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Variations of ^{137}Cs depositions and soil concentrations between alpine and montane soils in northern Colorado

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Abstract

^{137}Cs was measured in soil samples taken from two high-elevation sites in the northern Front Range of Colorado. The first site was in an alpine meadow adjacent to a glacial lake, while the second site was in a nearby montane forest at a slightly lower elevation. The samples were all of equal volume and represented an equal ground surface area. The coefficients of variation of ^{137}Cs soil activity concentration (Bq g^{-1}) were similar for the two sites, as were the CVs for activity deposition (Bq m^{-2}). The mean ^{137}Cs depositions we found were generally in agreement with values reported in the literature for similar elevations and higher than values found at lower elevation sites in the same region. Activity deposition was less variable than activity concentration at both sites. The alpine site had a significantly higher mean ^{137}Cs concentration than the montane site, but a significantly lower mean deposition value. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Radiocesium; Fallout; Deposition

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1. Introduction

^{137}Cs has been deposited in soils throughout the world via atmospheric deposition of fallout originating from aboveground nuclear weapons tests and from the Chernobyl accident. Many studies have been conducted which report ^{137}Cs levels in soils

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(for example, Arnalds, Cutshall & Nielsen, 1989; Coppinger, Reiners, Burke & Olson, 1991; Ivanov et al., 1997; Kagen & Kadatsky, 1996; Knatko, Skomorokhov, Asimova Strakh, Bogdanov & Mironov, 1996; Melin, Wallberg & Suomela, 1994; Ruhm, Kammerer & Wirth, 1996; Wallbrink & Murray, 1996). When intersite comparisons of ^{137}Cs activity are to be performed results are normally given in units of deposition (activity/area). But for specific mechanistic purposes (such as calculation of transfer coefficients or the study of topsoil erosion, for example) it is appropriate to report ^{137}Cs activities in units of concentration (activity/dry soil mass) (Gerzabek, Mohamad & Muck, 1992; Hoshi et al., 1994; Owens, Walling, Qingping, 1996).

In the United States, numerous public utilities have established soil monitoring programs at nuclear power generating stations and similar monitoring programs have been established at numerous U.S. Department of Energy former weapons production facilities and national laboratories. ^{137}Cs activity concentration data are routinely collected under these programs, but collection of activity deposition data is uncommon. As the US approaches a period of decomissioning and remediation of nuclear facilities and release of these areas to the private sector is contemplated, decision makers are relying on data collected under their biomonitoring programs to certify the success of their remedial efforts. This is usually accomplished by comparing remediated sites to uncontaminated background sites to demonstrate that no unacceptable levels of contamination remain. Unfortunately, soil activity concentration data are often inappropriate for such comparisons, because soil bulk density and activity depth distribution are confounding factors.

In this study, we examined both ^{137}Cs activity concentration and activity deposition values in the soils of two high-altitude sites in northern Colorado to determine whether there was any difference in variability between the two quantities. We hypothesized that activity deposition values should have lower variability because all samples represented an equal surface area and volume, while the samples had very different dry bulk densities and consequently, very different total masses. The topography was relatively uniform at a within-site scale, which we hypothesized would lead to values of activity deposition variability lower than activity concentration variability for a given site.

Another goal of this study was to add to the body of literature on ^{137}Cs soil concentration and deposition by examining high-altitude sites. Most investigations of cesium in soils have been conducted at low-to-mid-altitude sites. However, deposition and transport mechanisms prevalent at high altitudes may differ from those operating at low or mid-altitudes. Washout by snowfall is the primary means of atmospheric scouring in many high alpine areas, and most fallout is transferred from the atmosphere to soil in snowfall events (Whicker & Shultz, 1982). At lower altitudes, scavenging by rainfall events and dry deposition are the primary mechanisms of atmosphere to soil transfer. Snow is more effective at scavenging the atmosphere than rain (Sparmacher, Fulber & Bonka, 1993; Nicholson, Branson & Giess, 1991). Furthermore, snow is susceptible to post-precipitation movement by wind and this could therefore be expected to cause more complex spatial dispersal patterns. The two sites examined in this study represented two different types of high-altitude sites: the first site was on alpine tundra, and the second was in a montane forest. These two sites appear to have very different wind-scour patterns. We hypothesized that the montane region would have more variability in activity deposition values (expressed as coefficients of variation, or CVs) due to assumed higher tree-induced intrasite variability of snow depth. We further hypothesized that the alpine soils should have lower mean ^{137}Cs deposition values, because wind scour would remove some of the snowfall (and therefore some of the deposited ^{137}Cs) from the alpine area. In contrast, the montane area forest serves as a windbreak and appears to accumulate more snow.

2. Materials and methods

2.1. Study sites

The sites examined in this investigation are located approximately 100 km west of Fort Collins, Colorado, USA. The first site encompassed an area of approximately 1500 m^2 on a treeless alpine plain adjacent to Michigan Lake, a glacial lake above treeline (located at 105° 53'W, 40° 29'N; elevation = 3414 m). The dominant meadow vegetation species at the site were globeflower (*Trollius laxus*), Rocky Mountain lousewort (*Pedicularis sudetica*), *Senecio sp*., and two sedges (*Carex aquatilus* and *C. scripoidia*). There was an absence of defined soil horizons at this site as roots mixed with wet soil were present even at the bottom of the deepest sample (18 cm). Samples from the alpine site were characterized by high organic matter content and low dry bulk density. Thirty-eight surface soil samples (0–6 cm depth) were collected in this region, along with six sets of subsurface soil samples (6–12 and 12–18 cm depth) on August 1, 1996.

The second site (105° 52'W 40° 29.5'N; elevation = 3292 m) encompassed approximately 750 m^2 in a montane forest approximately 1.5 km northeast of the alpine site. Sixteen surface soil samples and three sets of subsurface soil samples were collected from the montane site on August 2, 1996. Engleman spruce (*Picea englemanni*) and subalpine fir (*Abies lasiocarpa*) trees were the dominant form of vegetation at this site, and the dominant understory was blueberry (*Vaccinium scoparium*). The upper soil profile consisted of a thin layer of duff, with sandy soil beneath.

The amount of snowfall near the study sites was determined from the US Department of Agriculture Natural Resource and Conservation Service's (NRCS) snowfall recording station at Cameron Pass, Colorado (105° 53'W 40° 31'N; elevation = 3133 m) approximately 5 km northwest of the study sites. The 25-year-average annual snowfall at that station is approximately 196 cm (water equivalent = 76 cm). Total annual precipitation was measured at the NRCS's precipitation recording station at Joe Wright Reservoir (105° 52'W 40° 33'N; elevation = 3048 m), approximately 7 km north of our study site and averages 116 cm (29 year average). Therefore, approximately two-thirds of the total annual precipitation at these sites falls as snow.

2.2. Sample collection, treatment, and counting

At the alpine site, we established a baseline axis along the longest dimension of the irregularly shaped plain. Seven transects running perpendicular to the baseline and extending to the edges of the site were evenly spaced along the baseline axis (approximately 15.2 m apart) and the total number of paces on all transects was counted by walking the first transect and returning along the next until all seven transects had been walked, giving a total of 376 paces. Based on logistical considerations, it was determined that 38 locations would be randomly sampled, therefore 38 random numbers of paces between zero and 376 were chosen using a table of random numbers. Surface soil samples (0–6 cm) were collected at all 38 locations. Six of the 38 locations were randomly chosen for collection of subsurface samples (6–12 and 12–18 cm). We were more interested in the surface soils, as previous research indicates that most ^{137}Cs collects in the top few cm of the soil profile (Arnalds et al. 1989; Ivanov et al., 1997; Kagen & Kadatsky, 1996; Owens et al., 1996; Ruhm et al., 1996). The main purpose of the subsurface samples was to verify the adequacy of our sampling strategy in capturing the vertical distribution of ^{137}Cs activity, and to determine the fraction of the total ^{137}Cs inventory found in the surface soil samples, rather than to establish a statistically robust population of subsurface samples. To further verify that we were sampling to an adequate depth, we plotted the activities for the sites where we collected subsurface samples and determined the relationship between soil depth and ^{137}Cs activity. We then integrated this function for both sites from 0 to 18 cm and from 0 to 30 cm. Based on these calculations, $< 3\%$ of the deposited activity is expected to be found below 18 cm. In fact, an average of $< 10\%$ of the total ^{137}Cs activity was found in our deepest samples (12–18 cm). Of the nine sets of subsurface samples taken at our study sites, only 1 had $> 10\%$ of the total activity in the deepest sample (27%).

Based on practical constraints, we determined that 16 sets of surface soil samples and three subsurface samples would be collected at the montane site. The presence of mature standing and fallen trees prevented us from establishing a baseline axis and parallel transects perpendicular to the axis as had been done at the alpine site, therefore we used another randomization protocol for selection of sampling sites. We started at the approximate center of the area and chose a random direction (a random number between zero and 360 corresponding to compass azimuth) and a random number of paces (from 1 to 10) for the first sampling location. The direction was established using a standard compass. The next location was chosen by repeating the process using the previous sampling location as the starting point. This process was repeated until all 16 surface and three subsurface sampling locations had been chosen.

All samples represented an equal ground surface area (78.5 cm^2). We assumed an adequate cesium binding capacity for soils to retain nearly all deposited material at both sites. The data from the subsurface soil samples supported this assumption, as ^{137}Cs activity declined rapidly with soil depth. Surface soil activity deposition values were adjusted to account for vertical migration of cesium into the deeper soils, as described in more detail in the Results section.

Surface soil samples were collected by removing the lid from metal sample cans (diameter = 10 cm, height = 6 cm), placing the cans with the open end down, and pressing them into the soil. A trowel was then used to excavate a trench beside the can until the open end could be reached. The trowel was then inserted horizontally over the open end, and the can containing the sample was removed and lidded. Subsurface samples were collected by repeating this process with a second and third can in the hole left by collection of the surface sample. In this manner, three consecutive samples representing depths of 0–6, 6–12, and 12–18 cm were collected. In the field, neither vegetation nor water was removed from any of the samples.

In the lab, the samples were oven dried at 150°C for 24 h and weighed to the nearest 0.1 gm. To avoid biasing subsequent textural analyses, the samples were not sieved. Samples were then ashed at 450°C in a muffle furnace for 24 h to destroy the organic fraction, then the samples were cooled and reweighed. No loss of ^{137}Cs through volatilization is expected at this temperature (Yaguchi, Waller & Griffith, 1973). This allowed calculation of the % soil organic matter for each sample. After ashing, textural analyses were performed using a hydrometer (Method 15-4, as described in Klute et al., 1986) on the remaining inorganic portions of 10 surface soil samples from the alpine site and eight surface soil samples from the montane site.

Following ashing, samples were counted on a coaxial high-purity germanium detector (EG&G Ortec model GMX-80230-S, crystal diameter = 76.4 mm, crystal length = 79.5 mm) attached to a multi-channel analyzer (Canberra AccuSpec A, model S304/305) for a determination of ^{137}Cs activity after a background count had been established. In the samples submitted for textural analyses, the procedure consumed a portion of the sample mass, therefore, due to low remaining sample mass, it was necessary to count these samples on a coaxial high purity germanium well detector (EG&G Ortec model GWL-200240-S, crystal diameter = 65.1 mm, crystal length = 73.0 mm, active well depth = 40 mm, well inside diameter = 15 mm) attached to an integrated spectroscopy system (EG&G Ortec 92X Spectrum Master). The measured activities were multiplied by the ratio of counted mass to the total ashed sample mass before textural analysis to obtain total sample activities. All calculations of ^{137}Cs activity included a calibration factor for sample height-dependent counting efficiency. We also performed a study to determine the effects of sample density on counter efficiency using material spiked with a known ^{137}Cs activity and a range of densities. Over the range of densities encompassed by the samples in this study, density had no significant effect on counter efficiency. All the samples had coefficients of variation of less than 6%, with the exception of three of the subsurface samples, which had CVs between 6 and 13%. Activity deposition values were calculated as activity/ground surface area and activity concentration values were calculated as activity/dry, unashed mass.

2.3. Data distributions and transformations

Before any comparison of activities were performed, the distribution of the sample masses, activity deposition and activity concentration data from the montane and alpine sites were determined. These determinations were accomplished using the W test for normality (and lognormality) developed by Shapiro and Wilk (1965). An Excel 97 spreadsheet was constructed to conduct these tests (and all other statistical calculations reported in this study).

The results of the W tests (conducted at $\alpha = 0.05$) indicated that the dry sample masses (and therefore the sample densities, since all samples had equal volumes) of the surface soil samples from the alpine site were neither normally nor lognormally distributed. The surface soil masses from the montane site were normally distributed. Therefore, nonparametric statistics were employed to compare sample masses between sites.

The activity deposition measurements from the alpine area were normally distributed. The activity deposition measurements from the montane site could be characterized as either normally or lognormally distributed, so to facilitate comparison between sites, statistical tests appropriate for normally distributed data were employed.

The activity concentration measurements from the alpine site could not be characterized as either normally or lognormally distributed, while activity concentration measurements from the montane site were lognormally distributed. Therefore nonparametric statistics were employed to compare activity concentration data.

3. Results

A wide range of soil dry masses and dry bulk densities were recorded at both sites (Table 1). The total dry mass for each 471 cm^3 sample for the alpine site ranged from 36 to 581 g with a mean of 93 g. For the montane surface soils, the dry mass varied from 67 to 400 g with a mean of 217 g. Dry bulk densities ranged from 0.077 to 1.23 $\mathrm{g\,cm}^{-3}$ (mean = 0.20 $\mathrm{g\,cm}^{-3}$) for the alpine site and from 0.14 to 0.84 $\mathrm{g\,cm}^{-3}$ (mean = 0.46 $\mathrm{g\,cm}^{-3}$) at the montane site. The results of a Wilcoxon rank sum test indicated that the alpine site's mean bulk density was statistically significantly less than that from the montane site ($\alpha = 0.05$). The distributions and statistical comparison tests performed are summarized in Table 2.

We next determined the percent soil organic matter (% SOM) for each sample, as previous studies have indicated that % SOM can be an important factor in determining a soil's ^{137}Cs holding capacity (Melin et al., 1994). The % SOM ranged from 1.1 to 83%, with a mean of 55% for the alpine site and from 11 to 89% with a mean of 36% for the montane site. The distributions of the % SOM measurements for both sites were also tested for normality and lognormality. Neither site's measurements were normally or lognormally distributed ($\alpha = 0.05$), therefore the Wilcoxon rank sum test was performed to compare the means. The results indicated that the alpine site's mean % SOM was not statistically significantly different from the montane site ($\alpha = 0.05$).

The range of % clay values for the alpine and montane sites, respectively, were 13–75 and 18–26%. The mean clay content was 29% for the alpine site and 21% for the montane site. The % clay measurements for the alpine site, with a standard deviation of 17% and a coefficient of variation of 0.60, were much more variable than the montane site, which had a standard deviation of 5.8% and a coefficient of variation of 0.28. The distribution of % clay values at the alpine site appeared to be lognormally distributed using the Shapiro–Wilk W test ($\alpha = 0.05$), and the distribution at the montane site could be characterized as either lognormal or normal. Since both of the % clay distributions tested positive for lognormality, a t-test was again employed to compare the means. The results of this test indicated that the mean

Table 1
Surface soil characteristics of samples taken at the alpine and montane sites

Poperty	Alpine	Montane
Dry bulk density (g cm^{-3})		
n	38	16
Range	0.077–1.23	0.14–0.84
Mean	0.20	0.46
Standard deviation	0.18	0.22
Coefficient of variation	0.98	0.45
Soil organic matter (%)		
n	38	16
Range	1.1–83	11–89
Mean	55	36
Standard deviation	16	16
Coefficient of variation	0.28	0.60
Sand (%)		
n	10	8
Range	24–68	40–58
Mean	39	49
Standard deviation	14	6
Coefficient of variation	0.35	0.12
Silt (%)		
n	10	8
Range	0–50	11–43
Mean	33	31
Standard deviation	15	17
Coefficient of variation	0.44	0.6
Clay (%)		
n	10	8
Range	13–75	18–26
Mean	29	21
Standard deviation	17	5.8
Coefficient of variation	0.60	0.28

% clay values were not statistically significantly different between the alpine and montane sites ($\alpha = 0.05$).

To calculate total activity deposition values, surface soil sample activities were adjusted to account for the vertical migration of ^{137}Cs into the soil. The ratio of activity in all three depths (0–6, 6–12 cm, and 12–18 cm) combined to the activity in the surface sample (0–6 cm) alone was calculated. The average value of this ratio for the six sampling locations where subsurface samples were collected at the alpine site was 1.5, and the average for the three locations at the montane site was 1.6. Therefore, each of the alpine surface sample activity deposition values was multiplied by 1.5 and each of the montane surface activity deposition values was multiplied by 1.6. The

Table 2
Distributional and comparison statistics for the mass, % clay, % SOM, and activity concentrations from the alpine and montane sites

	Distribution		Comparison test	Results
	Alpine	Montane		
Bulk density	U[a]	N[a]	WRS[b]	$\bar{X}_{\text{alpine}} < \bar{X}_{\text{montane}}$
Clay %	L[a]	L/N[a]	T[b]	$\bar{X}_{\text{alpine}} = \bar{X}_{\text{montane}}$
Soil organic matter%	U[a]	U[a]	WRS[b]	$\bar{X}_{\text{alpine}} = \bar{X}_{\text{montane}}$
Activity concentration	U[a]	L[a]	WRS[b]	$\bar{X}_{\text{alpine}} > \bar{X}_{\text{montane}}$
Activity deposition	N[a]	L/N[a]	T[b]	$\bar{X}_{\text{alpine}} < \bar{X}_{\text{montane}}$
			F[b]	$\sigma_{\text{alpine}} = \sigma_{\text{montane}}$

[a] U = distribution was neither normal nor lognormal; L = lognormal; L/N = distribution could be characterized as either normal or lognormal, but for the sake of comparison distribution was considered lognormal; L/N = distribution could be characterized as either normal or lognormal, but for the sake of comparison distribution was considered normal.

[b] WRS = Wilcoxon rank sum test; T = Student's t-test; F = F test. Values for α are listed in the text.

Table 3
Descriptive statistics for alpine and montane activity deposition and activity concentration data

	Activity concentration (kBq m^{-2})		Activity concentration (Bq g^{-1})	
Statistic	Alpine	Montane	Alpine	Montane
n	38	16	38	16
Arithmetic mean	3.6	5.2	0.26	0.15
Standard deviation	1.4	2.1	0.15	0.09
Coefficient of varia	0.40	0.41	0.56	0.60

resulting adjusted arithmetic mean activity deposition values were 3.6 and 5.2 kBq m^{-2} for the alpine and montane sites, respectively (Table 3). The standard deviations of activity deposition values were 1.4 and 2.1 kBq m^{-2} for the alpine and montane sites, respectively. The activity deposition coefficients of variation (CVs) were 0.40 and 0.41, respectively. As the activity deposition data sets were both normally distributed, a t-test was conducted to compare them. The alpine mean activity deposition was significantly less than the montane mean activity deposition ($\alpha = 0.05$).

The arithmetic mean activity concentration values were 0.26 and 0.15 Bq g^{-1} dry for the alpine and montane sites, respectively. The activity concentration standard deviations were 0.15 and 0.09 Bq g^{-1} dry for the alpine and montane sites, respectively. The CVs for activity concentration values were 0.56 and 0.60 for the alpine and montane sites, respectively. Because the activity concentration data sets are not both normally or both lognormally distributed, a Wilcoxon rank sum test was used to

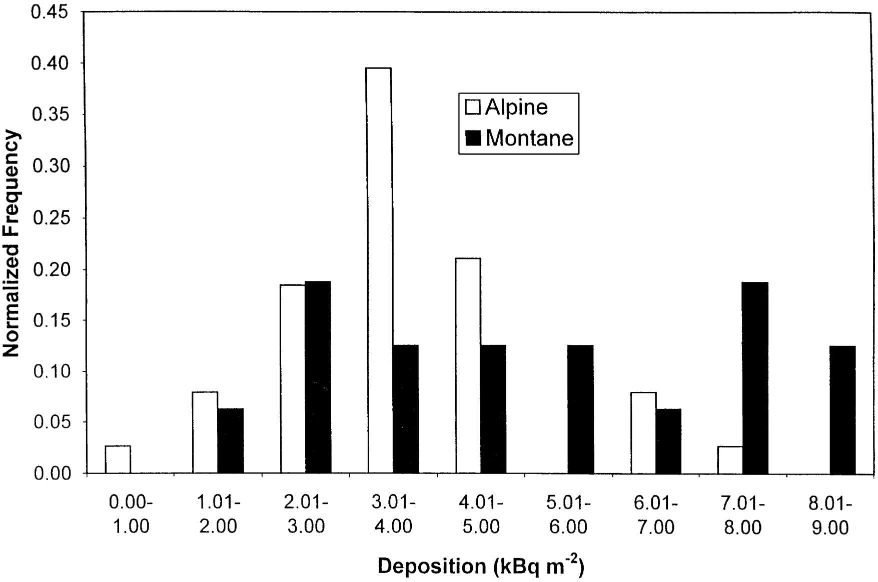

Fig. 1. Normalized ^{137}Cs deposition (kBq m^{-2}) frequency distributions for soils from the alpine and montane sites.

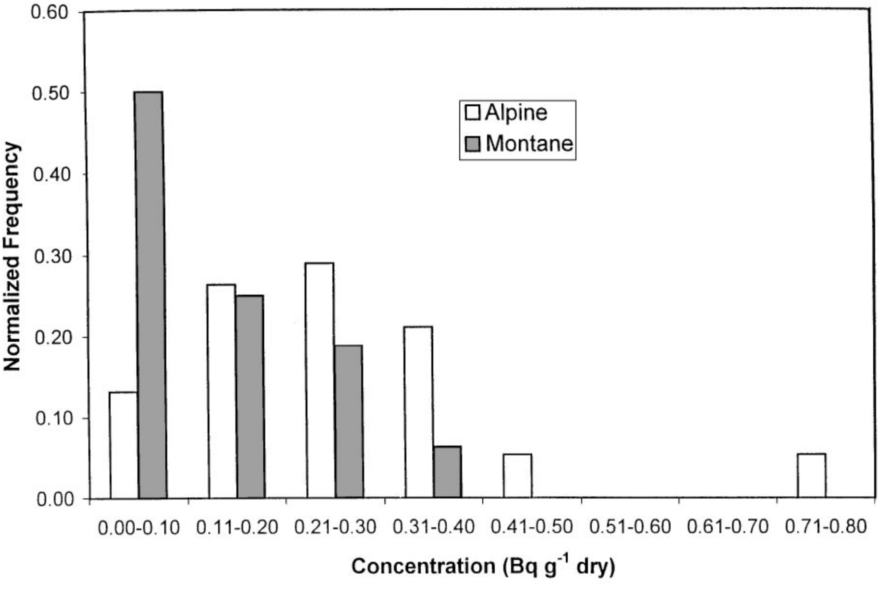

Fig. 2. Normalized ^{137}Cs concentration (Bq g^{-1}) frequency distributions for soils from the alpine and montane sites.

compare them. The mean activity concentration of the alpine site was significantly greater than the montane mean ($\alpha = 0.05$).

To better compare the distribution of the activities graphically, the untransformed data were normalized, that is the number of observations falling in an interval of activities was divided by the total number of observations in the data set (38 total observations for the alpine site, and 16 total observations for the montane site). The normalized activity deposition frequencies are plotted in Fig. 1 and normalized activity concentrations are plotted in Fig. 2.

Finally, six regression analyses were performed: (1) ^{137}Cs concentration vs. % clay; (2) ^{137}Cs concentration vs. % SOM; (3) ^{137}Cs concentration vs. both % clay and % SOM; (4) ^{137}Cs deposition vs. % clay; (5) ^{137}Cs deposition vs. % SOM and; (6) ^{137}Cs deposition vs. both % clay and % SOM. The regression of ^{137}Cs concentration vs. % clay had an adjusted R^2 value of 0.03, which was not significant at $\alpha = 0.05$. All of the other regressions were significant: ^{137}Cs concentration vs. % SOM (adjusted $R^2 = 0.24$, $p < 0.005$), ^{137}Cs concentration vs. % clay and % SOM (adjusted $R^2 = 0.16$, $p < 0.025$), ^{137}Cs deposition vs. % clay (adjusted $R^2 = 0.15$, $p < 0.05$), ^{137}Cs deposition vs. % SOM (adjusted $R^2 = 0.20$, $p < 0.025$), and ^{137}Cs deposition vs. % clay and % SOM (adjusted $R^2 = 0.22$, $p < 0.01$).

4. Discussion

We started the study with three hypotheses, each of which will be discussed below.

Hypothesis 1 (Cesium–137 deposition at the alpine site will exhibit lower intrasite variability than the samples from the montane site). This hypothesis was based on the assumption that activity deposition would be more uniform on the treeless alpine site than on the tree-covered montane site. This hypothesis was not unambiguously supported by our data. The alpine intrasite variability was less than that for the montane site, however, the difference was not quite significant as determined by an F-test ($\alpha = 0.1$). There are three possibilities to explain the failure of this hypothesis.

One potential possible explanation is that ^{137}Cs is deposited by some mechanism other than atmospheric washout by snow. This is unlikely, as the washout effect by snow is well documented (Nicholson et al., 1991; Sparmacher et al., 1993; Whicker & Shultz, 1982) and snowfall is the major form of annual precipitation at these sites. Another possible explanation is that the results are caused by an artifact in sampling location randomization schemes or in the fact that the area of the alpine site was approximately twice the area of the montane site. It is unlikely that the either of these factors was the cause, as both areas appeared spatially homogeneous in terms of topography and vegetation structure at the intrasite scale and both sample location selection procedures, while not identical, were random.

A more likely explanation is that there is less spatial variability in snow deposition at the montane site and/or more variability at the alpine site than previously assumed. In the treeless alpine tundra, deposition via snowmelt may be determined more by horizontal, post-precipitation redistribution of snow rather than by vertical movement during the precipitation event. On the other hand, the spruce and fir trees at the montane site have very few branches near ground level, and so present much less of a windbreak to snow moving horizontally than to snow falling vertically. It is therefore plausible that there would be less tree-induced heterogeneity in snow depth than we assumed at the outset of this study.

Interestingly, the alpine site exhibited slightly less variability in activity concentration values than the montane site (Table 3). This was surprising, since there was no significant difference in activity deposition variability, and the CV for density of alpine soil was 0.98, while the CV for density of montane soil was 0.45 (Table 1).

Hypothesis 2 (Cesium–137 activity deposition at both sites will have lower coefficients of variation than ^{137}Cs activity concentration). This hypothesis was based on the assumption that organic content and dry soil bulk densities at a particular site varied more than the snow deposition between sampling locations at that site. This assumption was at least partly verified by the wide range of soil dry masses and densities measured at both sites (Table 1). The intrasite variation of snow depth is unknown, but based on anecdotal observations, probably much less than the factor of 6 (for the montane site) to 16 (for the alpine site) variation in soil density.

The variability in activity concentration can only be compared qualitatively to the variability in activity deposition, as they are two different measures and therefore any test of statistical significance would be inappropriate. This hypothesis was qualitatively supported. The CV for activity deposition at the alpine site was 28% lower and the montane site was 32% lower than the CV for activity concentration. The alpine CVs were 0.40 and 0.56 for activity deposition and activity concentration, respectively, and the montane CVs were 0.41 and 0.60, respectively. It does appear that for these two sites, the activity deposition was less variable than the activity concentration, but no statistical significance can be attached to this conclusion.

Hypothesis 3 (The alpine site will have lower mean soil ^{137}Cs levels than the montane site). This hypothesis was based on the observation that snow depth, and hence activity deposition at snowmelt, is often greater in forested areas than in large nearby open, windswept areas, consequently ^{137}Cs levels should also be greater. The greater snow depth appears to be the result of the the trees reducing windspeed by serving as a windbreak, thereby trapping snow and reducing the amount that can be carried away by wind. This hypothesis was supported by our results for mean activity deposition, but not for mean activity concentration. The alpine samples had a lower adjusted mean activity deposition value ($\bar{X}_{\text{alpine}} = 3.6\ \text{kBq m}^{-2}$, $\bar{X}_{\text{montane}} = 5.2\ \text{kBq m}^{-2}$), but the alpine samples had a higher mean activity concentration ($\bar{X}_{\text{alpine}} = 0.26\ \text{Bq g}^{-1}$, $\bar{X}_{\text{montane}} = 0.15\ \text{Bq g}^{-1}$).

This result demonstrates the need to collect both ^{137}Cs activity deposition and activity concentration data. While activity concentration data are appropriate for certain specific purposes, they are inadequate for intersite comparisons because bulk soil density or other factors, such as activity depth profile, confound the results. In actuality, the samples taken from the montane site had a higher mean total ^{137}Cs inventory, but this is only evident from comparison of the activity deposition data.

While highly significant, our regressions of activity concentration and activity deposition against soil % SOM and % clay are not particularly strong. The vertical leaching of ^{137}Cs into soil is often an important process in removing ^{137}Cs from the shallower surface soils. The clay fraction of soils tenaciously binds ^{137}Cs, and retards this vertical movement. Soil clay fraction appears to have relatively less importance where precipitation is dominated by snowfall. This is not surprising since initial deposition and redistribution of snowfall, rather than the measured soil properties, are likely the most important factors in determining activity deposition and activity concentration values.

Most studies of ^{137}Cs in soils are conducted at low or mid altitudes, but the deposition and redistribution patterns operating at high altitudes, where precipitation is dominated by snowfall, apparently differ from areas that receive more rain than snow. The activity deposition values measured in this study are in general agreement with the results of Beck & Anspaugh (1991), but are significantly higher than those of Coppinger et al. (1991).

Beck & Anspaugh (1991) reported values of 3.6 and 3.8 kBq m^{-2} for a site in Craig, Colorado (approximately 150 km west of the study area, elevation = 1885 m, average annual precipitation = 32.5 cm (EarthInfo, 1994)) and 3.0 kBq m^{-2} in Rawlins, Wyoming (185 km northwest of the study site, elevation = 2060 m, average annual precipitation = 23 cm (EarthInfo, 1994)). Our mean activity deposition values of 3.6 and 5.2 kBq m^{-2} for the alpine and montane sites were slightly higher than Beck and Anspaugh's values, most likely as a result of higher elevations and greater total annual precipitation at our sites.

On the other hand, Coppinger et al, (1991) reported values of 0.3–0.6 kBq m^{-2} at the Stratton Sagebrush Hydrology Study Area in south central Wyoming (approximately 150 km northwest of the study area, elevation = 2400 m, average annual precipitation = 53 cm). These values are much lower than the values we found. The most likely explanation is that our sites likely received about 116 cm of precipitation annually, more than twice the average annual total precipitation as Coppinger's site. However, this would not explain why Coppinger's site had a higher average annual precipitation than Beck and Anspaugh's Craig and Rawlins sites, but a much lower ^{137}Cs deposition value. Possible explanations include differences in fraction of precipitation that falls as snow, and differences in wind-driven redistribution of snow.

5. Conclusions

The activity concentration and deposition of ^{137}Cs in soils at two high-altitude sites, one alpine (treeless), and one montane (forested) in northern Colorado were examined. We found that the alpine soil had slightly less variable ^{137}Cs activity concentrations than the montane soil. Activity deposition of ^{137}Cs was less variable than activity concentration at both sites, though no statistical significance could be attached to this conclusion. The alpine site had significantly greater mean ^{137}Cs activity concentrations than the montane site but significantly lower activity deposition values. This study demonstrates the need for activity deposition data to be collected as part of biomonitoring programs, particularly if data from such programs will be used to support the release of remediated sites from the public domain.

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