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Carbon and nutrient contents in soils from the Kings River Experimental Watersheds, Sierra Nevada Mountains, California

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ABSTRACT

Soil C and nutrient contents were estimated for eight watersheds in two sites (one high elevation, Bull, and one low elevation, Providence) in the Kings River Experimental Watersheds in the western Sierra Nevada Mountains of California. Eighty-seven quantitative pits were dug to measure soil bulk density and total rock content, while three replicate surface samples were taken nearby with a bucket auger (satellite samples) to the same depth as surface pit samples. Results showed that the higher elevation Bull watersheds had significantly greater C, N, and B contents and significantly lower extractable P, exchangeable Ca^{2+}, Mg^{2+}, and Na^{+} contents (kg ha^{-1}) and lower pH than the lower elevation Providence watersheds. Soil NH_4^+ and mineral N contents were high in both the Bull and Providence watersheds and could not be related to any measured soil property or attributed to known rates of atmospheric deposition. Nutrient analyses on satellite samples were comparable to those taken from pits when averaged on a watershed or site (Bull and Providence) scale, but quite variable on an individual grid point basis. Elevated Zn values from the quantitative pit samples suggested contamination by field sieving through a galvanized screen. Had the amount of large rocks within the soil sample not been accounted for with quantitative pit analyses, estimates of fine earth and associated C and nutrient contents (kg ha^{-1}) would have been overestimated by 16 to 43%.

1. Introduction

Estimating carbon and nutrient contents in soils with substantial amounts of large stones is fraught with uncertainty because of problems in obtaining good values for the volume and mass of fine earth (<2 mm fraction). Traditional coring, clod, or small scale excavation methods used in less stony agricultural soils (Blake and Hartge, 1986) are not of a suitable scale for measuring whole-soil bulk density in many wildland soils containing significant amounts of large rocks. To address this problem, Hamburg (1984) developed a method for measuring bulk density in rocky soils involving careful excavation and weighing of soils and rocks from quantitative pits dug with a 1 m^2 grid framework. He found that simple comparisons of C and N concentrations across the chronosequence he studied would have yielded results quite different from the nutrient content analyses using the quantitative pits. Other investigators later adopted quantitative pit methodologies similar to Hamburg's to investigate C and nutrient trends in rocky soils (Huntington and Ryan, 1990; Johnson, 1995; Johnson et al., 1991).

Harrison et al. (2003) compared four methods for determining bulk density and coarse fragment contents in two forest soils in the Pacific Northwestern US: (1) large pit excavation, (2) dug pit using a 54 mm hammer core bulk density sampler, (3) 31 mm punch auger, and (4) the clod method. They found that the soil core methods underestimated the >2 mm fraction because the sampling necessarily avoided large rocks, and that the clod method often did not work because soils did not form stable clods. They found that the large pit excavation method was the most reliable but by far the most time consuming and labor intensive. They also found a substantial amount of soil C in the >2 mm fraction of the more rocky soil.

In this paper, we summarize the results of 87 quantitative pits dug in eight watersheds in the Kings River Experimental Watersheds in the Sierra Nevada Mountains of California. The purpose of this study was three fold: (1) to quantify soil C and nutrient contents in advance of planned treatments involving harvesting and prescribed fire; (2) to assess the importance of rock fragments, including large surface boulders, in estimates of fine earth and associated C and nutrient contents, and (3) to compare results from quantitative pits with those obtained with bucket auger sampling which included chemical concentrations only.

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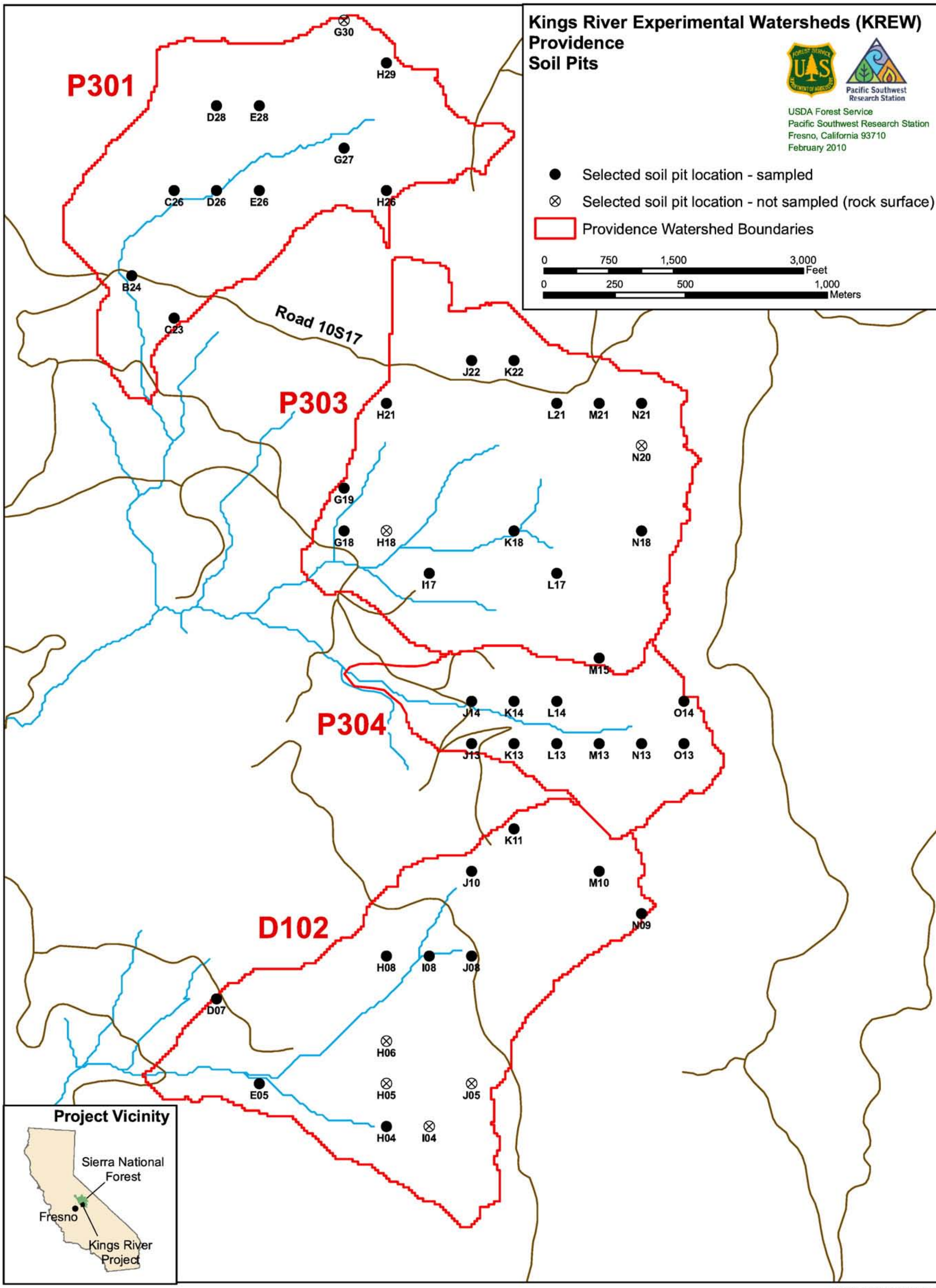

Fig. 1. The Kings River Experimental Watersheds are located on the Sierra National Forest northeast of Fresno, California.

2. Materials and methods

2.1. Sites

The Kings River Experimental Watersheds (KREW) were established in 2000 to develop data on the variability of headwater ecosystems of the southern Sierra Nevada and to study the effects of management activities (mechanical thinning and prescribed fire) designed to improve the sustainability of the forest ecosystem. This long-term experimental study is located on the Sierra National Forest in the Kings River drainage (Fig. 1). The watersheds range in size from 49 to 228 ha. Two sites were selected, Providence site and Bull site, that each contain four adjacent watersheds. The lower elevation Providence site (1485 to 2115 m elevation) receives both rain and snow while the higher elevation Bull site (2050 to 2490 m elevation) is snow dominated. This elevation range makes KREW an ideal location to evaluate possible climate change effects on forest ecosystem properties. Precipitation amount and timing are the same for the sites based on KREW meteorology data for water years 2004–2007; however, 75 to 90% of the precipitation comes as snow at Bull while only 35 to 60% is snow at Providence. Average temperatures for Providence and Bull were 11.3 ± 0.8 °C and 7.8 ± 1.4 °C, respectively for the four years, where ± refers to the standard deviation (C. Hunsaker, unpublished data).

The dominant vegetation cover is Sierran mixed-conifer which is defined as one third pine species (*Pinus* spp.), one third incense cedar (*Libocedrus decurrens*), and one third fir species (Table 1). At the Providence site the pine species are ponderosa pine (*Pinus ponderosa*) and sugar pine (*P. lambertiana*); at the higher elevation Bull site the pine species are sugar pine and Jeffrey pine (*P. jeffreyi*). White fir (*Abies concolor*) primarily occurs at the Providence site, and while white fir also occurs at the Bull site, red fir (*A. magnifica*) is dominant at the elevation of this mixed conifer forest. Meadows occur in all of the watersheds and make up from < 1 to 3% of watershed areas. The KREW watersheds have soils derived from granite and are dominated by three soil series: Cagwin, Gerle-Cagwin, and Shaver. The Shaver soils are dominant at the Providence site and the Cagwin soils are dominant at the Bull site. The Cagwin family of soils is a mixed, frigid Dystric Xeropsamments, the Gerle family is a coarse-loamy, mixed, frigid Typic Xerumbrepts, and the Shaver family is a coarse-loamy, mixed mesic Pachic Xerumbrepts. The entire Providence and Bull watershed complexes are underlain by granite, which is the parent material for all soils. Watershed T003 is located in the Teakettle Experimental Forest; it is the only watershed in KREW that has no roads or history of timber harvesting and for soils can be considered to be undisturbed.

In 2007 the Providence site became the National Science Foundation's Southern Sierra Critical Zone Observatory. KREW is also at the upper third of the elevation transect that will be the National Ecological Observatory Network's core site for California, Domain 17. This NEON site's focus is climate change.

2.2. Methods

A uniform grid was established across the watersheds for co-located sampling of terrestrial characteristics and nutrient fluxes. The grid was established at a randomly selected point, and the spacing is 150 m between points, except in the two smallest watersheds, P304 and B201, (Fig. 1). For these small watersheds the grid spacing was densified to 75 m between points in the north–south direction. A subset of these grid points was randomly selected, proportional to the size of each watershed (10 for the smallest watersheds up to 20 for the largest watershed), for measurements such as soil, forest litter, vegetation, and fuels loading.

Eighty-seven quantitative soil pits were dug at random azimuths at a distance of 32 m from the grid point (the design ensures that soil samples do not interfere with vegetation or fuel loading permanent transects). We used a variation of the quantitative pit method described by Hamburg (1984). In our method (Johnson et al., 2007, 2008), the volume of the hole is not measured directly, but calculated from the mass and density of the soil, stones, and woody material removed from the pits. In each quantitative pit, the forest floor component was sampled and removed and then a bulk density sample (core method) was taken at the top of the first mineral soil horizon. After this, all soil, rock and root materials were removed by horizon and field sieved (1 cm). Another bulk density sample was taken at the surface of the next horizon, and the total amount of material in each size fraction from the field sieving (> 1 cm and < 1 cm) was weighed in the field. Subsamples were then taken of the < 1 cm fraction, stored in water-tight containers until reaching the laboratory, weighed, dried at 105 °C, and weighed again for moisture content corrections. The > 1 cm fraction consisted primarily of pebbles and rocks of various sizes, which were subsamples for later density determinations in the laboratory by weighing and measuring water displacement for volume. Woody debris that did not pass through the sieve was field weighed if the amount warranted it and subsampled for later determinations of moisture content. In many cases, the volume of woody debris was small enough such that the entire sample was taken back to the laboratory. The volume of soil in the pit was calculated from the weight of the < 1 cm fraction (corrected for moisture content) and the bulk density sample for each horizon, assuming that they represented the same size fraction. The volume of rocks in the pit was calculated from the field weights and density determinations. Subsamples of the < 1 cm fraction were passed through a standard 2 mm sieve in the laboratory, and the weights of each fraction were then used with the above data to calculate a final value for fine earth (< 2 mm) and coarse fragment (> 2 mm) content. Whereas Hamburg (1984) avoided sample points that landed on surface rocks, we included these in our assessments of soil nutrient contents. For sample points that occurred on solid rock, soil fine earth was set to 0, % > 2 mm to 100%, and bulk density to the average density of the rock nearby (ranging typically from 2.4 to 2.6 g cm^{-3}).

Table 1
Attributes of each of the eight watersheds in the Kings River Experimental Watersheds.

Watershed code	Watershed area (ha)	Elevation range (m)	Dominant soil type (% cover)	Dominant land cover types (% cover)	
				Primary	Secondary
Providence watersheds					
P301	99	1790–2115	62% Gerle-Cagwin	82% Mixed conifer	10% barren
P303	132	1730–1990	66% Shaver	94% Mixed conifer	5% Barren
P304	49	1760–1980	55% Shaver	99% Mixed conifer	< 1% barren
D102	121	1485–1980	48% Shaver	76% Mixed conifer	11% Ponderosa pine
Bull watersheds					
B201	53	2145–2380	67% Cagwin	92% Mixed conifer	4% Barren
B203	138	2185–2490	80% Cagwin	47% Mixed conifer	44% Red fir
B204	167	2195–2490	98% Cagwin	48% Mixed conifer	41% Red fir
T003	228	2050–2465	94% Cagwin	78% Mixed conifer	19% Red fir

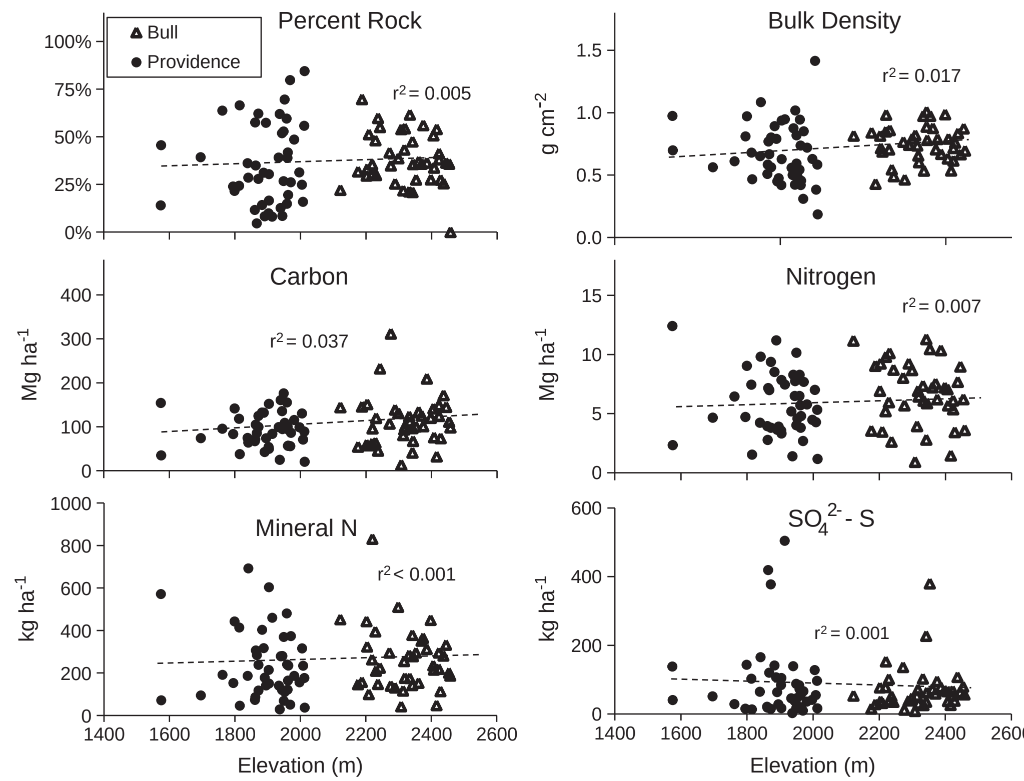

Fig. 2. Percent rock, bulk density, C, N, mineral N (NH_4^+–N + NO_3^-–N), and SO_4^{2-}–S contents plotted against elevation in the Bull and Providence watersheds. Solid lines indicated significant trend (P>0.05), dashed lines indicate non-significant trend.

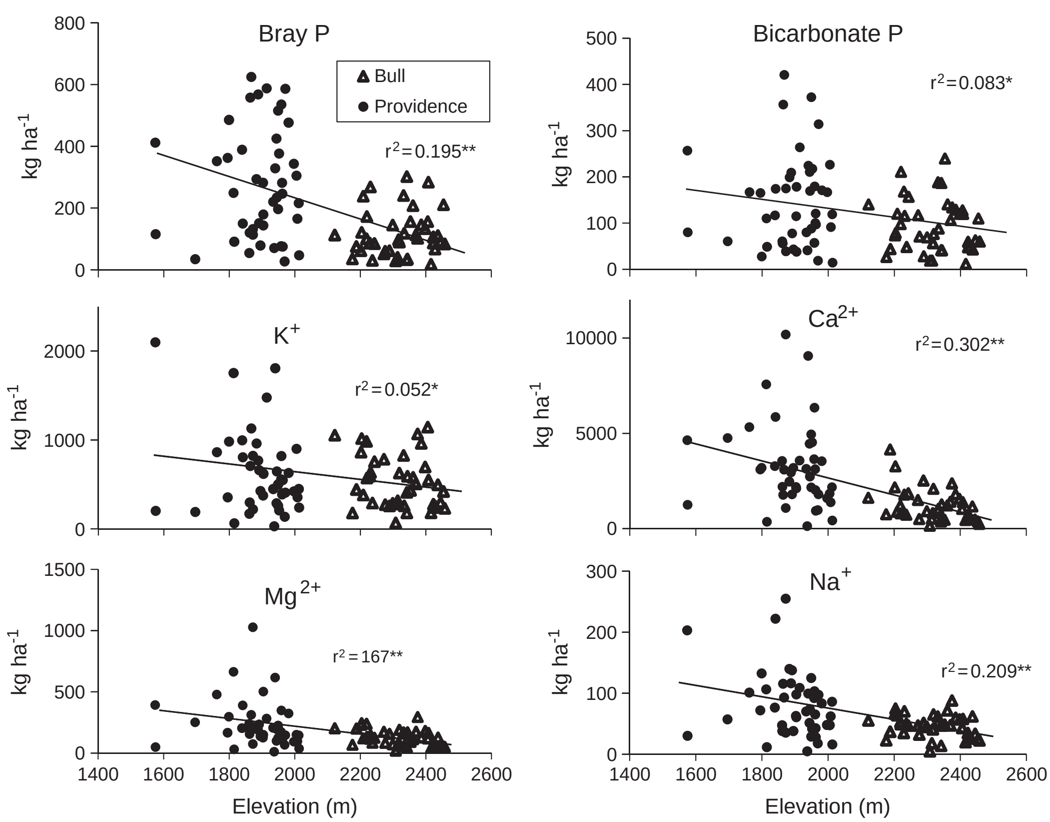

Fig. 3. Bray P, bicarbonate P, K^+, Ca^{2+} Mg^{2+}, and Na^+ contents plotted against elevation in the Bull and Providence watersheds. Solid lines indicated significant trend (P>0.05), dashed lines indicate non-significant trend.

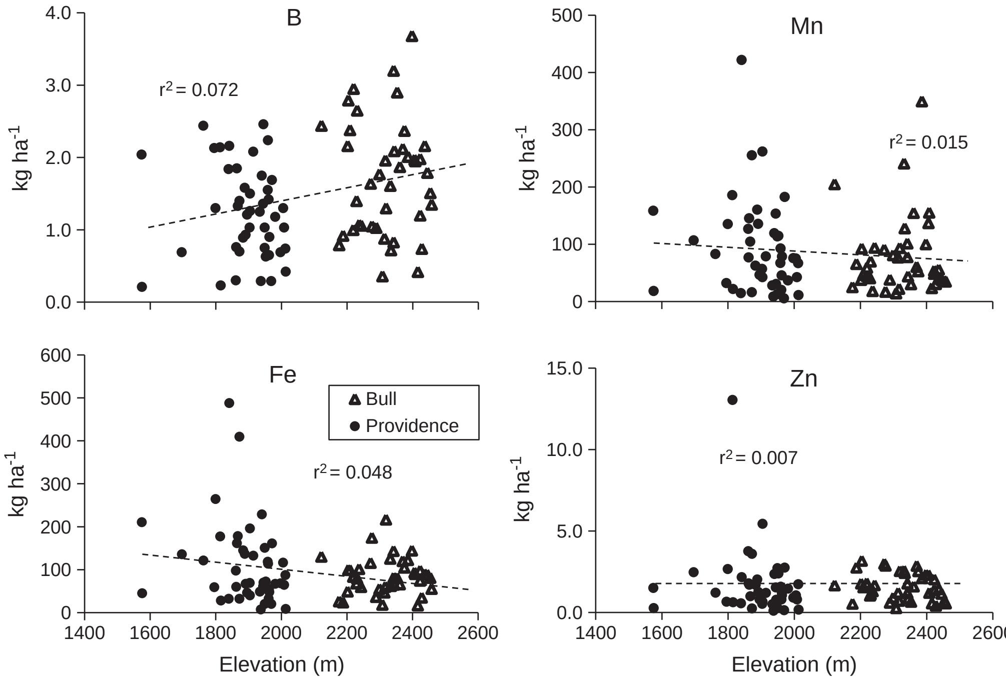

Fig. 4. B, Fe, Mn, and Zn contents plotted against elevation in the Bull and Providence watersheds. Solid lines indicated significant trend ($P>0.05$), dashed lines indicate non-significant trend.

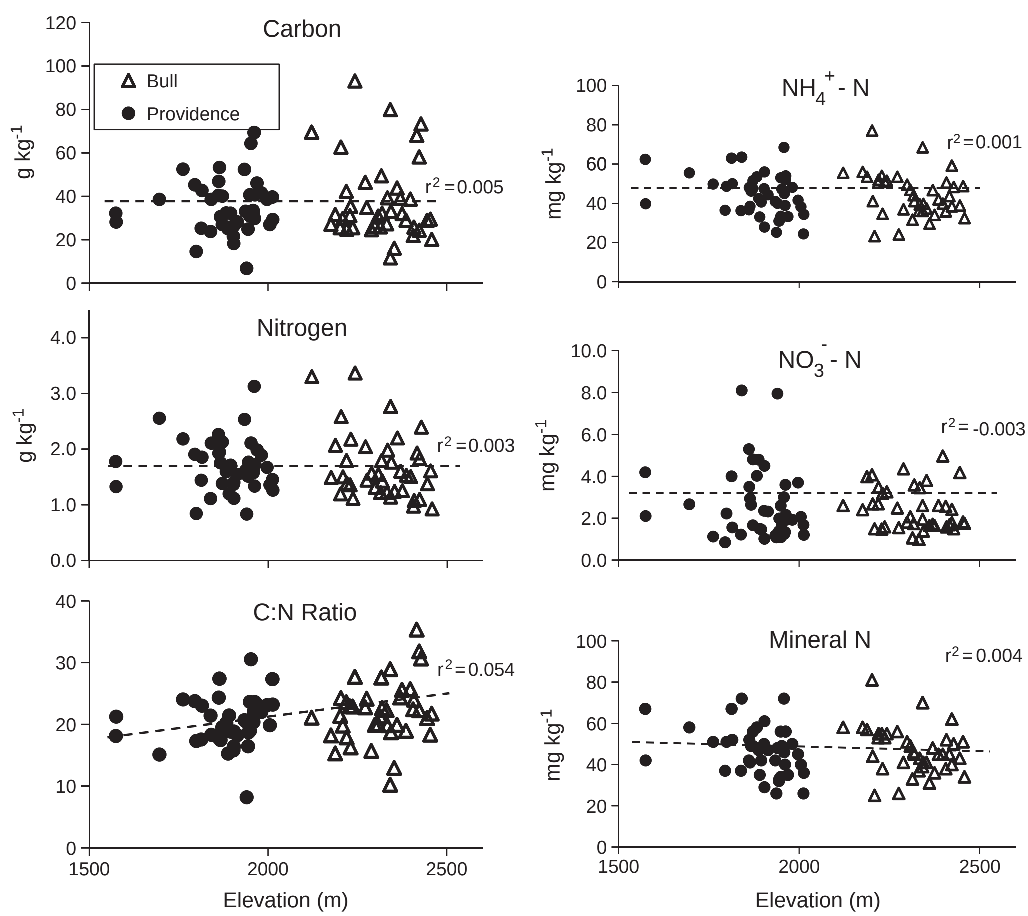

Fig. 5. Concentrations of C, N, NH_4^+–N, NO_3^-–N mineral N (NH_4^+–N + NO_3^-–N), and C:N ratio in surface (satellite) soils plotted against elevation in the Bull and Providence watersheds. Solid lines indicated significant trend ($P>0.05$), dashed lines indicate non-significant trend.

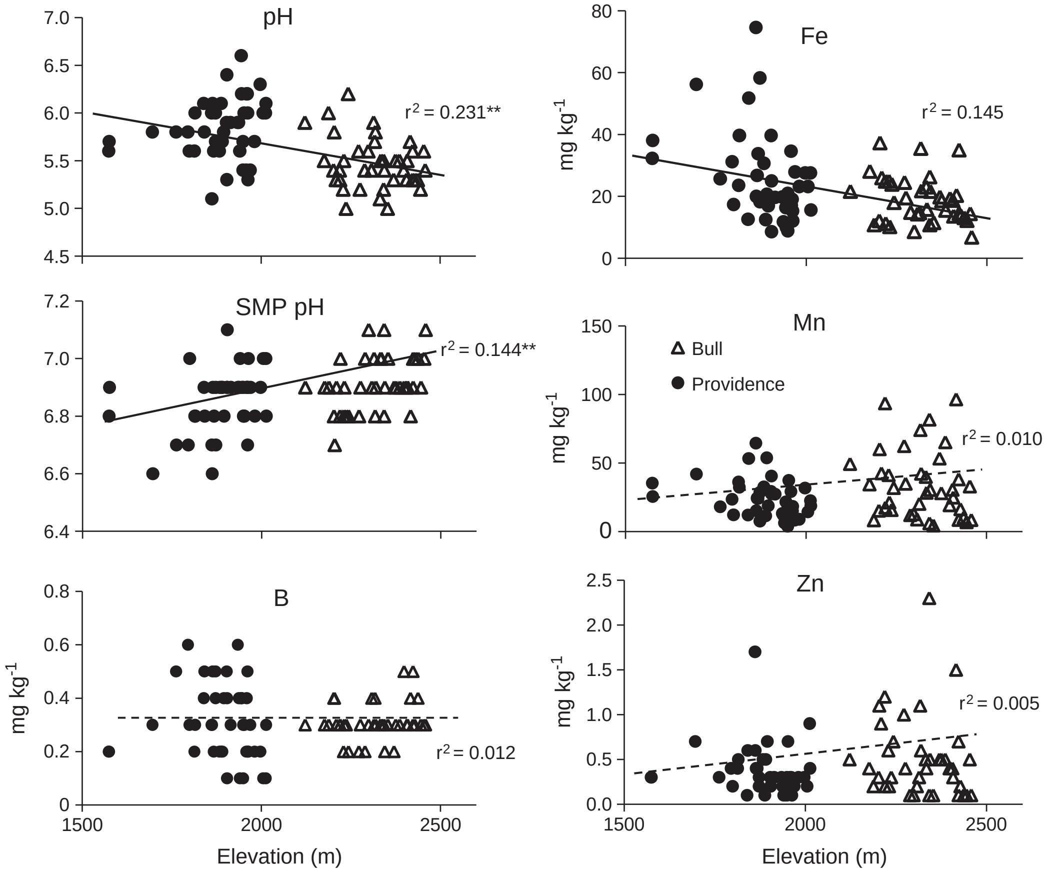

Fig. 6. pH, SMP pH, and concentrations of B, Fe, Mn, and Zn in surface (satellite) soils plotted against elevation in the Bull and Providence watersheds. Solid lines indicated significant trend (P>0.05), dashed lines indicate non-significant trend.

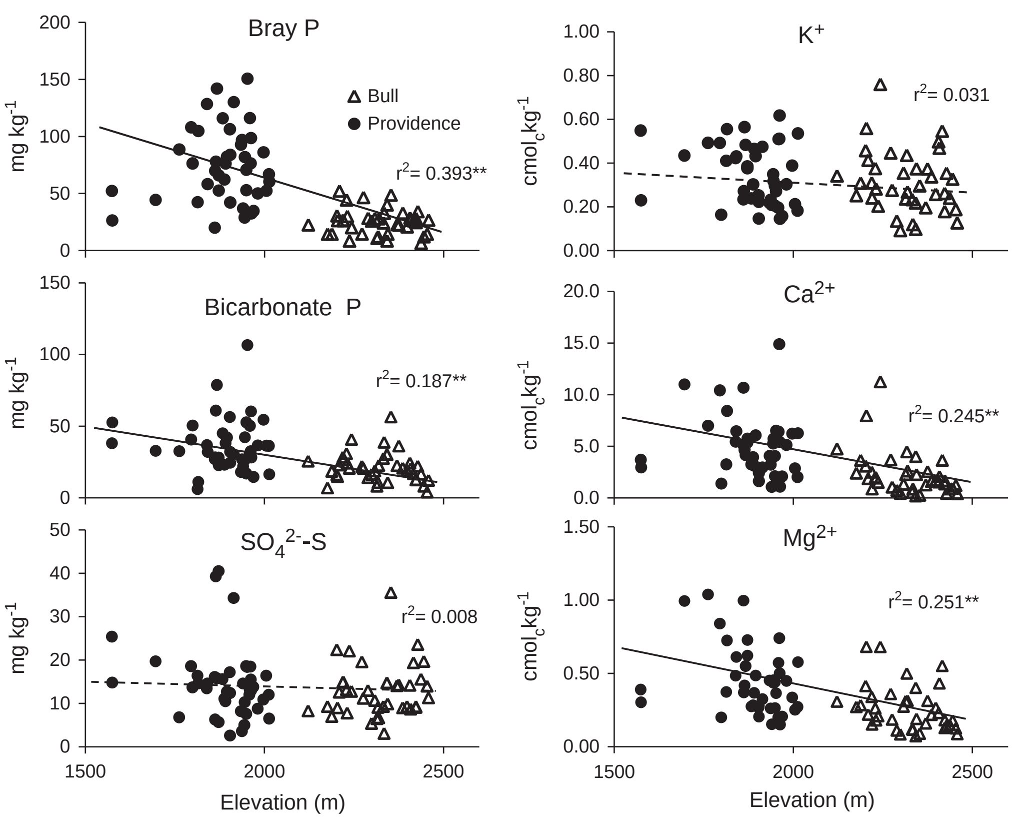

Fig. 7. Concentrations of Bray P, bicarbonate P, SO_4^{2-}−S, K^+, Ca^{2+} and Mg^{2+} in surface (satellite) soils plotted against elevation in the Bull and Providence watersheds. Solid lines indicated significant trend (P>0.05), dashed lines indicate non-significant trend.

In addition to the quantitative pit samples, three satellite sample points were taken with a bucket auger around the main pit at 0, 120, and 240° azimuth and at a distance of 8 m from the pit. The depth of the bucket auger samples corresponded to the depth of the first mineral soil horizon as determined in the quantitative pit. The satellite samples were bulked in the field by gridpoint.

In the laboratory, all soil samples were oven dried at 55 °C and passed through a 2 mm sieve. One subsample of the ≤2 mm fraction was analyzed for pH (1:1 soil:water ratio by volume), SMP pH (Shoemaker et al., 1961) exchangeable Ca^{2+}, Mg^{2+}, K^+, Na^{2+} (10 g soil in 50 mL 1 N ammonium acetate), bicarbonate-extractable P (2 g soil in 50 mL 0.05 M $NaHCO_3^-$), Bray-extractable P (2 g soil in 0.5 M HCl plus 1 M NH_4F) and extractable S (presumed to be SO_4^{2-}–S), Mn, B, Zn, and Fe (10 g soil in 50 mL 1 N ammonium acetate) at A&L Agricultural Laboratories, Modesto, CA. At A&L, soil extracts for Ca^{2+}, Mg^{2+}, K^+, Na^{2+}, SO_4^{2-}–S, Mn, B, Zn, and Fe were analyzed using a Jarrell Ash inductively coupled plasma spectrophotometer (Thermo Jarrell Ash Corp., Franklin, MA). Ortho-P on the Bray and bicarbonate extracts was measured colorimetrically on a Gilford Stasar III, Visible Spectrophotometer.

A separate soil subsample was sent to Oklahoma State University Soil, Water and Forage Laboratory (SWAFL). At SWAFL, total C and N were analyzed using a dry combustion C and N analyzer (LECO, St. Joseph, MI). For soil NH_4^+ and NO_3^-, 10 g of dried, ground soil was shaken with 20 ml of 1 M KCl for 30 min followed by analysis on a Lachat 8000 flow-injection analyzer with Cetac xyz autosampler.

2.3. Statistical analyses

Data were analyzed using student's t-tests (Microsoft Excel) to compare two mean values regression analyses were conducted using SAS® PROC REG software (Version 9.1 for Windows Copyright © 2002–2003, SAS Institute Inc., Cary, NC, USA.). Tests of significance were conducted at $P \leq 0.05$.

3. Results

3.1. Patterns with elevation and soil series

Figs. 2–4 plot percent rock (>2 mm), bulk density, and soil contents of C and nutrients against elevation. The soils broke out naturally broke into two elevation categories: the higher elevation Bull watersheds (2050 to 2490 m) and the lower elevation Providence watersheds (1485 to 2115 m). When all data (Bull and Providence) were combined, elevation was significantly (but poorly) negatively correlated to Bray- and bicarbonate-extractable P, exchangeable K^+, Ca^{2+}, Mg^{2+}, and Na^+. There were no significant correlations between elevation and rock content, bulk density C, N, mineral N, SO_4^{2-}–S, or extractable B, Mn, Zn, and Fe. When analyzed by location (Bull or Providence), the only significant correlations with elevation were for exchangeable Ca^{2+} and Mg^{2+} on the Bull watersheds, both of which were negatively correlated with elevation ($r^2 = -0.170$, $P = 0.007$ and $r^2 = 0.155$, $P = 0.003$, respectively).

Because there were no correlations between elevation and rock content or bulk density, the major factors affecting soil nutrient

Table 2
Average concentrations in Cagwin and Shaver series surface (satellite) soil samples.

	Cagwin			Shaver		
pH	5.70	±	0.06	5.58	±	0.09
SMP pH	6.90	±	0.02	6.81	±	0.04
Carbon (g kg^{-1})	34.96	±	2.32	33.35	±	3.03
Nitrogen (g kg^{-1})	1.62	±	0.08	1.67	±	0.12
C:N ratio	21.20	±	0.74	19.97	±	1.06
NO_3^-–N (mg kg^{-1})	2.51	±	0.24	2.50	±	0.36
NH_4^+–N (mg kg^{-1})	42.78	±	1.64	47.15	±	2.36
Mineral N (mg kg^{-1})	45.26	±	1.71	49.75	±	2.59
Bray P (mg kg^{-1})	46.65	±	5.15	57.38	±	7.49*
Bicarbonate P (mg kg^{-1})	25.56	±	1.98	34.25	±	3.48**
K^+ (cmol$_c$ kg^{-1})	0.30	±	0.02	0.38	±	0.03*
Ca^{2+} (cmol$_c$ kg^{-1})	3.32	±	0.45	4.76	±	0.99
Na^+ (cmol$_c$ kg^{-1})	0.06	±	0.00	0.06		0.01
Mg^{2+} (cmol$_c$ kg^{-1})	0.33	±	0.03	0.50	±	0.09*
SO_4^{2-}–S (mg kg^{-1})	13.76	±	1.36	14.64	±	2.59
Mn (mg kg^{-1})	29.17	±	3.55	26.75	±	4.87
Fe (mg kg^{-1})	21.51	±	3.55	25.37	±	3.66
Zn (mg kg^{-1})	0.47	±	0.07	0.38	±	0.06
B (mg kg^{-1})	0.31	±	0.02	0.33	±	0.04

* Indicate statistically significant difference, student's *t*-test, $P < 0.05$.
** Indicate statistically significant difference, student's *t*-test, $P < 0.01$.

Table 3
Depth, bulk density, and nutrient contents in the quantitative pit samples from the Bull and Providence sites. Data for all points include soil sampling points that occurred on solid rock; soil only points exclude the solid rock sampling points. Bold indicates Bull and Providence sites differ significantly (student's *t*-test); underline indicates that all points and soil only points differ.

	All points		Soil only	
	Bull (n = 43)	Providence (n = 53)	Bull (n = 41)	Providence (n = 46)
Depth (cm)	74 ± 4	65 ± 5	77 ± 4	75 ± 4
Bulk density (g cm^{-3})	1.29 ± 0.06	*1.38 ± 0.09*	**1.23 ± 0.04**	***1.11 ± 0.05***
% >2 mm	40 ± 3	44 ± 4	38 ± 2	36 ± 3
C contents (Mg ha^{-1})	**106 ± 9**	**80 ± 7**	**111 ± 8**	**93 ± 6**
N contents (kg ha^{-1})	**6342 ± 438**	**5022 ± 440**	6644 ± 402	5804 ± 396
NH4–N contents (kg ha^{-1})	231 ± 21	188 ± 21	242 ± 21	218 ± 22
NO3-N contents (kg ha^{-1})	18 ± 2	16 ± 3	18 ± 2	18 ± 3
Mineral N contents (kg ha^{-1})1)	249 ± 23	204 ± 23	260 ± 22	236 ± 24
Bray P contents (kg ha^{-1})	**109 ± 11**	**236 ± 26**	**114 ± 11**	**273 ± 26**
Bicarbonate P contents (kg ha^{-1})	**88 ± 9**	**125 ± 14**	**92 ± 9**	**145 ± 15**
K contents (kg ha^{-1})	490 ± 46	538 ± 66	513 ± 45	622 ± 69
Ca contents (kg ha^{-1})	**1118 ± 129**	**2739 ± 314**	**1172 ± 129**	**3165 ± 319**
Mg contents (kg ha^{-1})	**117 ± 10**	**199 ± 27**	**123 ± 10**	**230 ± 28**
Na contents (kg ha^{-1})	**44 ± 3**	**70 ± 8**	**46 ± 3**	**81 ± 8**
S contents (kg ha^{-1})	68 ± 10	76 ± 14	71 ± 10	88 ± 15
B contents (kg ha^{-1})	**1.65 ± 0.13**	**1.07 ± 0.10**	**1.73 ± 0.12**	**1.24 ± 0.09**
Mn contents(kg ha^{-1})	73 ± 10	80 ± 11	77 ± 10	92 ± 12
Fe contents (kg ha^{-1})	82 ± 7	96 ± 14	86 ± 7	111 ± 14
Zn contents(kg ha^{-1})	1.49 ± 0.13	1.46 ± 0.28	1.56 ± 0.13	1.69 ± 0.30

Table 4
Regression equations for pit versus satellite concentrations in surface soils. Pit samples came from the surface horizons of quantitative pits; satellite samples came from triplicate bucket auger cores taken 8 m from the pit. Both sets of samples were taken at the same depth (Satellite = a + b * pit).

	All grid points (n = 82)				Watershed averages (n = 8)			
	a	b	r^2	*P*	a	b	r^2	*P*
Total C	3.041	0.136	0.047	**0.048**	8.150	0.152	0.413	0.086
Total N	0.116	0.283	0.099	**0.004**	−2.470	1.097	0.708	**0.009**
C:N ratio	16.150	0.238	0.145	**<0.001**	7.090	8.680	0.329	0.137
NH_4^+	29.390	0.329	0.254	**<0.001**	1.721	0.960	0.772	**0.004**
NO_3^-	1.673	0.334	0.155	**<0.001**	2.224	0.107	0.027	0.699
Mineral N	30.660	0.338	0.255	**<0.001**	7.052	0.828	0.554	**0.034**
Bray P	18.860	0.639	0.431	**<0.001**	−2.430	1.053	0.920	**<0.001**
Bicarb. P	12.930	0.515	0.401	**<0.001**	0.761	0.719	0.772	**0.004**
K^+	105.600	0.197	0.034	0.091	0.180	0.511	0.302	0.159
Ca^{2+}	403.800	0.422	0.201	**<0.001**	1.060	0.778	0.705	**0.005**
Mg^{2+}	24.190	0.413	0.258	**<0.001**	0.146	0.614	0.680	**0.012**
Na^+	10.560	0.179	0.047	**0.047**	7.720	0.417	0.244	0.213
SO_4^{2-}	6.390	0.507	0.500	**<0.001**	5.220	0.601	0.750	**0.005**
Zn	0.308	0.161	0.094	**0.005**	−0.023	0.807	0.280	0.177
Mn	19.530	0.267	0.115	**0.002**	13.800	0.519	0.085	0.485
Fe	14.730	0.262	0.230	**<0.001**	14.770	0.295	0.163	0.321
B	0.125	0.615	0.289	**<0.001**	0.143	0.549	0.140	0.350
pH	2.631	0.539	0.367	**<0.001**	1.220	0.791	0.802	**0.003**
SMP pH	5.306	0.229	0.077	**0.011**	1.920	0.721	0.421	0.081

content are soil depth (which is negatively correlated with rock content) and concentration. Weighted average concentrations (nutrient content divided by soil mass) from soil pits reflected the same patterns with respect to elevation that soil contents did (not shown). Concentrations in the satellite samples also showed elevational patterns similar to those for nutrient contents in the soil pits: no trends for C; N; mineral N, SO_4^{2-}–S; extractable B, Mn, Zn, or Fe; significant but weak negative trends for Bray- and bicarbonate-extractable P; exchangeable K^+, Ca^{2+}, Mg^{2+}, and Na^+ (Figs. 5–7). In addition, the satellite soils showed a significant but weak negative trend for pH and a significant but very weak positive trend for SMP pH (Fig. 6), indicating more active acidity but lower reserve acidity in the Bull watersheds. When analyzed by location, concentrations of total N were negatively correlated with elevation on the Providence watersheds ($r^2=-0.137$, $P=0.004$), NH_4^+ and mineral N were negatively correlated with elevation at Providence ($r^2=-0.122$, $P=0.028$, and $r^2=0.108$, $P=0.032$, respectively), Ca^{2+} and Mg^{2+} were negatively correlated with elevation on the Bull watersheds ($r^2=-0.181$, $P=0.004$, and $r^2=0.101$, $P=0.049$, respectively), Mg^{2+} and Fe were negatively correlated with elevation at Providence ($r^2=-0.097$, $P=0.042$, and $r^2=0.160$, $P=0.008$, respectively), and Mn was positively correlated with elevation at Providence ($r^2=0.100$, $P=0.039$).

Although there are large differences in the general description and locations of the Shaver and Cagwin soils, there were no statistically significant differences in rock content, depth, bulk density, or the contents (kg ha^{-1}) of any measured nutrient (not shown). In the satellite samples, however, the Shaver soils had significantly greater

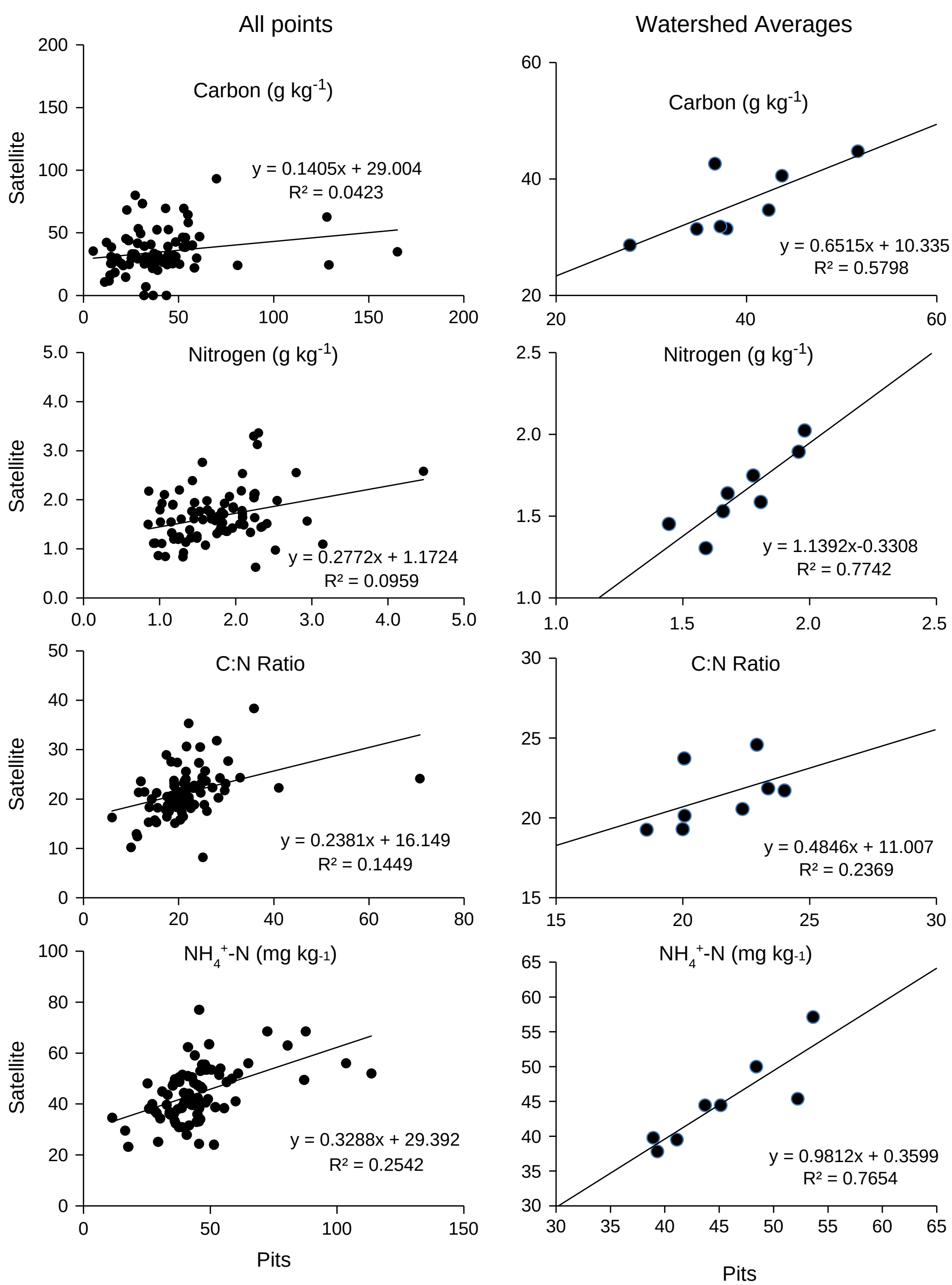

Fig. 8. Concentrations of C, N, C:N ratio, and NH_4^+—N in surface soils from pits plotted against satellite soils. All points plotted on the left, watershed average values plotted on the right. See Table 5 for regression coefficients and probabilities.

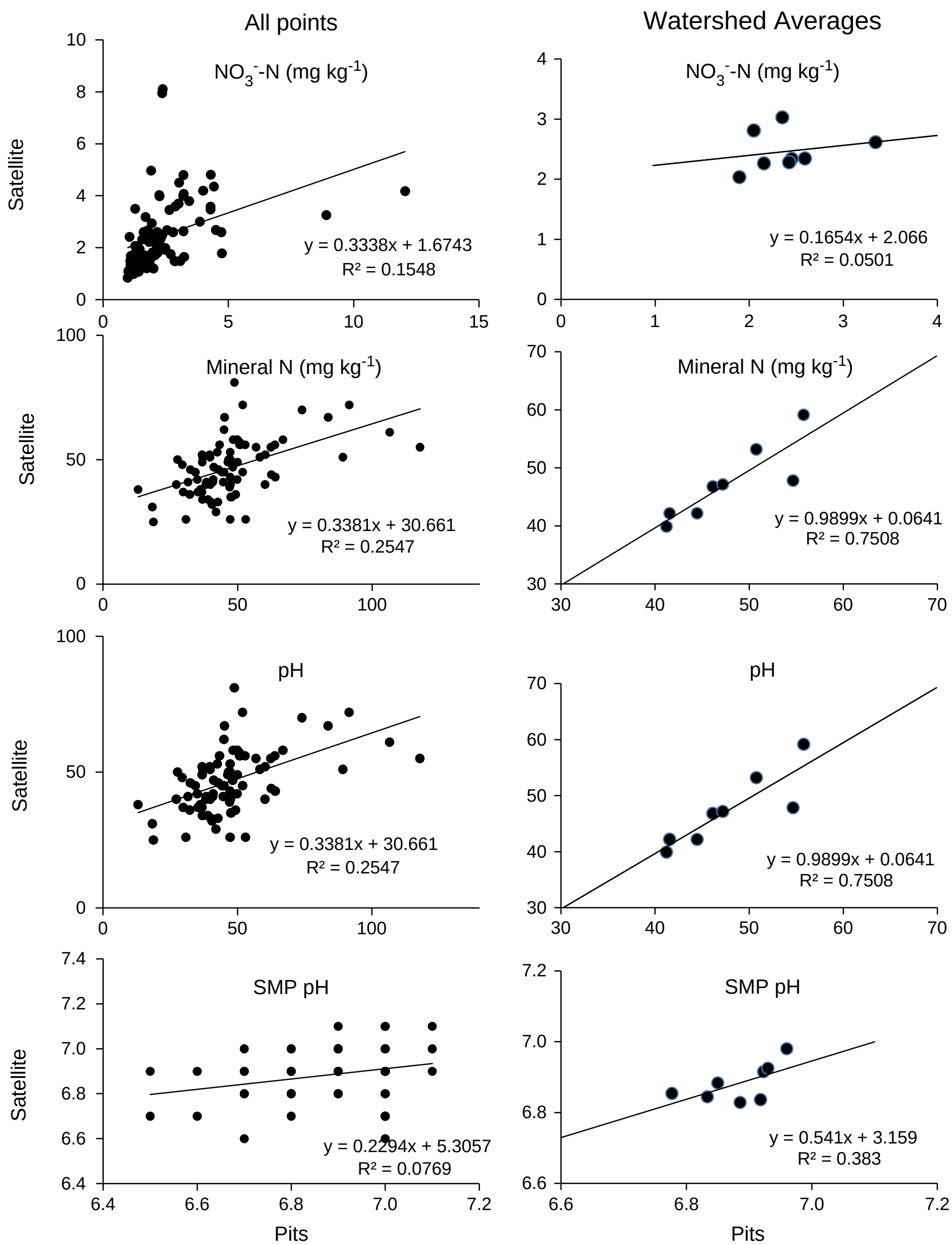

Fig. 9. Concentrations of NO_3^-–N, mineral N (NH_4^+–N + NO_3^-–N), pH and SMP pH in surface soils from pits plotted against satellite soils. All points plotted on the left, watershed average values plotted on the right. See Table 5 for regression coefficients and probabilities.

concentrations of Bray P, bicarbonate P, exchangeable K^+, and exchangeable Mg^{2+} than the Cagwin soils, reflecting the differences in these nutrients with elevation previously noted. Exchangeable Ca^{2+} was also greater in the Shaver soil, but not quite statistically significant ($P = 0.10$) (Table 2).

3.2. Effects of rock content

On the Bull watersheds, where only two of 43 sampling points landed on solid rock, average depth was 4% lower, whole-soil bulk density was 5% greater, and total rock fraction (>2 mm) was 13% greater for all sample points than for soil only points (Table 3). Average C and nutrient contents for all points were 5% lower than for soil only points at Bull. In the Providence watersheds, where seven of the 53 points landed on solid rock (13%), average depth was 13% lower, whole-soil bulk density was 24% greater, and total rock fraction (>2 mm) was 13% greater for all points than for soil only points. Average C and nutrient contents for all points were 13% lower than soil only points at Providence. The inclusion of solid rock points also caused some differences in statistical analyses: (1) average bulk density at the Bull watersheds was significantly greater than the Providence watersheds when soil only points were considered but not when all points were considered, and (2) average N contents at the Bull watersheds was significantly greater than at the Providence watersheds when all points were considered but not when soil only points were considered. Although there were no overall significant trends in C, N, or B contents with elevation (Figs. 2–4), C and B contents at Bull were significantly greater than at Providence whether all points or soil only points were considered (by 19 and 32% for C and by 54 and 40% for B) and N content at Bull was significantly greater (by 26%) than on the Providence watersheds when all points were considered (but not when soil only points were considered; Table 3).

The differences in Bray and bicarbonate P, Ca^{2+}, Mg^{2+}, and Na^{+} contents between Bull and Providence (ranging from 60 to 170% greater at Providence) were highly significant and reflected the patterns with elevation previously noted.

3.3. Comparisons of satellite and pit samples

The correlations between analyses of surface horizons from soil quantitative pits and soils taken nearby (to the same depths) by bucket auger (satellite samples) were nearly all statistically significant (K^{+} being the only exception, with a *P* value of 0.091), but the correlation coefficients were generally low (Table 4; Figs. 8–11). Unfortunately, some of the lowest r^2 values were for analyses of interest for the burning treatment effects: total C, total N, C:N ratio, NH_4^+, and NO_3^-. The best correlations (still with r^2 values of 0.5 or less) were for SO_4^{2-}, and extractable P (Bray and bicarbonate). When averaged on a watershed level, the r^2 values improved considerably but some of the correlations became non-significant (total C, C:N ratio, NO_3^-, K^+, Na^+, Zn, Mn, Fe, and B) (Figs. 8–11; Table 4). When averaged by site, (Bull versus Providence), the correspondence between the pit and satellite analyses was closer yet: average values for the pit and satellite soils on the Bull watersheds differed by less than 10% for total N, C:N ratio, NH_4^+, mineral N, Bray P, bicarbonate P, Ca^{2+}, Mg^{2+}, Na^+, B, and pH for both the Bull and Providence watersheds (Table 5). Only in the case of pH at Bull did pit and satellite values differ significantly. For total C, pit and satellite average values differed by 11% on Bull and 9% on Providence and the differences were not statistically significant. Other nutrients differed by larger percentages but in inconsistent directions: for SO_4^{2-}, satellite > pit by 6% on Bull, but satellite < pit by 12% on Providence, (neither difference statistically significant); for K^+, satellite > pit by 24% on Bull (statistically significant) 6% on Providence (not significant); for Fe, satellite < pit by 28% on Bull (statistically significant) and 5% on Providence (not significant); and for NO_3^- satellite < pit by 11% on Bull but satellite > pit by 18% on Providence (neither difference statistically significant). The largest and most consistent difference between pit and satellite samples was for Zn, where satellite Zn was 33% lower than pit Zn on Bull and 34% lower than pit Zn on Providence (both differences were statistically significant). We attribute the latter to the fact that the field sieve used for the pit samples was galvanized (rabbit wire) and contaminated the samples with Zn. The only statistically significant differences between satellite and pit samples were for K^+ and Zn at both Bull and Providence and for Fe at Bull. Statistically significant differences occurred between Bull and Providence for: (1) both pit and satellite samples with significantly lower Ca^{2+}, Mg^{2+}, pH, Bray and bicarbonate P at Bull, and (2) both pit and satellite samples with significantly greater Zn at Bull.

4. Discussion

The higher elevation Bull watersheds had somewhat greater C and N contents and considerably lower extractable P, exchangeable Ca^{2+}, Mg^{2+}, and Na^+ contents, and lower pH than the lower elevation Providence watersheds (Table 3). This is expected, given the differences in climate at these two sites (colder, with slower

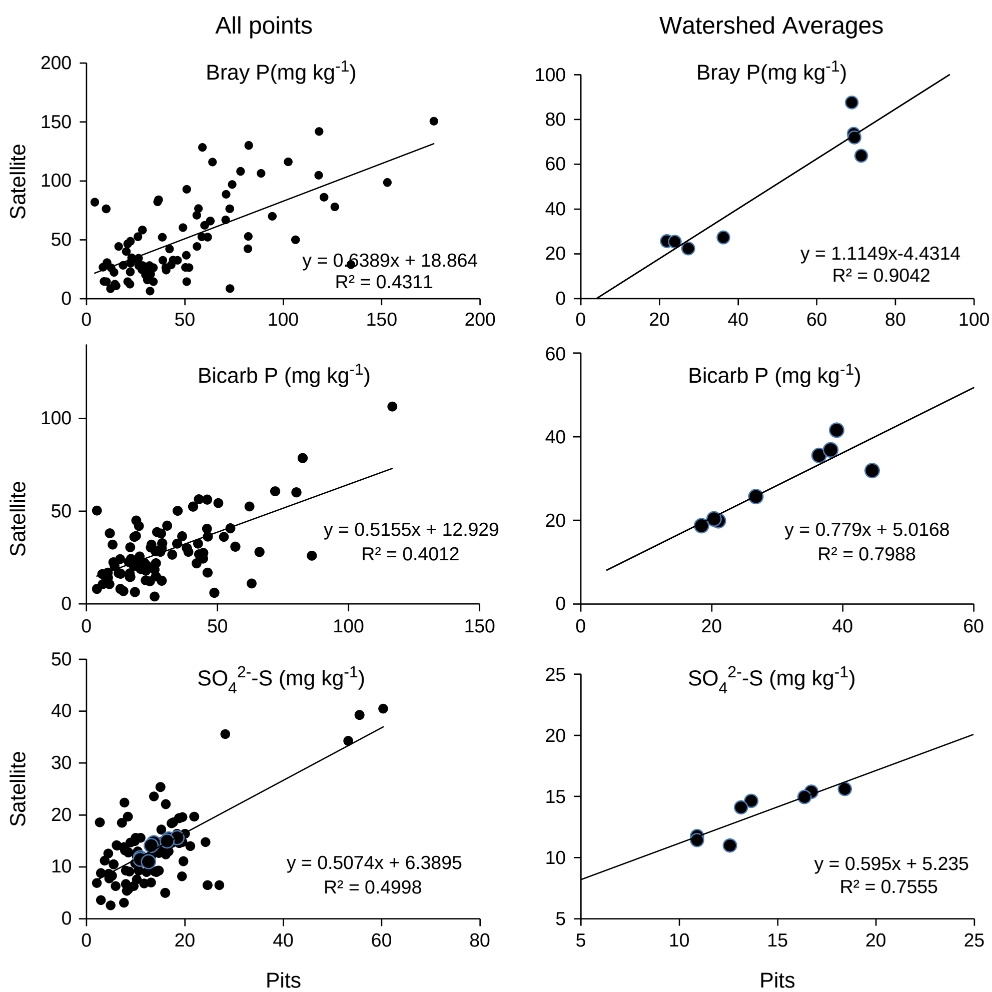

Fig. 10. Concentrations of Bray P, bicarbonate P, and SO_4^{2-}–S in surface soils from pits plotted against satellite soils. All points plotted on the left, watershed average values plotted on the right. See Table 5 for regression coefficients and probabilities.

decomposition and wetter, with greater leaching and acidification pressure at Bull). However, the Bull sites have higher SMP pH values (Table 5), indicating that they have less reserve acidity than the Providence sites. Unfortunately, we do not have reliable data for cation exchange capacity to further investigate the nature and perhaps causes of these differences.

Dahlgren et al. (1997) conducted a study of soil change with elevation along a transect just north of our sites and reported a pronounced change in soil properties at about 1600 m elevation, which coincides with the approximate elevation of the present-day average effective winter snow-line. Two points on their transect — Shaver (1800 m) and Sirretta (2195 m) roughly coincided with the elevation ranges of our sites (1485 to 2115 m for Providence and 2150 to 2490 m for Bull). Dahlgren et al. (1997) report A1, A2, and A3 horizon exchangeable Ca^{2+} values of 7.67, 2.88, and 1.77 $cmol_c\,kg^{-1}$ for Shaver and 3.36, 1.43, and 1.04 for Sirretta, which are comparable to our average exchangeable Ca^{2+} values in A horizons for Providence (4.64 ± 0.43 in pits and 4.62 ± 0.43 in satellite samples) and Bull (2.07 ± 0.39 in pits and 2.24 ± 0.33 in satellite samples) (Table 5). Values for exchangeable Mg^{2+} are somewhat greater in Providence (0.45 ± 0.04 in pits and 0.43 ± 0.03 in satellite samples) than Shaver (0.29, 0.16 and 0.14) and slightly greater in Bull (0.24 ± 0.03 in pits and 0.26 ± 0.02 in satellite samples) than Sirretta (0.21, 0.09, and 0.13). In both studies, changes in exchangeable K^+ with increasing elevation were negligible and the overall range of values (0.25 to 0.35 in Providence and Bull versus 0.27 to 0.36 in Shaver and Sirretta) are comparable.

The lower extractable P contents at Bull could be related to their lower pH (enhancing ortho-P adsorption to the soil sesquioxide

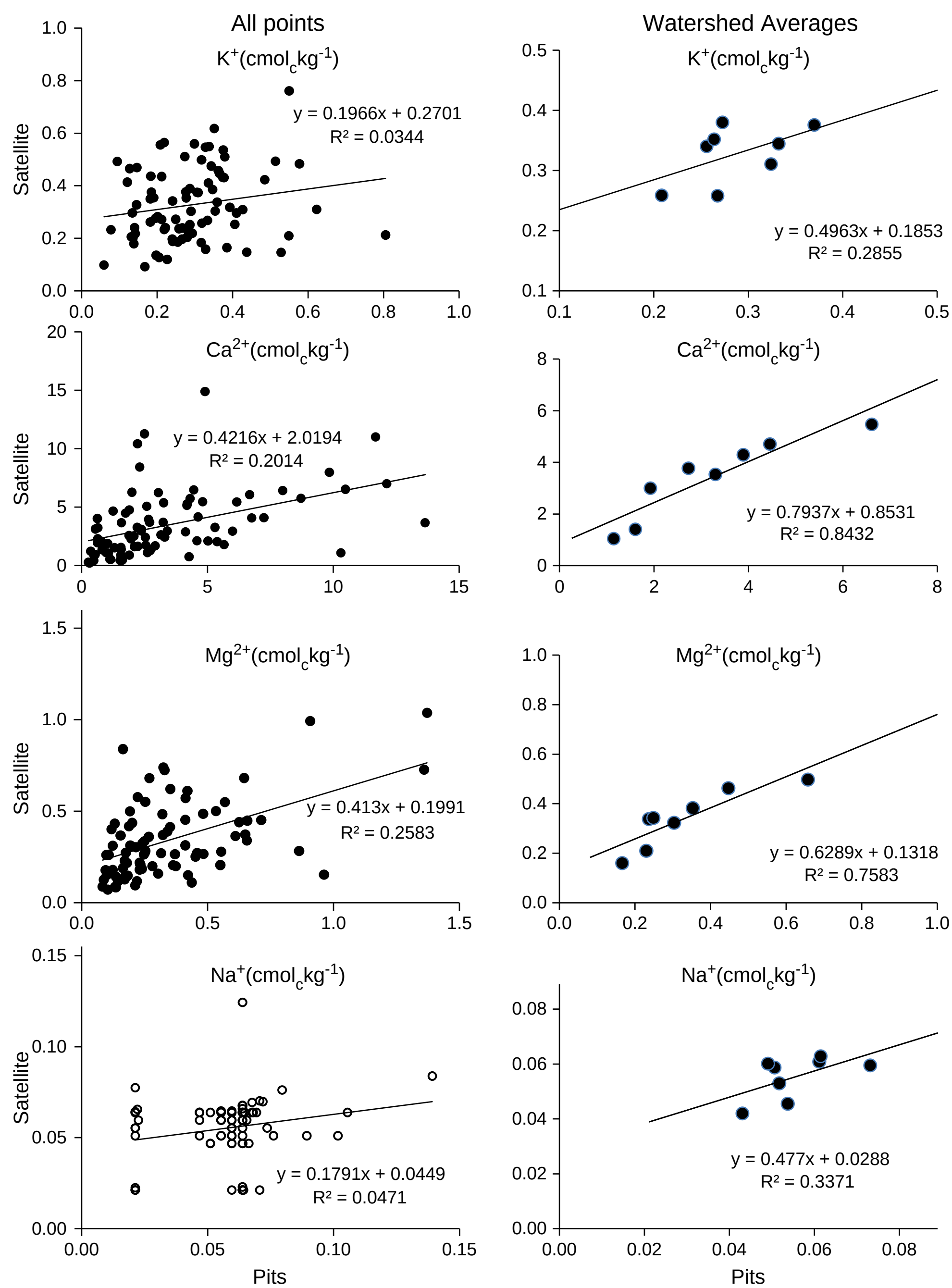

Fig. 11. Concentrations of exchangeable K^+, Ca^{2+} Mg^{2+}, and Na^+ in surface soils from pits plotted against satellite soils. All points plotted on the left, watershed average values plotted on the right. See Table 5 for regression coefficients and probabilities.

surfaces) and perhaps also lower sesquioxide contents. Further work is planned to examine the factors affecting P availability in these soils.

Soil mineral N pools (which were dominated by NH_4^+) averaged in excess of 200 kg ha^{-1} on the KREW watersheds (Table 3), which are levels most commonly associated with N fertilization in forests (Chappell, et al., 1991; Johnson, 1992). These relatively high levels of soil mineral N cannot be explained by known levels of atmospheric deposition at KREW (0.5–1.7 kg ha^{-1} $year^{-1}$, for bulk deposition values; Hunsaker et al., 2007) or by any measured soil property. Total N is significantly but poorly correlated to mineral N in the satellite and A horizon pit soils ($r^2 = 0.022$ and 0.046, respectively), but C:N ratio is not significantly related to mineral N concentration. The potential causes of the high mineral N concentrations in the KREW soils are currently under investigation.

The disparities in nutrient analyses of quantitative pit and satellite soils for any given gridpoint were quite large, but when averaged over the watershed or site (Bull and Providence) scale, the comparisons were much improved (with the exception of Zn, which was clearly contaminated in the pit samples by the galvanized field screen) (Figs. 8–12; Table 5). Because treatments will be implemented on a watershed scale, this result is encouraging: it would appear that a second round of quantitative pits may not be necessary and we can rely instead on much more easily obtained bucket auger samples, given that we already have good data on rock content and soil mass. Furthermore, with good data on coarse fragment content, we can scale up the post-treatment results to a kg ha^{-1} level with some confidence, given some post-treatment sampling for changes in surface soil bulk density obtained by the core method. Also, with multiple samplings per grid point, the bucket auger samples probably do a better job of capturing the chemical characteristics of a given grid point than single pit samples do.

The time and effort involved in sampling quantitative pits were considerable — so what did it tell us that simple bulk density coring would not have? For the Providence watersheds, the average large rock content per pit (that is, rock that was separated out with the 1 cm field sieve) was 16 ± 3%, and for the Bull watersheds it was 27 ± 2% (mean ± standard error, by weight). Thus, calculations of C and nutrient content in the fine earth fraction without knowledge of the large rock content of the soil profiles would have been overestimated by $1/(1–0.16) = 0.19$, or 19% for the Providence watersheds and $1/(1–0.27) = 0.37$, or 37% for Bull watersheds among the grid points that fell on soil. For all grid points (including those falling on solid rock), large rock accounted for 27 ± 4% for Providence and 30 ± 3% for Bull, resulting in overestimates of 37% and 43%, respectively, in fine earth weight and nutrient content. This would have introduced considerable error into estimates of C and nutrient stocks and therefore in the estimates of treatment effects on C and nutrient stocks in these soils.

5. Summary and conclusions

Quantitative pit and surface soil samples indicated that the higher elevation Bull watersheds had significantly greater C, N and B contents but lower extractable P, exchangeable Ca^{2+}, Mg^{2+} and Na^+ contents and lower pH than the lower elevation Providence watersheds. Presumably the differences in C and N reflect differences in decomposition rate (slower at the higher elevation sites). Presumably the differences in exchangeable Ca^{2+} and Mg^{2+} and pH were due to differences in leaching rates (greater at the snow dominated Bull watersheds). Reasons for the differences in extractable P are not known, but may be due to differences in pH and possibly also sesquioxide contents. Differences in other nutrients occurred in pit and surface soil concentrations, but were not as consistent.

Soil NH_4^+ and mineral N (NH_4^+ constituted 90% of mineral N) were surprisingly high in both the Bull and Providence watersheds and could not be related to any measured soil property or attributed to know rates of atmospheric deposition.

Nutrient analyses on samples taken with a bucket auger were comparable to those taken from the same surface horizon depths in nearby quantitative pits when averaged on a watershed or site (Bull and Providence) scale, but quite variable on an individual grid point basis. Elevated Zn values from the quantitative pit samples suggested contamination by field sieving through a galvanized screen.

Had quantitative pits not been dug on these watersheds and large rocks within them not accounted for, estimates of fine earth and associated C and nutrient contents would have been overestimated by 16 to 43%; thus, while soil concentration data can provide relatively good indices of differences among sites and watersheds, a lack of knowledge about large rock content can cause significant overestimates in soil C and nutrient contents and therefore also their responses to management treatments and climate change.

Acknowledgements

We wish to thank Alan Gallegos of the Sierra National Forest for assisting us with this large sampling effort that took several years. The establishment of KREW would not have been possible without funding

Table 5
Nutrient concentrations in the surface horizons of quantitative pits and satellite samples (the later taken with bucket auger near each pit, n = 3 per site and bulked). Bold indicates Bull and Providence sites differ significantly (student's *t*-test); underline indicates that pit and satellite values differ significantly.

	Bull			Providence		
	Pits	Satellite	% Diff	Pits	Satellite	% Diff
C (mg g^{-1})	42.0 ± 5.2	37.2 ± 2.9	−11%	37.8 ± 2.1	34.3 ± 1.9	−9%
N (mg g^{-1})	1.76 ± 0.11	1.64 ± 0.09	−7%	1.74 ± 0.07	1.66 ± 0.07	−5%
C:N ratio	22.1 ± 1.6	22.5 ± 0.9	2%	21.3 ± 0.7	20.3 ± 0.6	−5%
NH_4^+ (mg kg^{-1})	46.7 ± 2.7	44.5 ± 1.7	−5%	44.1 ± 2.4	44.2 ± 1.6	0%
NO_3^- (mg kg^{-1})	2.7 ± 0.3	2.4 ± 0.2	−11%	2.2 ± 0.1	2.6 ± 0.3	18%
Mineral N (mg kg^{-1})	49.4 ± 2.7	47.0 ± 1.7	−5%	46.2 ± 2.4	46.8 ± 1.8	1%
Bray P (mg kg^{-1})	**28.0 ± 2.2**	**25.5 ± 1.7**	−9%	**68.9 ± 5.9**	**74.2 ± 4.9**	8%
Bicarb. P (mg kg^{-1})	**21.8 ± 1.9**	**21.2 ± 1.6**	−3%	**39.6 ± 3.6**	**36.2 ± 2.9**	−9%
K^+ ($cmol_c$ kg^{-1})	0.25 ± 0.02	0.31 ± 0.02	24%	0.33 ± 0.02	0.35 ± 0.02	6%
Ca^{2+} ($cmol_c$ kg^{-1}))	**2.07 ± 0.39**	**2.24 ± 0.33**	8%	**4.64 ± 0.43**	**4.62 ± 0.43**	0%
Mg^{2+} ($cmol_c$ kg^{-1})	**0.24 ± 0.03**	**0.26 ± 0.02**	8%	**0.45 ± 0.04**	**0.43 ± 0.03**	−4%
Na^+ ($cmol_c$ kg^{-1})	0.05 ± 0.00	0.05 ± 0.00	0%	0.06 ± 0.00	0.06 ± 0.00	0%
SO_4^{2-}(mg kg^{-1})	12.0 ± 0.9	12.7 ± 1.0	6%	16.2 ± 1.9	14.3 ± 1.2	−12%
Fe (mg kg^{-1})	26.3 ± 3.5	18.9 ± 1.2	−28%	25.1 ± 2.4	23.9 ± 1.9	−5%
Mn (mg kg^{-1})	**33.8 ± 4.5**	**33.2 ± 3.9**	−2%	**24.6 ± 3.2**	**22.1 ± 1.9**	−10%
Zn (mg kg^{-1})	**0.76 ± 0.13**	**0.51 ± 0.07**	−33%	**0.50 ± 0.07**	**0.33 ± 0.03**	−34%
B (mg kg^{-1}))	0.31 ± 0.01	0.31 ± 0.01	0%	0.29 ± 0.02	0.31 ± 0.02	7%
pH	**5.37 ± 0.04**	**5.47 ± 0.04**	2%	**5.83 ± 0.05**	**5.83 ± 0.05**	0%
SMP pH	6.90 ± 0.02	6.91 ± 0.02	0.03%	6.86 ± 0.02	6.86 ± 0.02	0%

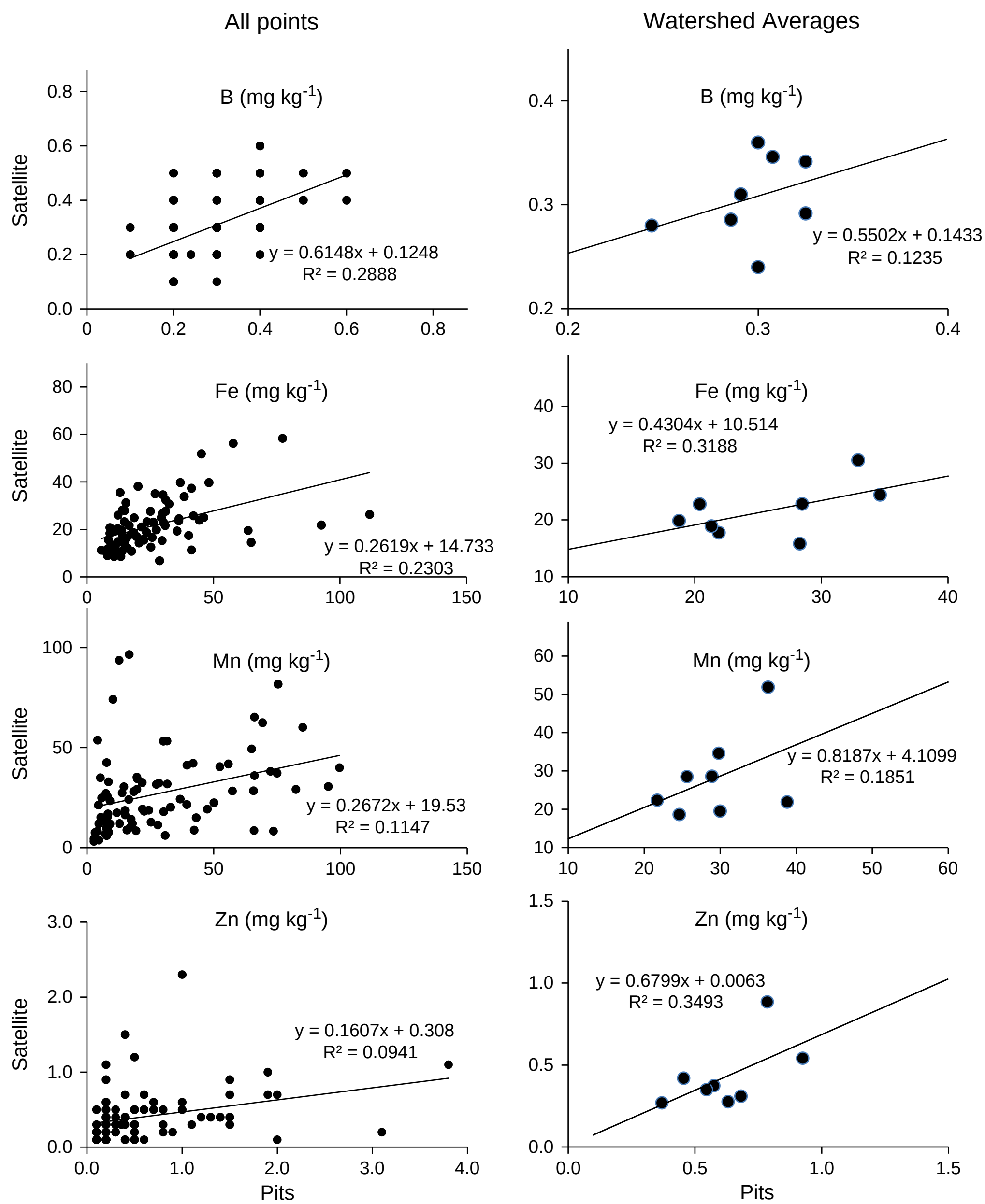

Fig. 12. Concentrations of exchangeable B, Fe, Mn, and Zn in surface soils from pits plotted against satellite soils. All points plotted on the left, watershed average values plotted on the right. See Table 5 for regression coefficients and probabilities.

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