
1343 Figure EA4: Chloride, nitrate and sulfate concentrations of the soil solutions from  
1344 (a) 10 cm and 70 cm depths at the spruce (HP) site and (b) 5 cm, 10 cm, 30 cm  
1345 and 60 cm depths at the beech (VP) site for 1992–2010.

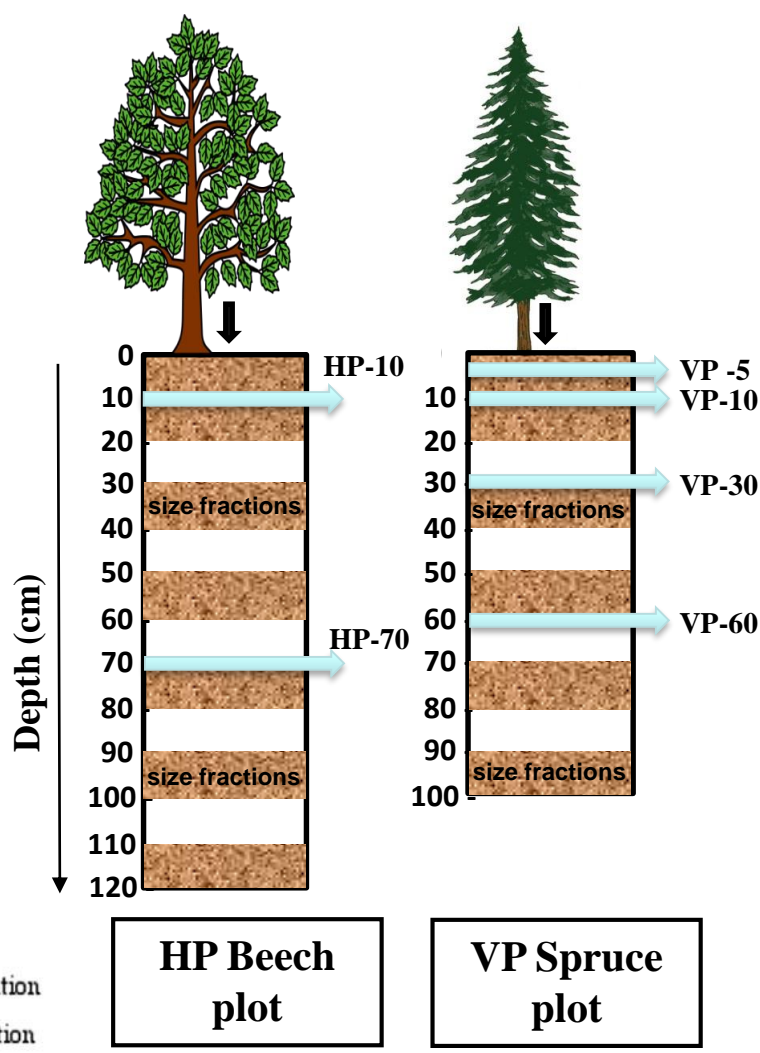
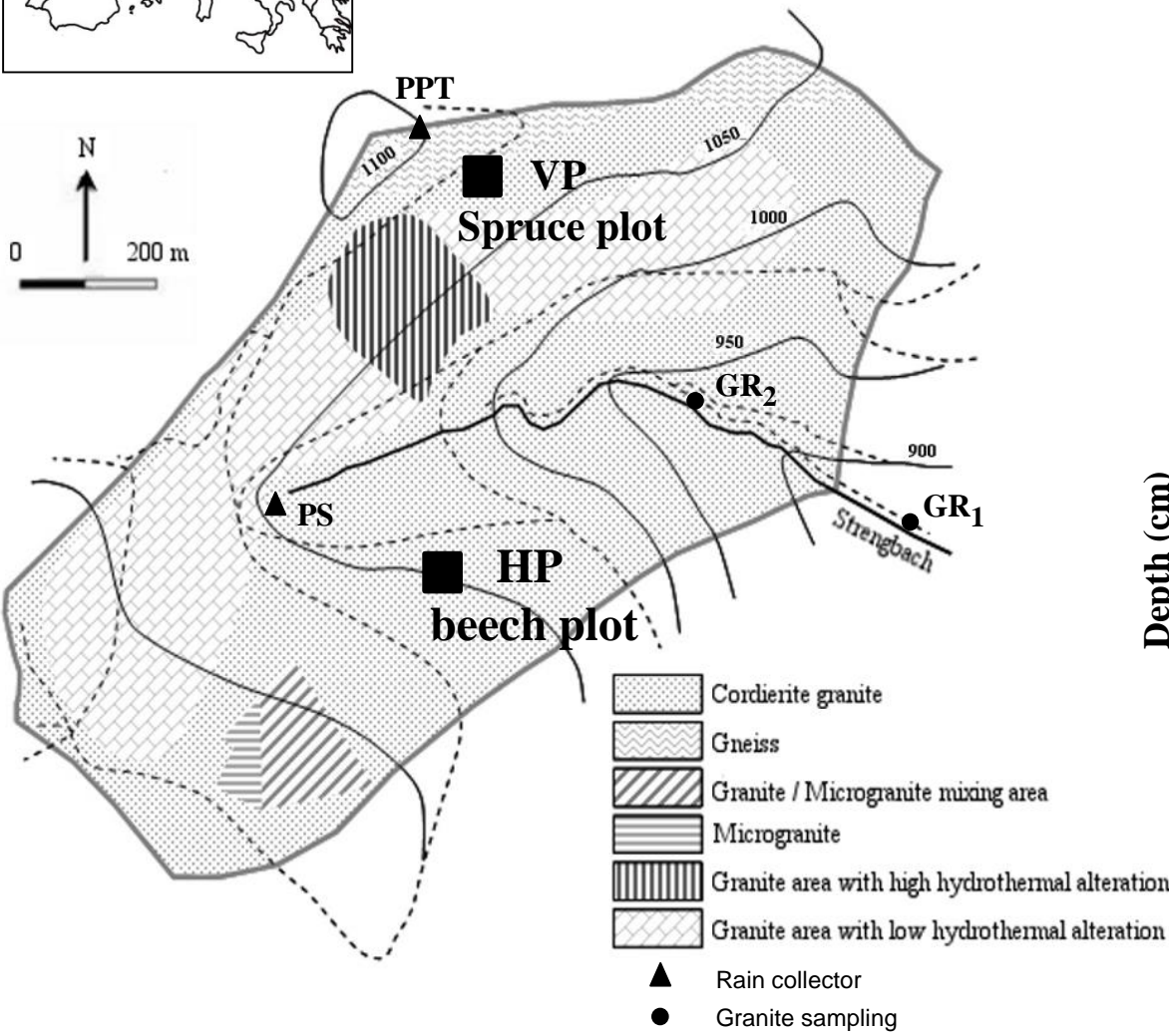
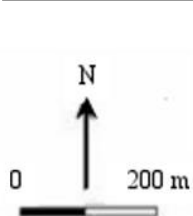


Fig.1

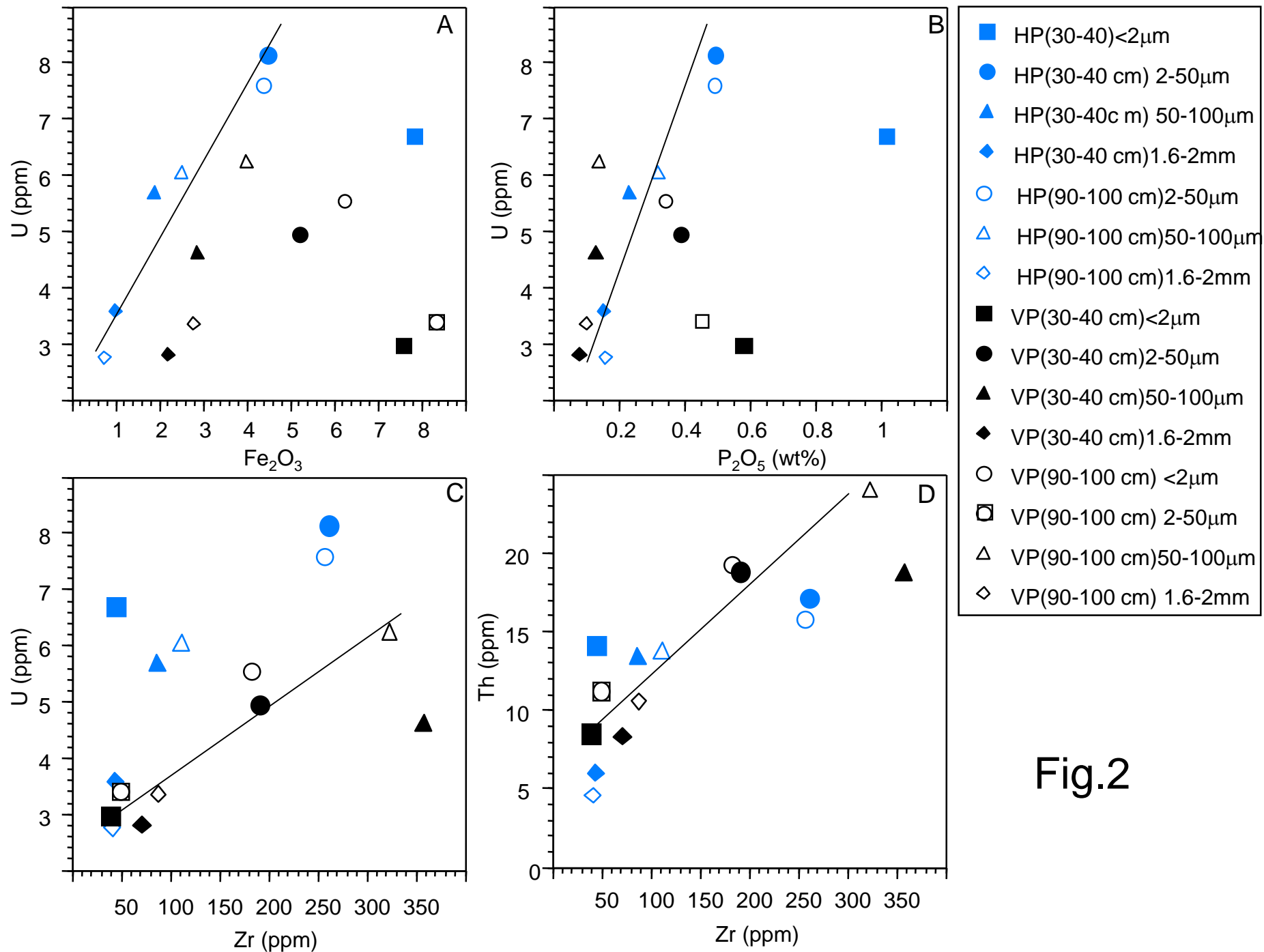


Fig.2

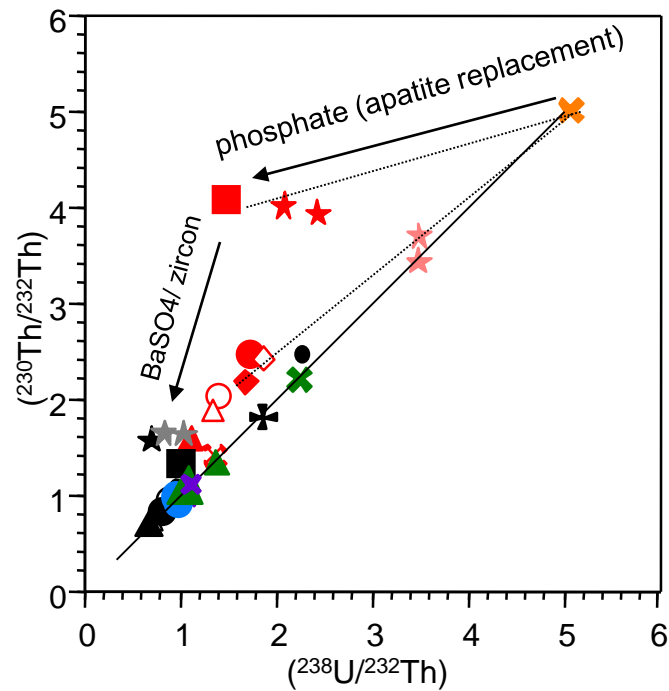
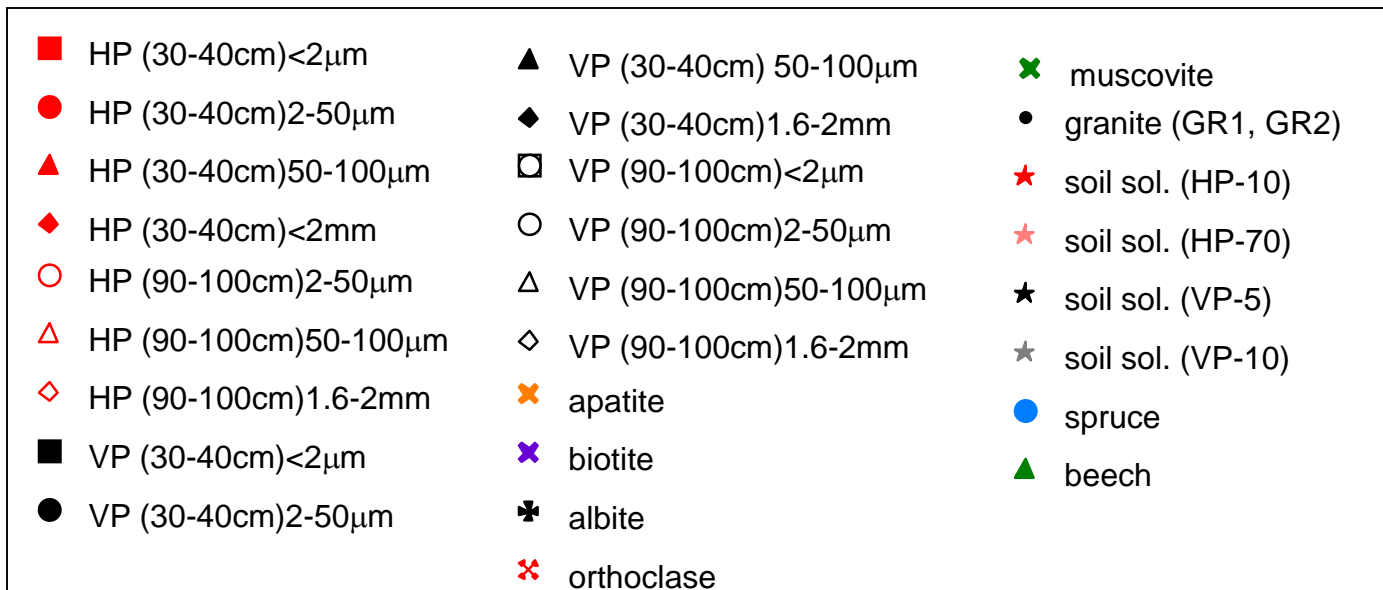


Fig.3



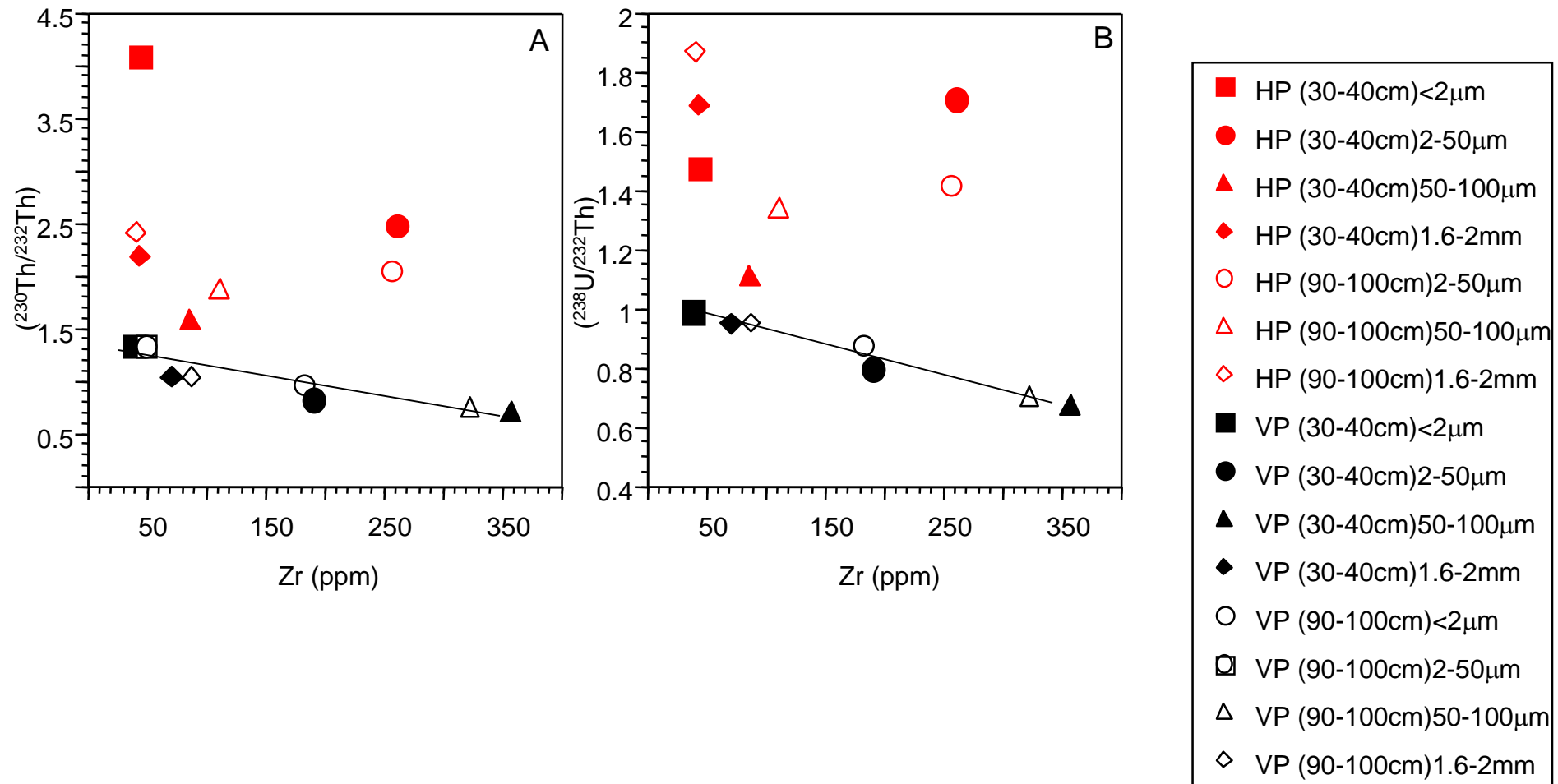


Fig.4

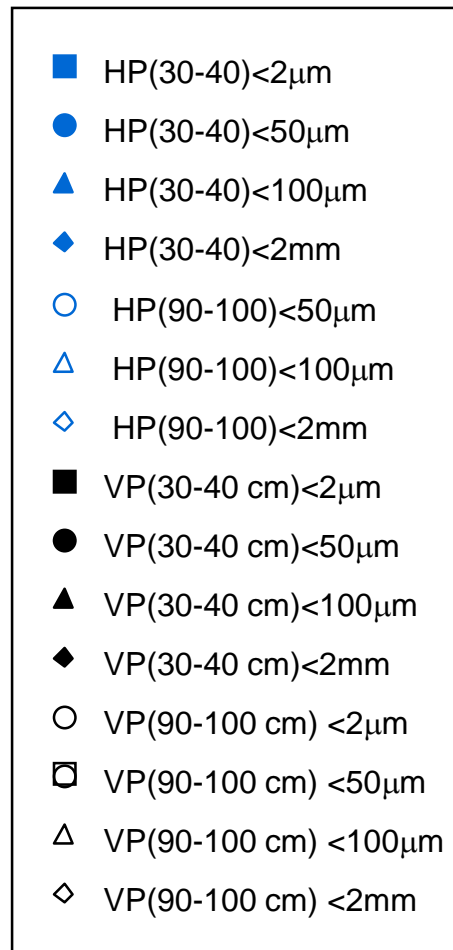
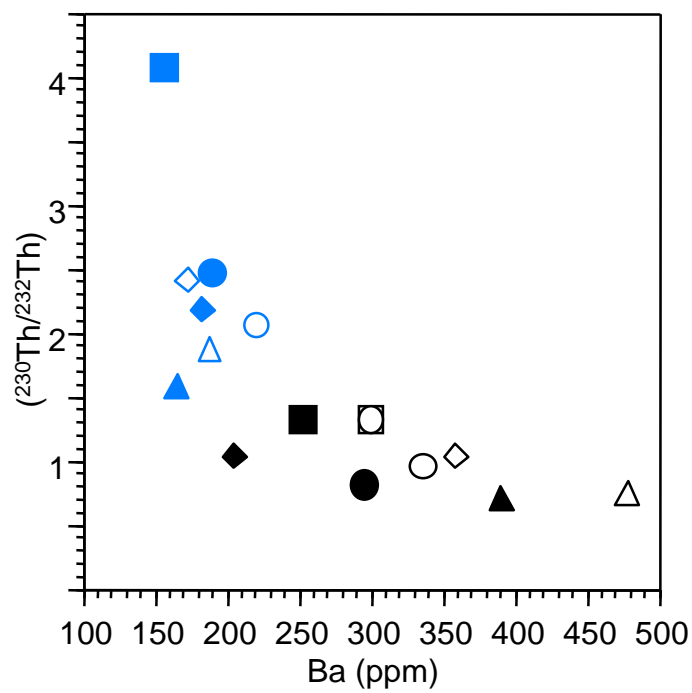
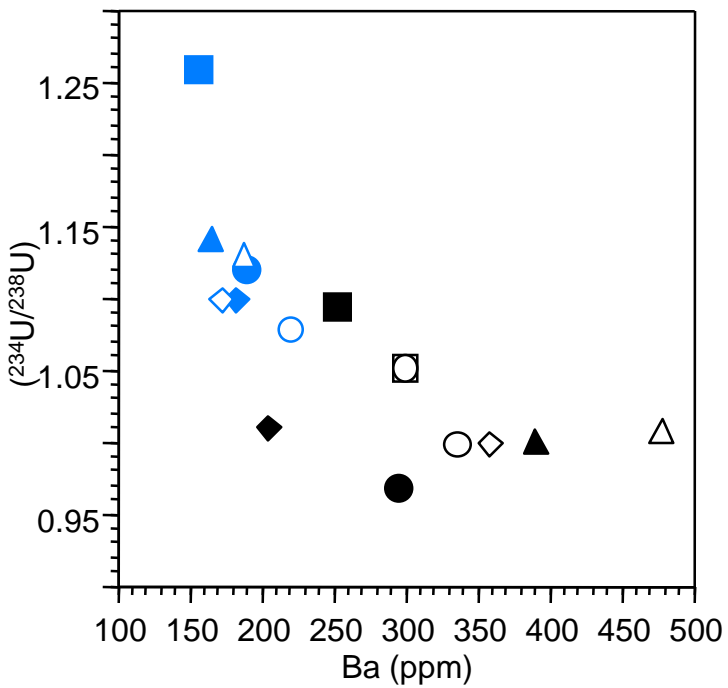


Fig.5

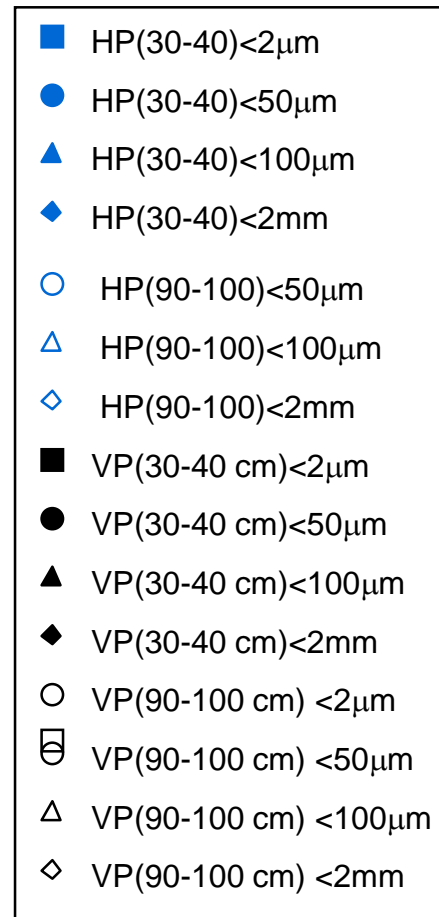
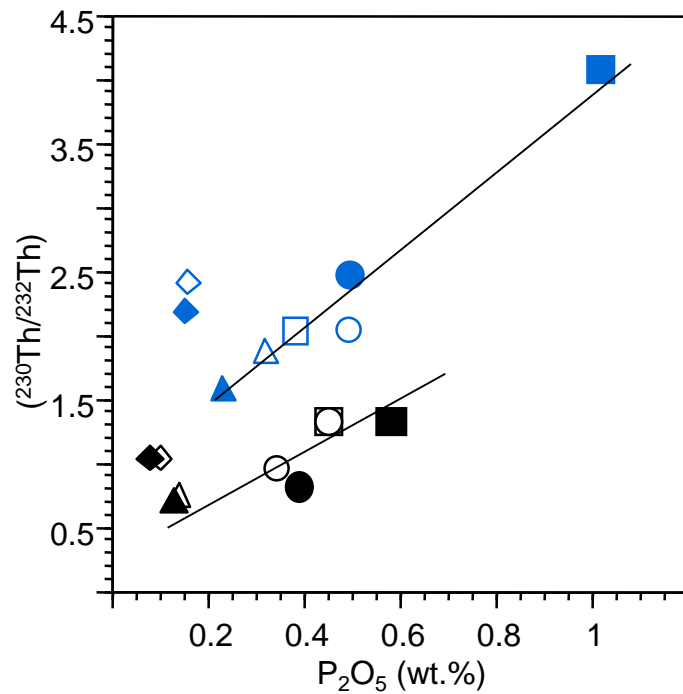


Fig.6

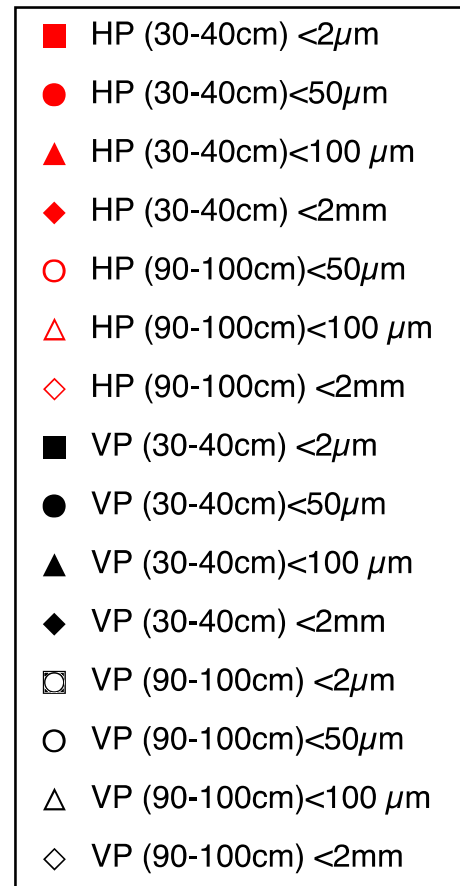
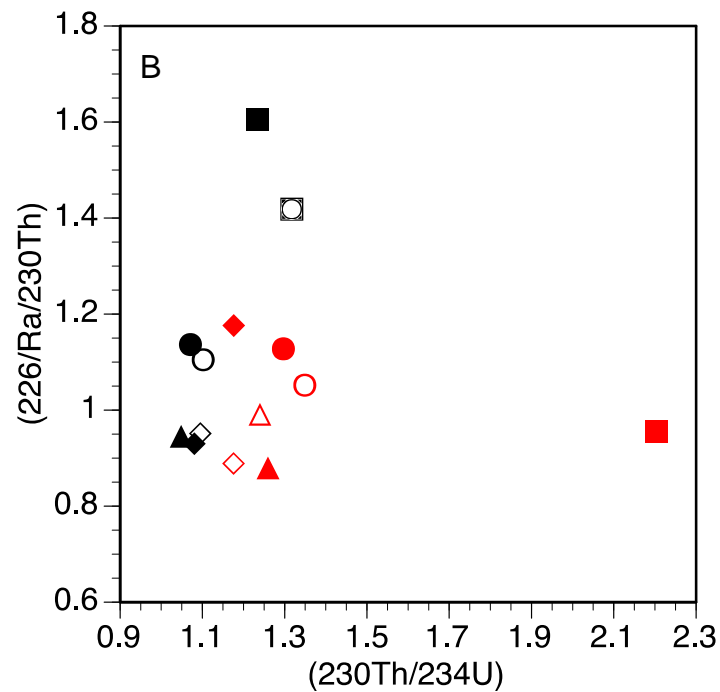
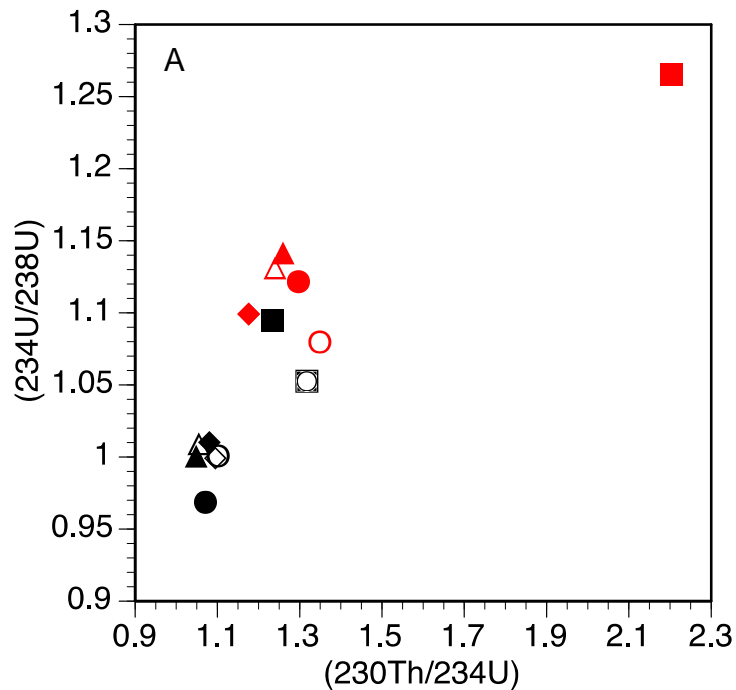
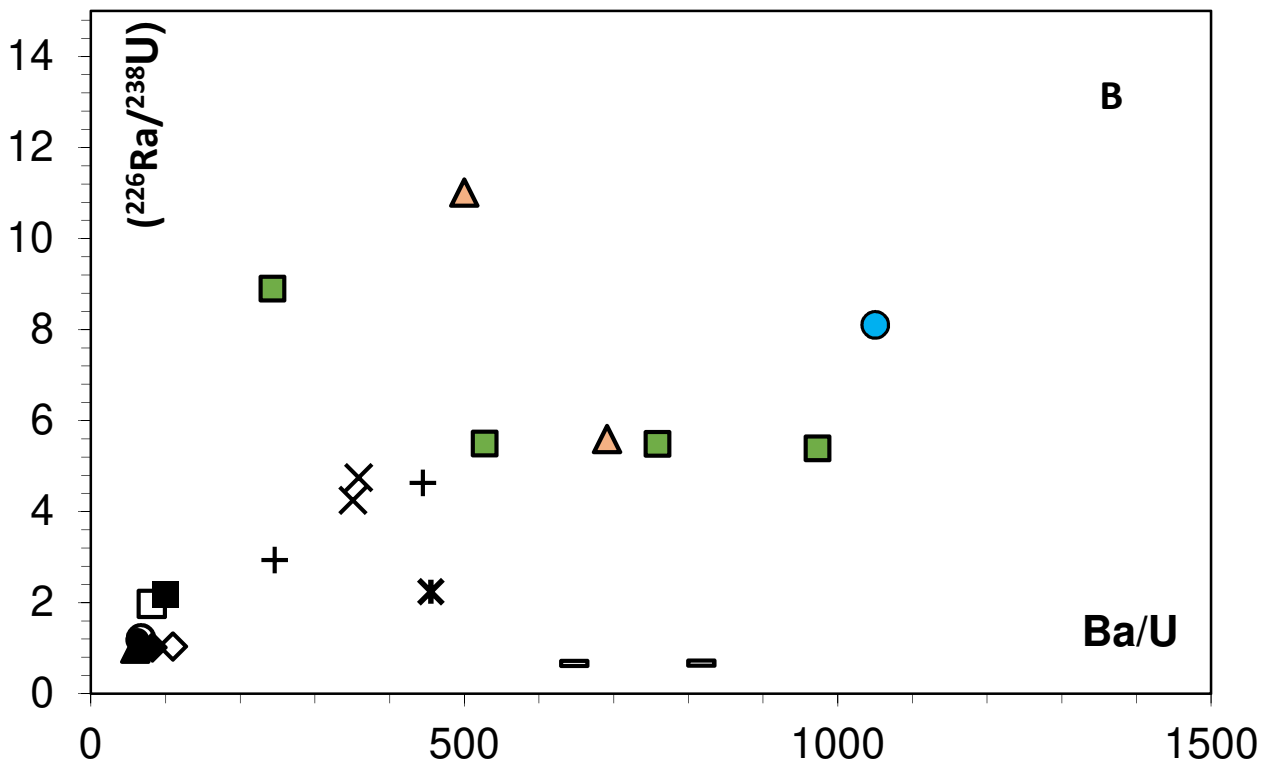
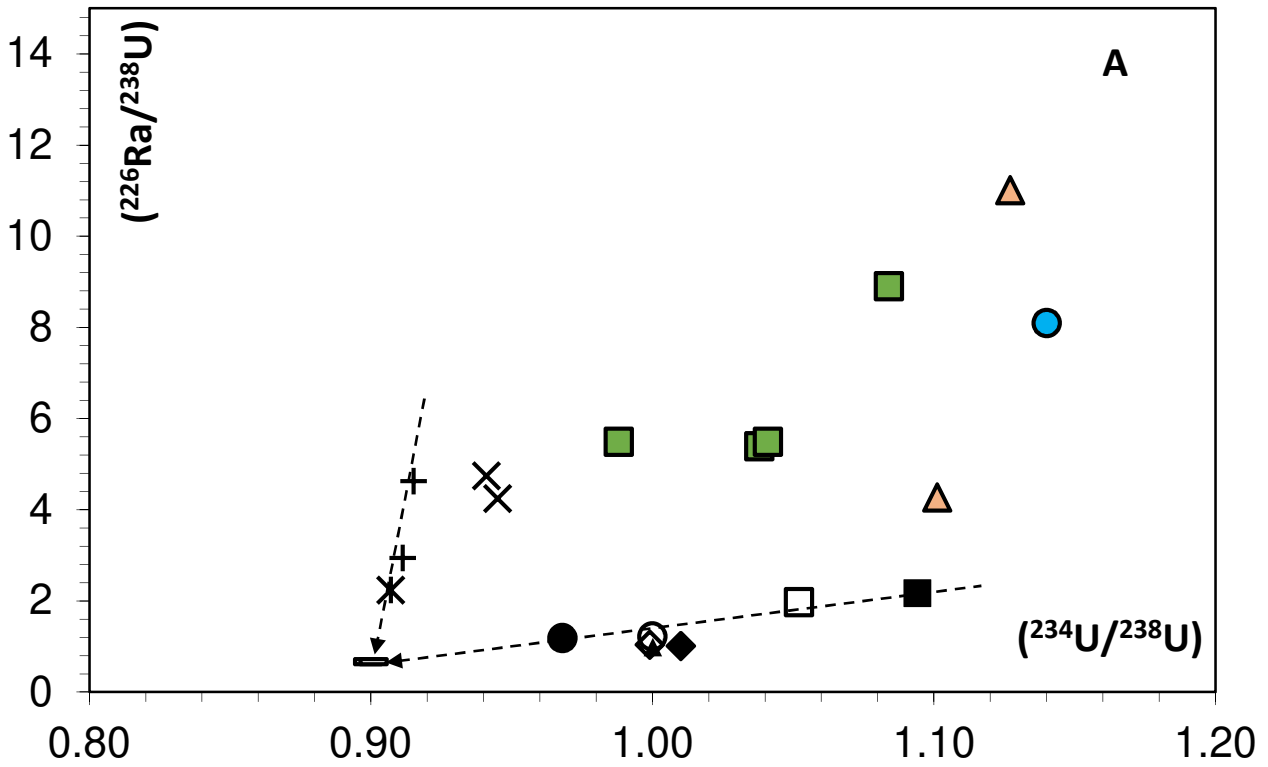


Fig.7

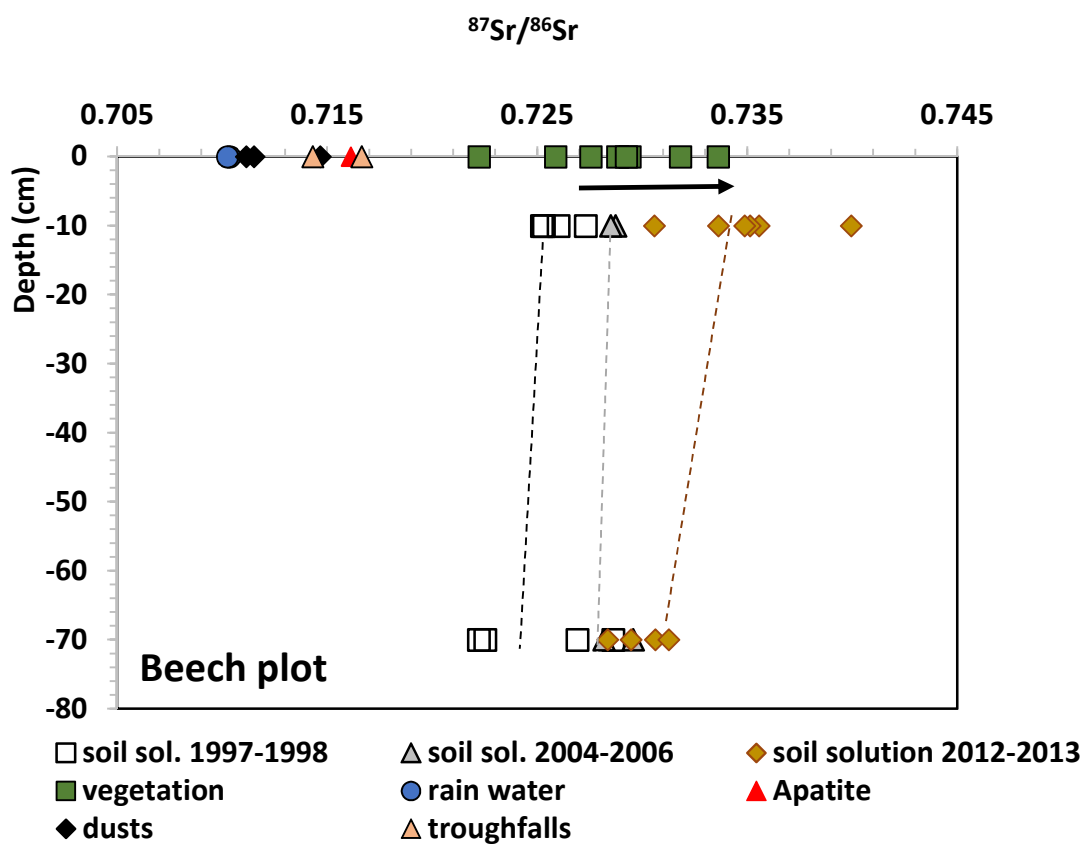
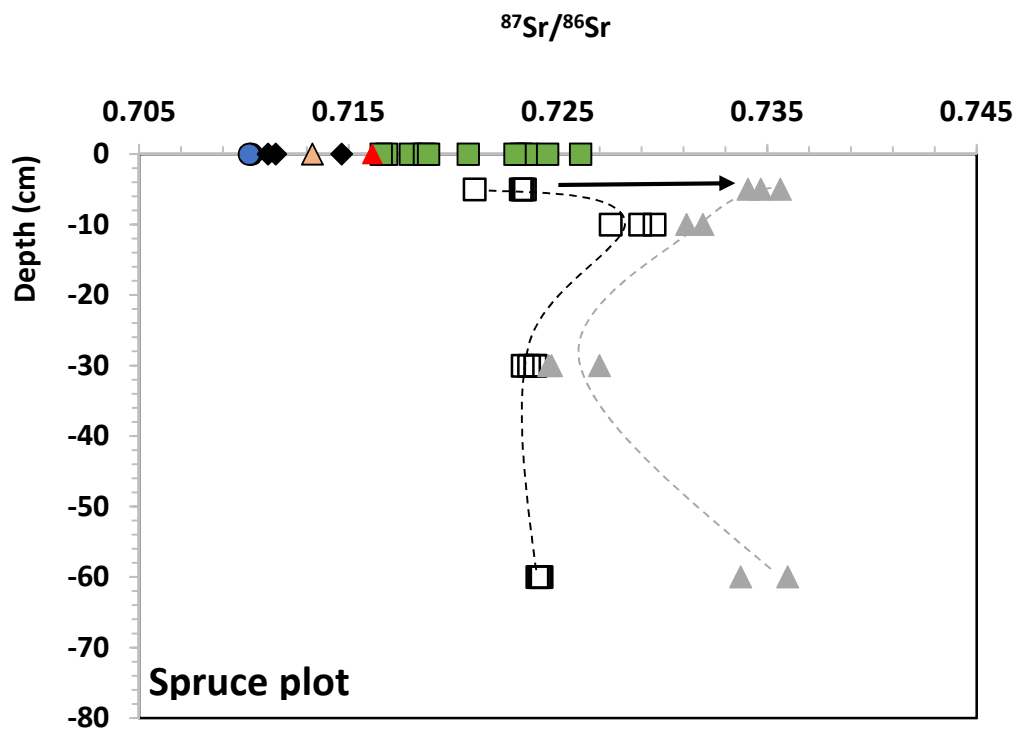






- |                      |                         |                          |
|----------------------|-------------------------|--------------------------|
| ● Rain water         | ▲ throughfalls          | ■ <2 μm (VP 30-40)       |
| ● 2-50 μm (VP 30-40) | ▲ 50-100 μm (VP 30-40)  | ◆ 1.6 - 2 mm (VP 30-40)  |
| □ <2 μm (VP 90-100)  | ○ 50-100 μm (VP 90-100) | ◇ 1.6 - 2 mm (VP 90-100) |
| ■ vegetation         | × Soil sol. -5cm        | + soil sol. -10cm        |
| — soil sol. -30cm    | ✱ soil sol. -60cm       |                          |

**Figure 8**



**Figure 9**

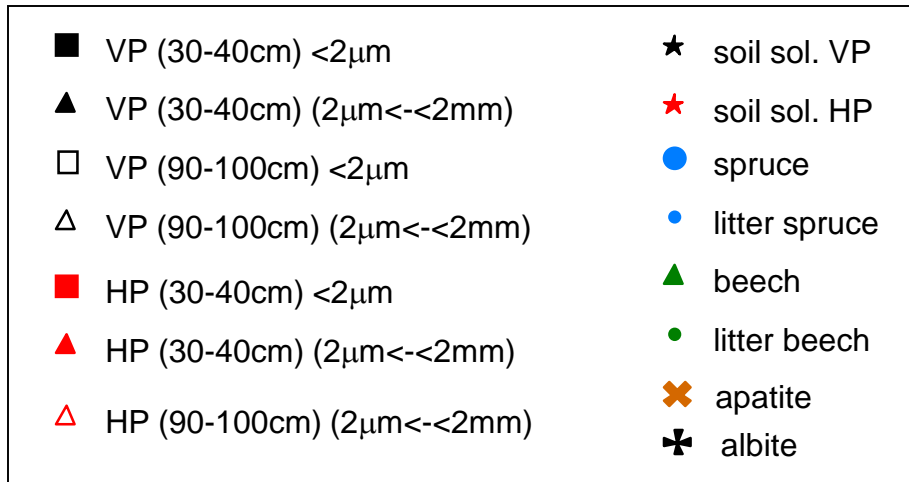
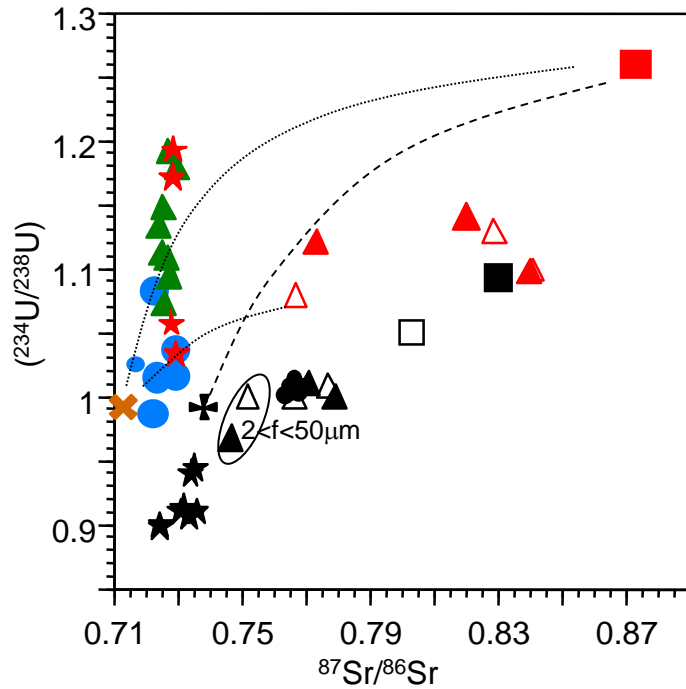


Fig.10

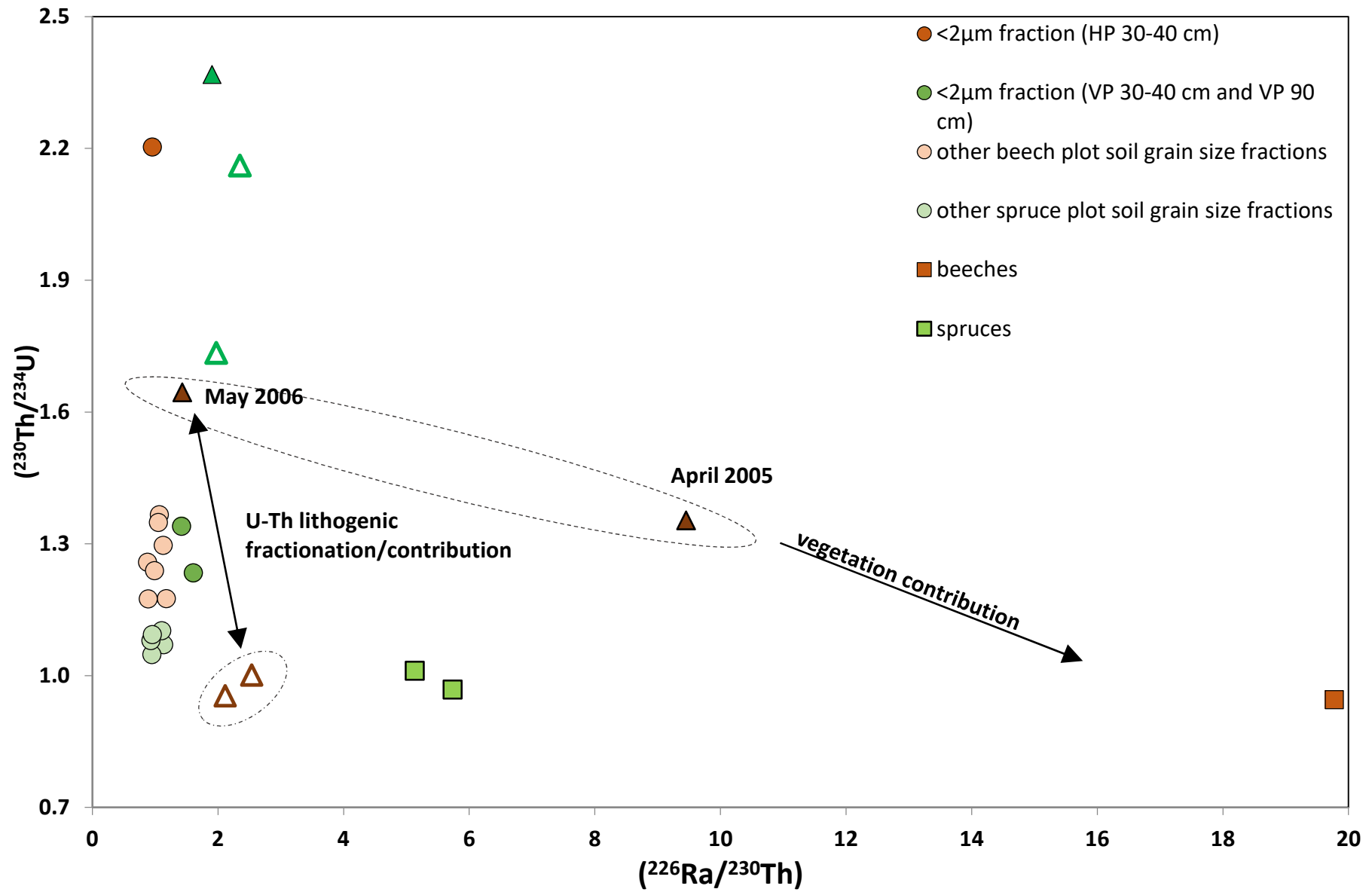


Figure 11

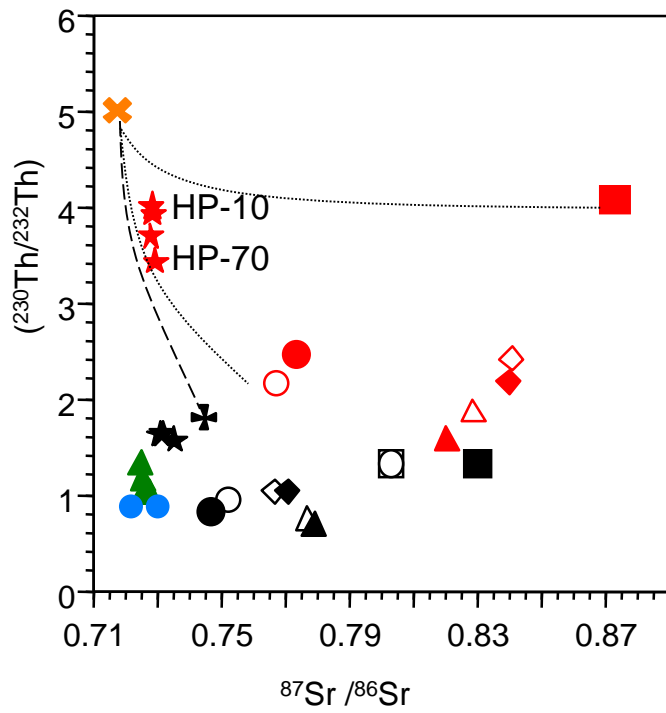
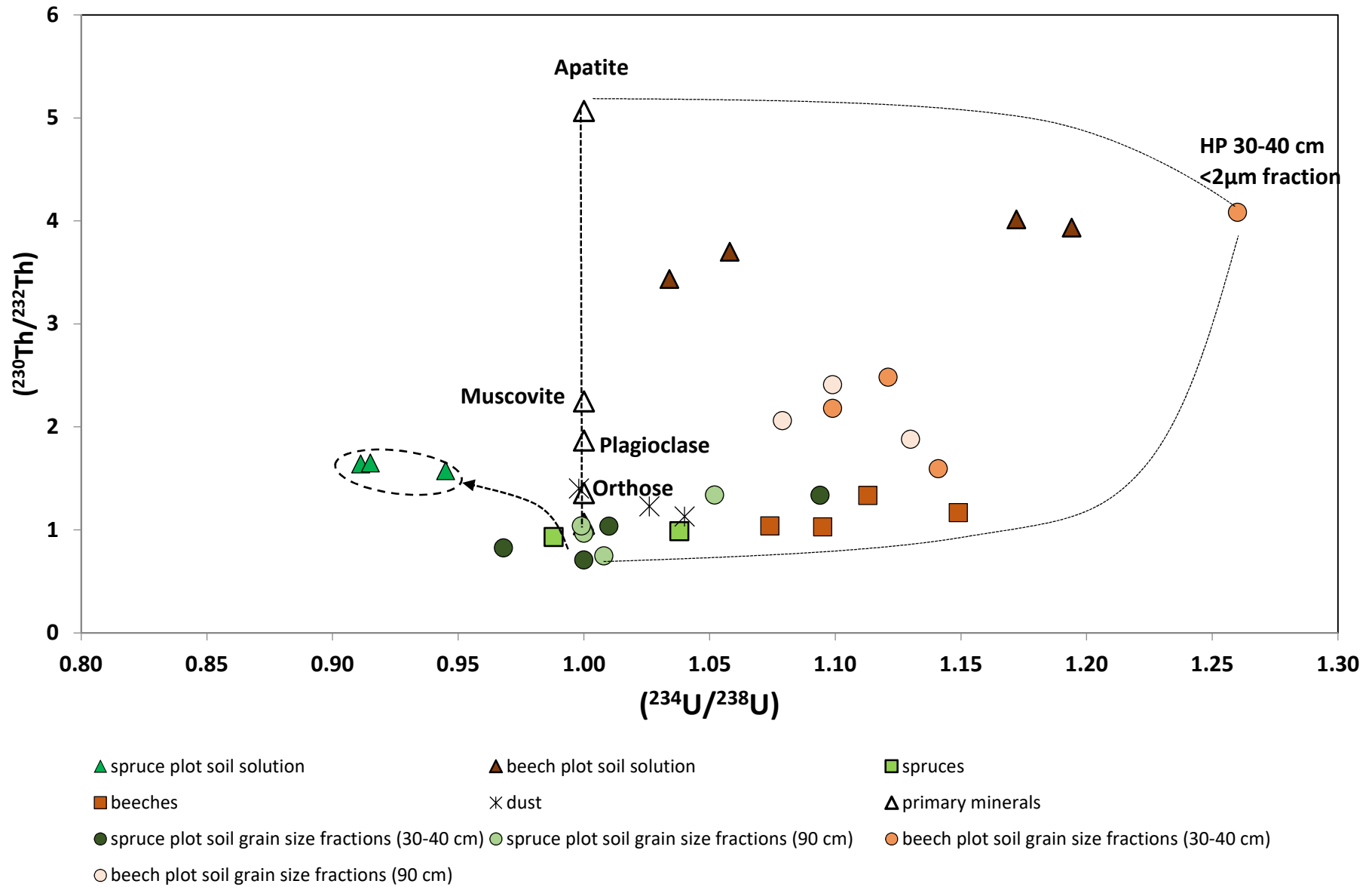


Fig.12

- HP (30-40cm)<2 $\mu\text{m}$
- HP (30-40cm)<50 $\mu\text{m}$
- ▲ HP (30-40cm)<100 $\mu\text{m}$
- ◆ HP (30-40cm)<2mm
- HP (90-100cm)<50 $\mu\text{m}$
- △ HP (90-100cm)<100 $\mu\text{m}$
- ◇ HP (90-100cm)<2mm
- VP (30-40cm)<2 $\mu\text{m}$
- VP (30-40cm)<50 $\mu\text{m}$
- ▲ VP (30-40cm)<100 $\mu\text{m}$
- ◆ VP (30-40cm)<2 $\mu\text{m}$
- VP (90-100cm)<2 $\mu\text{m}$
- VP (90-100cm)<50 $\mu\text{m}$
- △ VP (90-100cm)<100 $\mu\text{m}$
- ◇ VP (90-100cm)<2mm
- ✕ apatite
- ✦ plagioclase
- ★ soil sol. HP
- ★ soil sol. VP
- spruce
- ▲ beech



**Figure 13**

**Table 1 a** : Major and trace element concentrations,  $^{87}\text{Sr}/^{86}\text{Sr}$  and U-Th-Ra activity ratios in soil grain size fractions of two horizons 30-40 cm and 90-100 cm from spruce (VP) and beech (HP) profiles.

Site	Depth (cm)	Sample name	Size of the soil grain fractions	Fe <sub>2</sub> O <sub>3</sub> wt %	MnO <sub>2</sub> wt %	P <sub>2</sub> O <sub>5</sub> wt %	Ba mg/kg	Zr mg/kg	Pb mg/kg	Sr mg/kg	U mg/kg	Th mg/kg	Ra pg/kg	$^{87}\text{Sr}/^{86}\text{Sr}$ (2σ)	$^{234}\text{U}/^{238}\text{U}$ (2σ)	$(^{230}\text{Th}/^{232}\text{Th})$ (2σ)	$(^{238}\text{U}/^{232}\text{Th})$ (2σ)	$(^{226}\text{Ra}/^{238}\text{U})$ (2σ)	$(^{226}\text{Ra}/^{230}\text{Th})$ (2σ)
VP spruce site	30-40	VP-F1A	<2 μm	5.89	0.115	0.580	251	39.0	99.6	36.5	2.508	7.635	1820	0.83003 ± 2	1.094 ± 3	1.34 ± 1	0.99 ± 1	2.17 ± 3	1.60 ± 2
		VP-F2A	2-50 μm	4.04	0.086	0.390	295	190	85.3	133	4.717	17.83	1858	0.74672 ± 2	0.968 ± 3	0.826 ± 8	0.797 ± 8	1.18 ± 2	1.14 ± 2
		VP-F3A	50-100 μm	2.22	0.032	0.130	390	358	49.3	66.1	6.587	29.31	2183	0.77931 ± 1	1.000 ± 3	0.710 ± 7	0.677 ± 7	0.99 ± 2	0.94 ± 1
		VP-F4A	1.6-2 mm	1.71	0.049	0.080	205	71.0	53.9	47.1	2.488	7.884	844.9	0.77082 ± 1	1.010 ± 3	1.04 ± 1	0.95 ± 1	1.01 ± 2	0.93 ± 1
	90-100	VP-F1B	< 2μm	6.47	0.156	0.450	299	49.0	40.7	36.9	3.653	11.37	2402	0.80289 ± 1	1.052 ± 3	1.34 ± 1	0.97 ± 1	1.96 ± 3	1.42 ± 2
		VP-F2B	2-50 μm	4.85	0.155	0.340	335	183	51.0	102	4.965	17.01	2022	0.75209 ± 1	1.000 ± 3	0.97 ± 1	0.879 ± 9	1.22 ± 2	1.10 ± 2
		VP-F3B	50-100 μm	3.10	0.112	0.140	478	323	132	72.3	5.464	23.33	n.d	0.77721 ± 1	1.008 ± 3	0.750 ± 8	0.706 ± 7	n.d	n.d
		VP-F4B	1.6-2 mm	2.16	0.188	0.100	359	88.0	50.6	55.8	3.271	10.35	1139	0.76657 ± 8	0.999 ± 3	1.04 ± 1	0.95 ± 1	1.04 ± 2	0.95 ± 1
HP beech site	30-40	HP-F1A	< 2μm	6.09	0.076	1.02	155	44.2	38.0	20.9	6.404	13.12 (12.09)	5674	0.87288 ± 2 (0.87289±2)	1.260 ± 3 (1.265±3)	4.09 ± 4 (4.10 ± 4)	1.47 ± 2	2.65 ± 4	0.95 ± 1
		HP-F2A	2-50 μm	3.48	0.042	0.494	188	260.6	22.9	57.3	7.425	13.10	4071	0.77335 ± 2	1.121 ± 3	2.48 ± 3	1.71 ± 2	1.64 ± 3	1.13 ± 2
		HP-F3A	50-100 μm	1.46	0.018	0.231	165	86.6	20.8	45.7	5.286	14.34	2234	0.82036 ± 2	1.141 ± 3	1.60 ± 2	1.11 ± 1	1.26 ± 2	0.88 ± 1
		HP-F4A	1.6-2 mm	0.77	0.032	0.154	183	43.9	20.4	31.7	3.253	5.803	1424	0.8402 ± 2	1.099 ± 3	2.18 ± 2	1.69 ± 2	1.31 ± 2	1.18 ± 2
	90-100	HP-F2B	2-50 μm	3.40	0.038	0.490	219	256	41.9	71.6	7.425	15.79	3799	0.76688 ± 1	1.079 ± 3	2.06 ± 2	1.42 ± 2	1.53 ± 2	1.05 ± 2
		HP-F3B	50-100 μm	1.94	0.036	0.320	188	111	70.5	49.8	5.809	13.02	2692	0.82885 ± 1 (0.82882±4)	1.130 ± 3	1.88 ± 2	1.34 ± 1	1.38 ± 2	0.99 ± 2
		HP-F4B	1.6-2 mm	0.57	0.013	0.160	172	41.0	42.3	34.7	3.401	5.487	1307	0.84092 ± 2	1.099 ± 3	2.41 ± 2	1.87 ± 2	1.15 ± 2	0.89 ± 1

U-Th-Ra data were determined by isotope dilution (n.d.: no defined). Replicates in brackets.



**Table 1b:** Major and trace element concentrations,  $^{87}\text{Sr}/^{86}\text{Sr}$  and U-Th-Ra activity ratios in soil solutions, rainwaters and throughfalls from the Strengbach catchment.

Site	Sample name	Depth (cm)	date	SO <sub>4</sub> <sup>2-</sup> mmol/L	DOC mg/kg	Fe mg/kg	Ba μg/kg	Sr μg/kg	U μg/kg	Th μg/kg	Ra fg/kg	$^{87}\text{Sr}/^{86}\text{Sr}$ (2σ)	( <sup>234</sup> U/ <sup>238</sup> U) (2σ)	( <sup>230</sup> Th/ <sup>232</sup> Th) (2σ)	( <sup>238</sup> U/ <sup>232</sup> Th) (2σ)	( <sup>226</sup> Ra/ <sup>238</sup> U) (2σ)	( <sup>226</sup> Ra/ <sup>230</sup> Th) (2σ)
VP spruce site (7°1983 E, 48°216N)	VP-5 (soil solution)	-5	29/03/2005	0.040	16.7	0.470	14.3	4.18	0.0400	0.0740	63.38	0.73407 ± 2	0.941 ± 3	n.d	n.d	4.75 ± 7	n.d
		-5	22/05/2006	0.030	26.6	0.690	13.9	4.24	0.0379	0.1620	54.00	0.73561 ± 2	0.945 ± 4	1.58 ± 2	0.704 ± 7	4.25 ± 6	1.90 ± 3
	VP-10 (soil solution)	-10	29/03/2005	0.038	10.9	0.270	10.9	2.33	0.0444	0.1230	44.14	0.73114 ± 5	0.9112 ± 8	1.64 ± 2	1.04 ± 1	2.94 ± 4	1.97 ± 3
		-10	22/05/2006	0.030	13.7	0.290	14.3	3.17	0.0321	0.1160	49.80	0.73191 ± 2	0.915 ± 4	1.65 ± 2	0.838 ± 8	4.63 ± 7	2.35 ± 4
	VP-30 (soil solution)	-30	29/03/2005	0.045	4.38	0.026	30.3	3.09	0.0370	0.0350	8.300	0.72468 ± 2	0.899 ± 3	n.d	n.d	0.670 ± 1	n.d
		-30	22/05/2006	0.037	4.97	0.024	19.3	2.11	0.0298	0.0440	6.700	0.72455 ± 2	0.901 ± 1	n.d	n.d	0.667 ± 1	n.d
VP-60 (soil solution)	VP-60 (soil solution)	-60	02/11/2004	0.049	2.61	0.003	17.8	2.65	0.0120	0.0070	n.d	0.73597 ± 2	0.911 ± 4	n.d	n.d	n.d	n.d
		-60	29/03/2005	0.052	1.76	0.008	13.7	3.22	0.0300	0.0050	22.64	0.73372 ± 2	0.907 ± 4	n.d	n.d	2.24 ± 3	n.d
HP beech site (7°1963 E, 48°211 N)	HP-10 (soil solution)	-10	29/03/2005	0.031	5.74	0.200	4.38	1.44	0.0380	0.0470	194.5	0.72872 ± 2	1.194 ± 3	3.94 ± 4	2.44 ± 2	15.1 ± 2	9.4 ± 1
		-10	22/05/2006	0.012	12.93	0.470	3.03	1.05	0.0740	0.1080	68.70	0.72850 ± 2	1.172 ± 2	4.02 ± 4	2.08 ± 2	2.76 ± 4	1.43 ± 2
	HP-70 (soil solution)	-70	29/03/2005	0.027	2.26	0.009	4.52	0.68	0.0290	0.0253	26.08	0.72817 ± 2	1.058 ± 3	3.70 ± 4	3.50 ± 4	2.68 ± 4	2.53 ± 4
Top of watershed	PPT (rain water) PS (rain water)	31/05/2005	0.018	0.81	0.003	0.63	0.90	0.0006	n.d	1.100	0.71024 ± 4	1.140 ± 3	n.d	n.d	5.25 ± 8	n.d	
		03/05/2005	0.013	0.72	0.007	3.19	0.81	0.0006	n.d	1.600	n.d	n.d	n.d	n.d	8.1 ± 1	n.d	
VP spruce site (7°1983 E, 48°216N)	VP-PL5 (Throughfall)	29/03/2005	0.202	19.0	0.050	27.8	16.0	0.0028	<i>0.006</i>	27.97	n.d	n.d	n.d	n.d	21.9 ± 3	n.d	
		31/05/2005	0.025	4.1	0.030	11.0	2.77	0.0029	<i>0.001</i>	4.100	0.71327 ± 2	1.101 ± 3	n.d	n.d	4.27 ± 6	n.d	
HP beech site (7°1963 E, 48°211 N)	HP-PLH (Throughfall)	29/03/2005	0.041	4.47	0.010	4.14	5.26	0.0060	<i>0.007</i>	11.32	n.d	n.d	n.d	n.d	6.00 ± 8	n.d	
		31/05/2005	0.033	9.04	0.010	0.510	0.56	0.0010	<i>0.005</i>	3.800	0.71664 ± 3	1.127 ± 4	n.d	n.d	11.0 ± 2	n.d	

U-Th-Ra italic data were determined by ICP-MS and the others by isotope dilution (n.d.: no defined). Replicates in brackets.

**Table 1c :** Major and trace element concentrations,  $^{87}\text{Sr}/^{86}\text{Sr}$  and U-Th-Ra activity ratios in litter and in different parts of tree samples.

Site	Sample	Sample name	Date	Ca mg/kg	K mg/kg	Mn mg/kg	Ba mg/kg	Sr mg/kg	U $\mu\text{g}/\text{kg}$	Th $\mu\text{g}/\text{kg}$	Ra pg/kg	$^{87}\text{Sr}/^{86}\text{Sr}$ (2 $\sigma$ )	( $^{234}\text{U}/^{238}\text{U}$ ) (2 $\sigma$ )	( $^{230}\text{Th}/^{232}\text{Th}$ ) (2 $\sigma$ )	( $^{238}\text{U}/^{232}\text{Th}$ ) (2 $\sigma$ )	( $^{226}\text{Ra}/^{238}\text{U}$ ) (2 $\sigma$ )	( $^{226}\text{Ra}/^{230}\text{Th}$ ) (2 $\sigma$ )
VP spruce site	Litter	VP-LT	21/06/2004	3487	992.5	1038	13.8	7.17	<i>19.6</i>	<i>59.0</i>	n.d	0.71653 $\pm$ 2	1.026 $\pm$ 5	n.d	n.d	n.d	n.d
	Sapwood	VP-SW	23/05/2006	594	338.8	1117	28.4	6.25	0.3830	1.154	10.13	0.72915 $\pm$ 4	1.017 $\pm$ 4	n.d	n.d	79 $\pm$ 1	n.d
	Tree roots ( $\varnothing = 2\text{-}5$ mm)	VP-MR	23/05/2006	2647	3415	81.1	29.55	5.89	56.01	173.3	102.9	0.72195 $\pm$ 3	0.988 $\pm$ 3	0.932 $\pm$ 9	0.97 $\pm$ 1	5.49 $\pm$ 8	5.73 $\pm$ 9
	Top tree branches ( $\varnothing = 2\text{-}5$ mm)	VP-TB	15/05/2007	2148	5140	91.6	9.32	5.25	9.583	30.67	17.29	0.71934 $\pm$ 3	1.038 $\pm$ 3	0.99 $\pm$ 1	0.941 $\pm$ 9	5.39 $\pm$ 8	5.13 $\pm$ 8
	Needles ( $>$ 1yr)	VP-ON4	15/05/2007	1736	4080	88.6	1.42	1.20	1.876	<i>5.92</i>	0.7057	0.72345 $\pm$ 3	1.016 $\pm$ 3	n.d	n.d	1.12 $\pm$ 2	n.d
	Needles ( $<$ 1yr)	VP-YN1	15/05/2007	458	11293	141	0.601	0.36	2.467	<i>5.91</i>	7.349	0.72222 $\pm$ 2	1.084 $\pm$ 3	n.d	n.d	8.9 $\pm$ 1	n.d
HP beech site	Litter	HP-LT	21/06/2004	5766	2043	757	16.3	12.7	<i>15.5</i>	<i>35.2</i>	n.d	n.d	1.049 $\pm$ 4	n.d	n.d	n.d	n.d
	Sapwood	HP-SW	21/09/2005	182	273.2	16.2	7.41	2.69	0.234	1.089	110.8	0.72977 $\pm$ 2	1.179 $\pm$ 11	n.d	0.648 $\pm$ 6	1413 $\pm$ 21	n.d
	Buds	HP-B	05/05/2005	5057	21872	533	11.7	7.28	1.104	3.495	80.19	0.72726 $\pm$ 8	1.192 $\pm$ 5	n.d	0.95 $\pm$ 1	217 $\pm$ 3	n.d
	Leaves (180 cm high)	HP-L2	13/09/2005	6698	9520	743	17.1	9.86	3.365	9.036	170.2	0.72744 $\pm$ 3	1.095 $\pm$ 4	1.03 $\pm$ 1	1.12 $\pm$ 1	151 $\pm$ 2	164 $\pm$ 2
	Top leaves	HP-SL	21/09/2005	5460	11253	738	7.63	5.82	2.449	7.380	<i>71.97</i> (72.47)	0.72577 $\pm$ 1	1.074 $\pm$ 4	1.04 $\pm$ 1	1.00 $\pm$ 1	88 $\pm$ 1	84 $\pm$ 1
	Tree roots ( $\varnothing = 2\text{-}5$ mm)	HP-MR	13/09/2005	2965	2324	108	27.7	10.6	7.307	16.82	262.2	0.72433 $\pm$ 3	1.133 $\pm$ 4	n.d	1.31 $\pm$ 1	107 $\pm$ 2	n.d
	Tree roots ( $\varnothing = 1\text{-}1.5$ cm)	HP-SR	13/09/2005	1229	2114	67.1	13.0	5.38	16.75	47.09	120.8	0.72550 $\pm$ 2	1.149 $\pm$ 3	1.17 $\pm$ 1	1.08 $\pm$ 1	21.5 $\pm$ 3	19.8 $\pm$ 3
	Fine rootlets	HP-FR	13/09/2005	1419	2651	107	24.7	7.96	68.28	148.9	687.7	0.72518 $\pm$ 1	1.113 $\pm$ 3	1.34 $\pm$ 1	1.38 $\pm$ 1	30.1 $\pm$ 5	31.1 $\pm$ 5
Top tree branches ( $\varnothing = 2\text{-}5$ mm)	HP-TB	21/09/2005	2954	2311	290	22.8	8.92	0.879 (0.892)	2.070	70.46	0.72664 $\pm$ 1 (0.72672 $\pm$ 8)	1.109 $\pm$ 4 (1.118 $\pm$ 6)	n.d	1.28 $\pm$ 1	239 $\pm$ 4	n.d	

U-Th-Ra italic data were determined by ICP-MS and the others by isotope dilution (n.d. : no defined). Replicates in brackets

**Table 2a**

	<b>Ca Flux</b> kg/m <sup>2</sup> /a	<b>(Ba/Ca)</b> µg/g	<b>(U/Ca)</b> µg/g	<b>(Th/Ca)</b> µg/g	<b>(Ra/Ca)</b> pg/g	<b>Ba flux</b> µg/m <sup>2</sup> /a	<b>U flux</b> µg/m <sup>2</sup> /a	<b>Th flux</b> µg/m <sup>2</sup> /a	<b>Ra flux</b> µg/m <sup>2</sup> /a
<b>Spruce Plot</b>	12	0.8 - 4	1 - 5.3	3 - 15	4 - 16	900 - 1500	0.7 - 6	2 - 17	4.10 <sup>-6</sup> - 2. 10 <sup>-5</sup>
<b>Beech Plot</b>	17.6	1.4 - 7.7	0.3 - 0.5	0.7 - 1.3	13 -25	2000 - 13000	0.5 - 1	1 - 2.3	2.10 <sup>-5</sup> - 4.5 10 <sup>-5</sup>

Ba, U, Th and Ra fluxes are calculated by using the Ca flux given in Poszwa et al. (2000) and the range of Ba/Ca, U/Ca, Th/Ca and Ra/Ca concentrations ratios estimated for aerial parts (needles, leaves and branches) of trees analysed in each plot.

**Table 2b**

	Flux kg/m <sup>2</sup> /a	(U) µg/kg	(Th) µg/kg	(Ba) µg/kg	(Ra) µg/kg	U flux µg/m <sup>2</sup> /a	Th flux µg/m <sup>2</sup> /a	Ba flux µg/m <sup>2</sup> /a	Ra flux µg/m <sup>2</sup> /a
<b><i>Spruce (VP) plot : Litter<sup>a</sup></i></b>	0.3	2.2/19	5.9/59	10.1/13.8 10 <sup>3</sup>	4	0.7/5.7	1.8/17.7	3/4.1 10 <sup>3</sup>	0.62 10 <sup>-5</sup>
<b>Throughfall</b>	1322	0.015±0.01	0.009±0.006	6±5	16	5.5±4	12±8	10±8 10 <sup>3</sup>	2.1 10 <sup>-5</sup>
<b>soil solution (-5cm)</b>	1246	0.03±0.01	0.11±0.05	13±6	59	37±17	137±65	16.6±8 10 <sup>3</sup>	7.3 10 <sup>-5</sup>
<b>soil solution (-10cm)</b>	1185	0.03±0.01	0.11±0.04	14±8	50	41±15	136±45	17.5±9.5 10 <sup>3</sup>	5.6 10 <sup>-5</sup>
<b>soil solution (-30cm)</b>	1119	0.03±0.01	0.04±0.01	30±9	7.5	32±7	48±11	35.±10.5 10 <sup>3</sup>	0.8 10 <sup>-5</sup>
<b>soil solution (-60cm)</b>	1107	0.012±0.01	0.005±0.004	10±4	22.6	13±10	6±4	11.3±4.2 10 <sup>3</sup>	2.5 10 <sup>-5</sup>
<b><i>Beech (HP) Plot : Litter<sup>b</sup></i></b>	0.4	3/15	8.2/35	12.3/16 10 <sup>3</sup>	140	1.2/3	3.3/14	4.9/6.5 10 <sup>3</sup>	17 10 <sup>-5</sup>
<b>Throughfall</b>	1376	0.01±0.005	0.01±0.005	1.24±1	7.55	7±6	9±7	2±1.5 10 <sup>3</sup>	1.03 10 <sup>-5</sup>
<b>soil solution (- 10cm)</b>	1295	0.065±0.02	0.1±0.03	4.3±1.5	132	84±30	118±40	5.5±2 10 <sup>3</sup>	17 10 <sup>-5</sup>
<b>soil solution (- 70cm)</b>	1160	0.024±0.01	0.021±0.01	4.8±1.2	24	28±9	24±9	5.6±1.4 10 <sup>3</sup>	2.7 10 <sup>-5</sup>

A daily water balance model developed by Granier et al. (1999) has been used to estimate the soil drainage at different depths. This model simulates the dynamics of soil water depletion and recharge, and predicts the main components of forest water balance (at $\approx$ ±10%). <sup>a</sup> Litter Flux in Ignatova and Dambrine, 2010 ; <sup>b</sup> Litter flux in Rihs et al., 2011. The U, Th, and Ba concentrations are the 2004-2006 mean annual concentrations and the standard deviation from data given in Table EA 1. The Ra concentration data are the average of the few analyses obtained in the present study. For the litters, the fluxes are calculated with the concentrations analyzed in the litter samples, which can contain some soil materials. If using leaf or needle data (in italic in table), the calculated U and Th fluxes would be  $\approx$  one order of magnitude lower for U and Th.