

# Assessing the Suitability of Rotary Coring for Sampling in Rocky Soils

**Carrie R. Levine\***

**Ruth D. Yanai**

Department of Forest and Natural  
Resource Management  
State University of New York  
College of Environmental Science  
and Forestry  
1 Forestry Dr.  
Syracuse, NY 13210

**Matthew A. Vadeboncoeur**

Earth Systems Research Center  
University of New Hampshire  
8 College Road  
Durham, NH 03824

**Steven P. Hamburg**

Environmental Defense Fund  
18 Tremont St.  
Boston, MA 02108

**April M. Melvin**

Department of Ecology and  
Evolutionary Biology  
Cornell University  
Ithaca, NY 14853

Current address:  
Department of Biology  
University of Florida  
Gainesville, FL 32611

**Christine L. Goodale**

Department of Ecology and  
Evolutionary Biology  
Cornell University  
Ithaca, NY 14853

**Benjamin M. Rau**

USDA-Agricultural Research Service  
Building 3702 Curtin Rd.  
University Park, PA 16802

**Dale W. Johnson**

Department of Natural Resources and  
Environmental Science  
University of Nevada, Reno  
1000 Valley Rd.  
Reno, NV 89512

Forest soils are difficult to sample quantitatively because of obstruction by rocks and coarse roots. Collecting quantitative soil cores with a motorized diamond-tipped cylindrical bit can provide much faster access to deep soil samples than digging quantitative soil pits. However, the grinding of rock and soil during coring could elevate exchangeable cation concentrations relative to samples collected manually. We compared soils collected by rotary coring to those collected from quantitative pits at four sites in the United States with differing soil types: Alfisols in California (CA), Mollisols in Nevada (NV), Inceptisols in New York (NY), and Spodosols in New Hampshire (NH). Estimates of soil mass were 34% higher from cores than pits at the NY site ( $p < 0.0001$ ). Estimates of rock mass were lower in cores than pits by 60% at the NH site ( $p < 0.0001$ ), by 36% at the NY site ( $p < 0.0001$ ), and by 55% at the CA site ( $p = 0.002$ ). Exchangeable K was significantly elevated in cores relative to pits at all four sites by 32 to 1700%, and Ca, Mg, and Na showed elevated concentrations at one or more sites. We tested whether the inner portion of the core was comparable to samples from pits, but found that the rotary action of the corer mixed soils throughout the core bit at the two sites we tested. Coring does have the advantage that more samples can be collected for the same effort, compared to pits. Some degree of inaccuracy might be acceptable in a tradeoff for greater precision in the site-level mean, for example in studies aimed at detecting change in soil nutrients over time.

**Abbreviations:** CA, California; NH, New Hampshire; NV, Nevada; NY, New York.

Forest and wildland soils are difficult to characterize because they can be rocky, inaccessible, and spatially heterogeneous (Kulmatiski et al., 2003). Methods of collecting soils for analysis include punch corers, bucket augers, and drive-type corers operated by machine or by hand (Boone et al., 1999; Jurgensen et al., 1977; Ponder and Alley 1997). However, scaling these observations up to site-level nutrient contents requires estimating soil depth, coarse fraction, and bulk density. In contrast, quantitative soil sampling methods allow direct estimation of soil mass and rock volume. For example, soils can be removed from a quantitative soil pit by depth increment and weighed in the field (Hamburg, 1984; Vadeboncoeur et al., 2012). However, quantitative soil pits are time consuming to excavate.

An alternative method for extracting quantitative soil samples at depth uses a diamond-tipped cylindrical drill bit powered by a rotary engine (Ponder and Alley, 1997). This type of corer can cut through large roots and rocks to a depth of 90 cm or more. Sampling by rotary coring is faster than digging quantitative pits. Rau et al. (2011) report coring to a depth of >1 m in 20 to 45 min. In the time required

Soil Sci. Soc. Am. J. 76:1707–1718

doi:10.2136/sssaj2011.0425

Received 10 Nov. 2011.

\*Corresponding author (crlevi01@syr.edu).

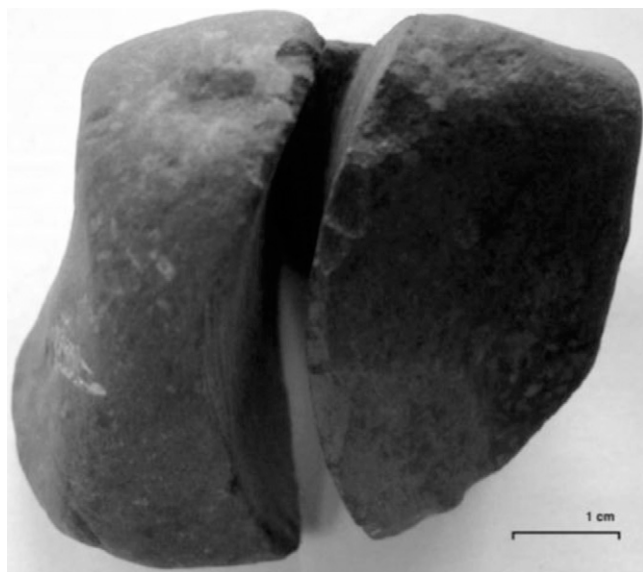
© Soil Science Society of America, 5585 Guilford Rd., Madison WI 53711 USA

All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Permission for printing and for reprinting the material contained herein has been obtained by the publisher.

to dig one quantitative soil pit, several cores distributed across a site can be extracted, which allows a more precise estimate of the site mean.

The rotary coring method has been compared to quantitative soil pits for estimating soil mass, rock mass, and percent C and N at three sites in the United States, with no systematic differences reported between core samples and quantitative pits to a depth of 50 to 60 cm (Rau et al., 2011). However, the grinding of rock during the coring process (Fig. 1) may make such samples problematic for estimating cation concentrations in rocky soils. Grinding through rocks and soil could be expected to expose weatherable minerals, disrupt stable aggregates, increase surface area, and artificially elevate exchangeable cation concentrations in the cored samples.

The objective of this study was to compare the physical and chemical properties of samples collected by rotary coring with those from quantitative soil pits as a function of soil depth in a variety of forest soil types. We also evaluated modified coring methods, including capturing the contamination contributed during the insertion and removal of the core bit and sampling from the inner portion of the core. We tested whether these various sources of contamination would account for differences between results obtained from cores and pits in four soil types: Alfisols (CA), Mollisols (NV), Inceptisols (NY), and Spodosols (NH). These and additional plots at three of these sites (CA, NV, and NY) were included in previous analyses of soil mass, rock mass, and C and N (Rau et al., 2011). The validation of rotary coring for quantifying base cation concentrations in soils would improve the efficiency of monitoring long-term soil nutrient dynamics in rocky, heterogeneous soils.



**Fig. 1.** An example of a granite cobble from the New Hampshire (NH) site cut by the diamond-tipped cylindrical drill bit during sample collection. The convex side of the cobble was found in the cored sample and the concave side remained in the wall of the cored hole. The cobble broke before it was cut through, which shows the width of the ground portion (8 mm).

## METHODS

### Site Descriptions

We compared soil pits and rotary cores at four sites in the United States (Table 1). The CA site is located in the Tahoe National Forest. Soils are fine-loamy, mixed, frigid Alfisols derived from andesite (Ultic Haploxeralfs; Murphy et al., 2006). Overstory vegetation is predominantly Jeffrey pine (*Pinus jeffreyi* Grev. and Balf.) with some white fir [*Abies concolor* (Gord. and Glend.) Lindl. Ex Hildebr.] and understory vegetation including sagebrush (*Artemisia tridentata* Nutt.), bitterbrush (*Purshia tridentata* DC.), mule's-ears (*Wyethia mollis* A. Gray), green leaf manzanita (*Arctostaphylos patula* Green), and squawcarpet (*Ceanothus prostratus* Benth.; Murphy et al., 2006).

The NV site is located in the Humboldt–Toiyabe National Forest. Soils are coarse-loamy, mixed, frigid Mollisols derived from welded and unwelded silica ash-flow tuff (Typic Haploxerolls; Rau et al., 2009). Vegetation is dominated by sagebrush (*Artemisia tridentata* Nutt.) and single leaf pinyon (*Pinus monophylla* Torr. and Frém.), with Utah juniper (*Juniperus osteosperma* Torr. Little) and associated grasses and forbs also present (Rau et al., 2009).

The NY site is located at the Connecticut Hill Wildlife Management Area in Tompkins County. Soils are channery silt loam Inceptisols (Typic Fraguidepts) developed on glacial till derived from Devonian shale bedrock (Neeley, 1965). Dominant tree species include red maple (*Acer rubrum* L.) and white ash (*Fraxinus americana* L.).

The NH site is located in the Bartlett Experimental Forest. Soils are coarse-loamy, mixed, frigid Spodosols (Typic Haplorthods) developed on glacial till derived from granite and gneiss bedrock (Vadeboncoeur et al., 2012). The overstory is dominated by sugar maple (*Acer saccharum* Marsh), American beech (*Fagus grandifolia* Ehrh.), and yellow birch (*Betula allegheniensis* Britton). We sampled soils at one mid-successional and one mature stand, referred to in other studies as C6 and C8 (Vadeboncoeur et al., 2007; Park et al., 2007).

### Soil Pits

Soil pits in the CA and NV sites were 0.25 m<sup>2</sup> in area, while soil pits in NY and NH were 0.5 m<sup>2</sup> in area. In the CA site, soil pits were excavated in three depth increments (0–20 cm, 20–40 cm, and 40–60 cm). In NV, pits were excavated in four depth increments (0–8 cm, 8–23 cm, 23–38 cm, and 38–52 cm). In NY, mineral soil was excavated in 10-cm depth increments to 50 cm. In NH, mineral soil was excavated in four depth increments (0–10 cm, 10–30 cm, 30–50 cm, 50 cm–C horizon) and a fifth sample was taken 0 to 25 cm into the C horizon.

Soils were sieved in the field (to 10 mm in CA and NV and to 12 mm in NY and NH), weighed, mixed well, and subsampled. Rocks >10 mm in CA and NV and rocks >12 mm in NY and NH were weighed to derive coarse fraction mass. When rocks could not be removed from a pit, the volume of rocks extending into the pit was estimated, and their mass was calculated using a particle density of 2.65 g cm<sup>-3</sup>. Soil subsamples were taken back

**Table 1. Description of sampling locations included in this study.**

Site	Latitude	Longitude	Elevation	Average annual temperature	Average annual precipitation	Soil suborder	Parent material	Date of sampling
			m a.s.l	°C	cm			
Tahoe National Forest, CA†	39°15' N	120°49' W	1760	6	70	Haploxeralfs	Andesite	Pit:2002; Core: 2008
Humboldt-Toiyabe National Forest, NV	39°15' N	117°35' W	2210–2230	8.5	20	Haploxerolls	Silica ash flow tuff	Pit: 2005; Core: 2006
Tompkins County, NY	42°27' N	76°27' W	290	7.7	90	Fragiudepts	Shale	Pit: 2005–2006; Core: 2010
Bartlett Experimental Forest, NH	44°03' N	71°17' W	330–460	5	140	Haplorthods	Granite	Pit: 2004; Core: 2009

† CA, California; NV, Nevada; NY, New York; NH, New Hampshire.

to the lab, weighed, air-dried, and sieved to 2 mm. The <2 mm fraction was archived until analysis. A subsample was oven-dried to calculate soil moisture content. Methods for measuring bulk density and soil volume differed among sites (Rau et al., 2011; Hamburg, 1984; Vadeboncoeur et al., 2012), but these variables were not analyzed in this study.

### Soil Cores in California and Nevada

We used data from four pairs of pits and cores at the CA site and nine pairs at the NV site (Rau et al., 2011). One soil core was extracted near each soil pit in depth increments corresponding to the depth increments of pit excavation. Cores were taken with a 7.6 cm internal-diameter diamond-tipped core bit (Diteq, Lees Summit, MO) mounted on a rotary motor. Each sample increment was extracted before the core was taken to the next depth increment. Cores were bagged individually, brought back to the lab, dried at 100°C for 48 h, and weighed. Cores were then sieved to 2 mm and the >2 mm fraction and the <2 mm fraction were weighed.

### Soil Cores in New York and New Hampshire

We collected cores near three pits at the NY site and five pits at the NH site, three at C6 and two at C8. Two cores were taken near each pit, except for one pit at C8, which had four associated cores. Cores were located 1.5 m north and east of the center of the pit. In the NH site, a core location was disqualified if there was a rock of any size at the surface, as this made it impossible to begin coring. A core location was abandoned if there was a rock larger than the drill bit within the top 30 cm of mineral soil. When a location was rejected, we moved the core 0.5 m closer to the pit. If this spot was also rejected, we moved the core to the east or south side of the pit. At the NY site, we encountered only one rock at depth that prohibited further coring. When rocks were encountered at a depth >30 cm, we retained the depth increments above the obstructed layer.

We used a 9.5 cm internal-diameter diamond-tipped drill bit (Diteq, Lees Summit, MO) mounted on a rotary motor (Briggs and Stratton, Milwaukee, WI). When coring, we first removed the forest floor in a 15 by 15 cm block. We then installed a 15 by 15 cm wooden box in the block where the organic soil had been removed, with the bottom of the box flush with the top of the mineral soil. The box had a circular opening that was the

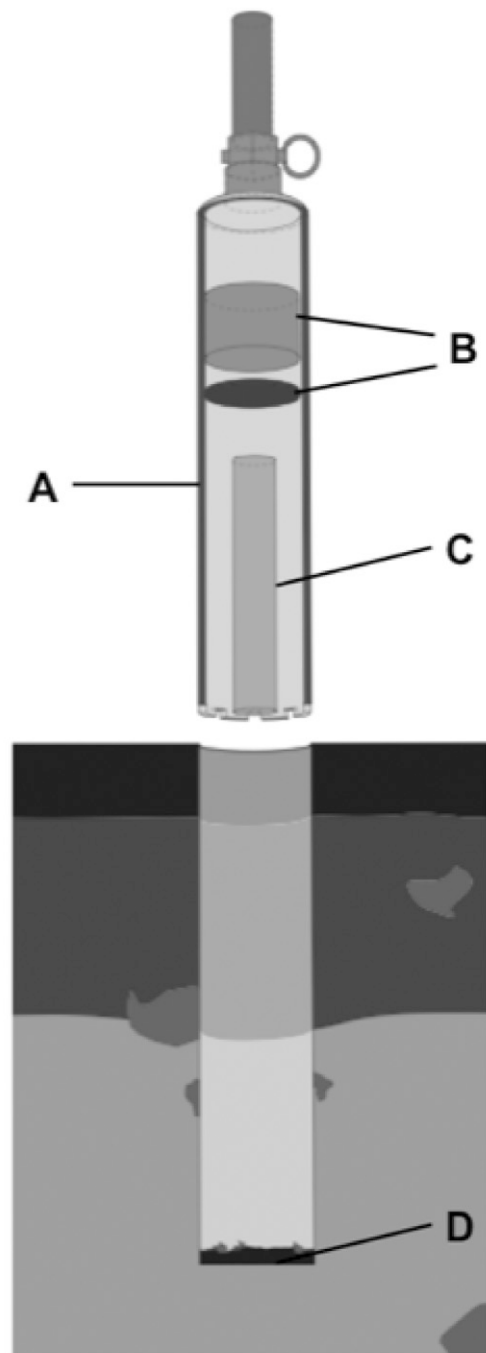
same diameter as the outer diameter of the drill bit. This helped to keep the bit vertical and prevent loose soil near the top of the hole from falling into the hole during insertion and removal of the bit. We cored in sequential increments of 0 to 10 cm, 10 to 30 cm, and 30 to 50 cm in NH and NY, with additional increments of 50 to 70 cm, and 70 to 90 cm in NH. In NY, the core increments corresponded to the increments of the neighboring pits. In NH, the core increments corresponded to the depth increments of the B horizon of the pits, but differed from the pits once the pits reached the C horizon. Due to the difficulty of accurately determining a change in horizon using the cores (core samples are not removed intact), we cored by depth.

### Assessing Contamination in Cores in New York and New Hampshire

We used three methods to assess possible contamination sources during the coring process. To compare the inner portion to the outer portion of the core, where we expected to find the greatest contamination from ground rock, we used a 4-cm diam. PVC soil corer to extract a sample from the inner portion of the core. We refer to the inner subsample as the “inner” sample, and the rest of the sample as the “outer” sample. The “whole” core sample is composed of the inner and outer samples (Fig. 2).

To estimate contamination resulting from inserting and removing the drill bit, we used two methods. To capture the soil introduced when the drill bit was reinserted into the cored hole, we placed a cardboard disk at the bottom of the hole, and inserted a 4 cm-thick wooden disk into the drill bit (Fig. 2). Any soil introduced into the hole when the bit was inserted was captured between the cardboard disk and the wooden disk. We collected this sample for all depth increments except the 0- to 10-cm increment, which we assumed had no contamination introduced to the surface of the sample. We refer to this contamination sample as the “insertion” sample. All insertion samples for each core were pooled and used to estimate the potential contamination for the total core.

To capture the contamination introduced to the sample when the bit was removed, we collected any loose material from the bottom of the cored hole (Fig. 2). We collected this sample for the 0- to 10-, 10- to 30-, and 30- to 50-cm depth increments. We were unable to reach further than 50 cm into the hole, so this contamination sample was not collected from the deep soil



**Fig. 2.** Diagram of the coring apparatus, showing (A) the power-driven rotary drill bit, (B) the method for capturing the “Insertion” sample, (C) the “Inner” core, and the (D) “Removal” sample.

samples. We refer to this contamination sample as the “removal” sample. All removal samples for each core were pooled in the field and used to estimate the potential contamination for the total core.

All samples were bagged individually, brought back to the lab, dried until a constant weight was reached, and weighed. Cores were then sieved to 2 m and the > 2 mm fraction and the <2 mm fraction were weighed.

## Sample Processing

Exchangeable cations in soils from CA and NV were extracted by mixing 5 g of air-dry soil with 15 mL of 1 M ammonium acetate solution for 10 min. Extracts were centrifuged at 3000 rpm for 3 min, and the supernatant was filtered through Whatman no. 54 filter paper. The process was repeated four times and extract was diluted to 100 mL. The soils from NH and NY were extracted by mixing 5 g of soil with 100 mL 1 M  $\text{NH}_4\text{Cl}$  on a shaker table for 60 min at room temperature. The extractant was filtered through Whatman no. 42 filter paper. A separate subsample of air-dry soil was oven-dried, allowing correction for soil moisture content.

Samples from CA and NV were analyzed using an atomic absorption/emission spectrophotometer (PerkinElmer, Norwalk, CT) for Na, Mg, K, and Ca. Samples from NY and NH were analyzed for concentrations of Na, Mg, K, and Ca on an Optima 3300DV inductively coupled plasma–optical emission spectrometer (PerkinElmer, Norwalk, CT) using a four-point calibration curve, and cation concentrations were corrected to account for the moisture content of the air-dried soils.

We measured C and N concentrations for the insertion and removal contamination samples collected in the NY and NH sites and for all pit and core samples from the NH site. Concentrations of C and N in pits and cores at these and additional CA, NV, and NY sites are reported in Rau et al. (2011). Pulverized NH samples were analyzed on a Vario EL III elemental analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). Samples from NY were analyzed with an Electron DeltaPlus XP isotope ratio mass spectrometer (Thermo Fisher Scientific, Waltham, MA).

## Data Analysis

At the CA and NV sites, one core was paired with each pit. To calculate total soil mass, rock mass, and exchangeable cation contents for the profile, we summed the depth increments for each core and each pit. Standard error (SE) for pits and cores was based on the number of pit-core pairs ( $n = 4$  in CA,  $n = 9$  in NV). At the NH and NY site, multiple cores were taken around each pit and not all cores reached the maximum depth (90 cm at NH, 50 cm at NY). To calculate the total soil mass, rock mass, and exchangeable cation contents for the profile, we took the average of the individual depth increments before summing the depth increments to get an average for the soil profile. We compare cores and pits for soil mass, rock mass, and cation concentrations using the ratio of cores to pits; for example, a ratio of 1.2 is reported as a 20% difference. When estimating soil mass, rock mass, and exchangeable cation content, we used site as the experimental unit, and estimates were derived by taking the ratio of the site averages of pits and of cores (Table 2). When comparing exchangeable cation concentrations within site (Table 3), we considered the paired pit and core as the experimental unit, and estimates were derived from the repeated-measures mixed model, described below. The SE for the whole profile is the square root of the sum of the squared SE for each depth increment. This ap-

**Table 2. Soil mass, rock mass, and cation contents (g m<sup>-2</sup>) of exchangeable cations in pit and core soil samples. Cation contents of inner cores were based on concentrations from the inner cores applied to the entire core soil mass. Whole core content values are the sum of the inner and outer cation contents. Numbers are weighted means of profile totals. Standard errors are shown in parentheses. Significant differences ( $p < 0.05$ ) between pits and whole cores are bolded. Significant differences ( $p < 0.05$ ) between pits and inner cores are italicized. Detailed analysis of the data on soil mass and rock mass at the California (CA), Nevada (NV), and New York (NY) sites can be found in Rau et al. (2011).**

Site	Stand	Sample type	Final depth	n	Soil mass, <2 mm	Rock mass, >2 mm	Cation contents			
							Na <sup>+</sup>	K <sup>+</sup>	Mg <sup>2+</sup>	Ca <sup>2+</sup>
			cm		– Mg ha <sup>-1</sup> –		– g m <sup>-2</sup> –			
NY		Inner core	50	6			9.1 (1.3)	49.1 (4.8)	35.4 (5.7)	194 (18.6)
		Whole core	50	6	<b>3744 (139)</b>	<b>2282 (167)</b>	<b>12.0 (1.6)</b>	<b>68.7 (3.1)</b>	<b>44.3 (4.5)</b>	<b>251 (30.6)</b>
		Pit	50	3	<b>2797 (143)</b>	<b>3843 (197)</b>	<b>2.5 (0.3)</b>	<b>37.6 (8.8)</b>	<b>24.4 (4.4)</b>	<b>136 (12.2)</b>
NH†	C6	Inner core	70	6			9.6 (1.6)	21.1 (3.0)	6.2 (0.4)	89.7 (36.2)
		Whole core	70	6	5537 (159)	<b>161 (8.7)</b>	<b>13.8 (2.8)</b>	<b>27.3 (4.5)</b>	<b>7.9 (1.1)</b>	59.2 (10.9)
		Pit	70	3	5787 (365)	<b>364 (103)</b>	<b>8.0 (0.9)</b>	<b>18.0 (0.8)</b>	<b>5.6 (0.3)</b>	39.1 (4.6)
	C8	Inner core	90	6			10.6 (2.1)	29.1 (8.0)	7.0 (0.7)	86.5 (10.0)
		Whole core	90	6	7570 (507)	<b>337 (67)</b>	15.2 (4.1)	32.3 (7.3)	9.2 (1.0)	92.7 (9.4)
		Pit	90	2	7364 (287)	<b>945 (166)</b>	11.6 (1.7)	19.7 (2.3)	12.4 (2.3)	99.4 (24.4)
CA	Core	60	4	4025 (176)	<b>2068 (315)</b>	3.79 (0.52)	<b>71.5 (4.99)</b>	<b>149 (19.5)</b>	<b>586 (58.0)</b>	
	Pit	60	4	3578 (95)	<b>4579 (164)</b>	3.98 (0.28)	<b>3.78 (0.57)</b>	<b>63.2 (2.83)</b>	<b>323 (20.4)</b>	
NV	Core	52	9	3158 (329)	3513 (188)	23.1 (8.13)	342 (40.5)	23.0 (1.13)	239 (14.3)	
	Pit	52	9	3112 (153)	3988 (47)	37.5 (4.35)	212 (45.3)	23.7 (1.64)	255 (15.4)	

† NH, New Hampshire.

proach may overestimate the SE of the profile mean because the increments in each core are not truly independent.

We analyzed soil mass, rock mass, and exchangeable cation concentrations for differences between soil pits and total cores at each site using a mixed linear model. The model included repeated measures to account for depth increments within cores and an interaction between depth and concentration or mass. The analyses for the NH sites also included a blocking factor for the two stands in which the pits were grouped, and in cases where more than one core sample was taken near a pit, the cores are blocked by pit. Depth and type of sample (core or pit) were treated as fixed effects. Site, stand, and pit were treated as random effects. We also tested for correlations between rock mass and exchangeable cation concentrations because we expected that contamination would be greatest in samples where the corer encountered more rocks during sampling. Finally, we used paired *t* tests to compare site-level average estimates by pits vs. cores for soil mass, rock mass, and exchangeable cation contents across the five locations: CA, NV, NY, and the two stands in NH.

For the NH and NY sites, we analyzed the difference in exchangeable cation concentration between the inner core and total core and between the inner core and the soil pit using the same model described above. We analyzed the difference between exchangeable cation concentrations (at both sites) and %C and %N (at the NH site) in the inner portion of the core with no contamination included, with only the insertion contamination included, with only the removal contamination included, and with both contamination sources included over the total soil profile. We compared these combinations to each

other and to the same combinations using the concentrations from the total core. All analyses were performed in SAS (version 9.2, SAS Institute, Inc., Cary, NC).

## RESULTS

### Soil Mass, Rock Mass, and Exchangeable Cation Concentrations

Soil mass measured using soil cores was not systematically higher than that estimated with soil pits when compared across the five locations ( $p = 0.23$ ). At the site level, only in NY were

**Table 3. Average ratio of exchangeable cation concentrations in paired core and pit soil samples. Inner concentrations are derived from the center subsample of the whole core, and whole core ratios are a weighted average of the inner and outer core samples. Ratios are based on weighted means of profile totals and the average ratio (not the ratio of averages) is reported. The significance levels for the New York (NY) and New Hampshire (NH) sites were corrected for multiple tests.**

Site	Ratio	n	Major base cations			
			Na <sup>+</sup>	K <sup>+</sup>	Mg <sup>2+</sup>	Ca <sup>2+</sup>
NY	Core/Pit	6	3.60†	1.32‡	1.33	1.42
	Inner Core/Pit	6	2.60†	0.94	1.01	0.99
NH	Core/Pit	12	1.44	1.41	0.92	0.93
	Inner Core/Pit	12	1.07	1.74	0.76	1.20
CA§	Core/Pit	4	0.77	16.6**	2.06*	1.57*
NV§	Core/Pit	9	1.22	1.64*	0.93	0.90**

\* Significant at  $p < 0.05$ .

\*\* Significant at  $p < 0.01$ .

† Significant at  $p < 0.017$ .

‡ Significant at  $p < 0.0001$ .

§ CA, California; NV, Nevada.

cores significantly different from pits ( $p < 0.0001$ , 34% higher; Fig. 3). The differences between pits and cores might be explained by spatial variation within sites; coefficients of variation (CV) ranged from 5 to 20% in pits and 9 to 21% in rotary cores.

Cores underestimated rock mass relative to the soil pits in all four sites, by 55% at the CA site ( $p < 0.0001$ ), 36% at the NY site ( $p > 0.0001$ ) 60% at the NH ( $p = 0.002$ ) sites, and a nonsignificant 12% at the NV site (Fig. 4). Rock mass summed over all depth increments was most uniform in the NV site, with a CV of 2% for pits and 10% for cores (Table 2). The rock mass at the NH site was the most variable of the four sites; the CV was 68% for cores and 99% for pits.

We tested whether exchangeable base cations were elevated in samples collected by rotary coring relative to soil pits (Table 3). For K, concentrations in cores were significantly higher

than in pits at all four sites, using a repeated-measures mixed-effects model within site ( $p \leq 0.04$ ; Fig. 5). Concentrations of Na were higher in cores at the NY and NH sites ( $p \leq 0.03$ ; Fig. 6). Concentrations of Ca were higher in cores at the CA site ( $p = 0.05$ ), but higher in the pits at the NV site ( $p = 0.007$ ; Fig. 7). Concentrations of Mg were higher in cores in CA ( $p = 0.02$ ) (Fig. 8). Only K was consistently elevated across all sites ( $p = 0.04$ ) in  $t$  tests comparing pits and cores across the sites. We did not observe an interaction between sample type and depth for any of the elements.

We compared soil cation contents estimated by pits and cores, using the site-level average (Table 2). For NY, the greater mass estimated by cores resulted in significantly greater contents of all cations. For NH, cores had significantly greater contents of Na, K, and Mg in one stand; differences were not significant in

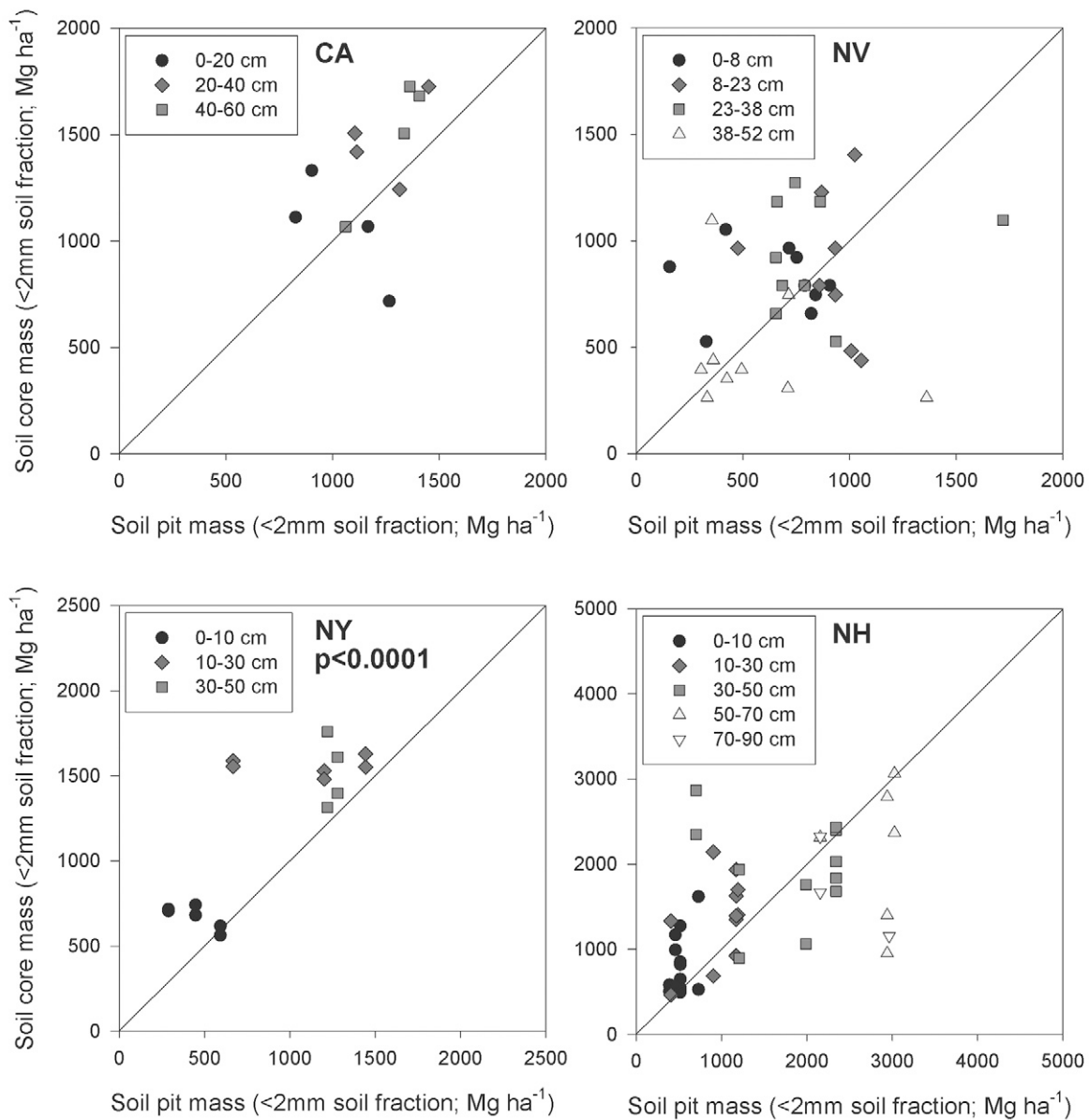


Fig. 3. Soil mass ( $\text{Mg ha}^{-1}$ ) in quantitative soil pits compared to rotary cores at the four sites. The lines represent a 1:1 relationship. The California (CA) site has four pit-core pairs; the Nevada (NV) site has nine pit-core pairs; the New York (NY) site has two cores for each of three pits; and the New Hampshire (NH) site has two cores paired with each of four pits and four cores paired with one pit. The  $p$  values show the significance of the mixed model comparing pits and cores.

the other stand. For CA, cores had significantly greater contents of K, Mg, and Ca, as was the case for concentration. For NV, although cores differed significantly in concentrations of K and Ca, the differences were not significant when contents were compared.

At the NH site, the concentration and content of C and N estimated by coring was not significantly different from the pits. At CA and NY, at some depth increments, pits had significantly higher concentrations of C and N than cores, but in NV, cores had higher concentrations than pits (Rau et al., 2011; data not shown here).

At the NH and NY sites, where the inner portion of the core was sampled, we detected systematically higher concentrations of exchangeable cations in the outer portion of the core relative to the inner core (data not shown), indicating contamination by the grinding action of the drill bit and incomplete radial mixing within the core. At the NY site, concentrations of

exchangeable K, Mg, and Na were greater in the outer portion of the core than the inner. At the NH site, exchangeable Na and Mg concentrations were significantly greater in the outer portion of the core than the inner ( $p \leq 0.01$ ). Compared to the soil pits at these sites, some exchangeable cation concentrations in the inner cores were still elevated, though to a lesser degree than the whole cores as compared to the pits (Table 3).

### Contamination Effects in Cores at New York and New Hampshire

We tested the importance of the contamination of samples during the insertion and removal of the drill bit at the NH and NY sites. Concentrations of exchangeable cations, C, and N in the removal and insertion contamination sources were generally similar to the concentrations found in the upper 30 cm of mineral soil. The combined contamination samples contributed only

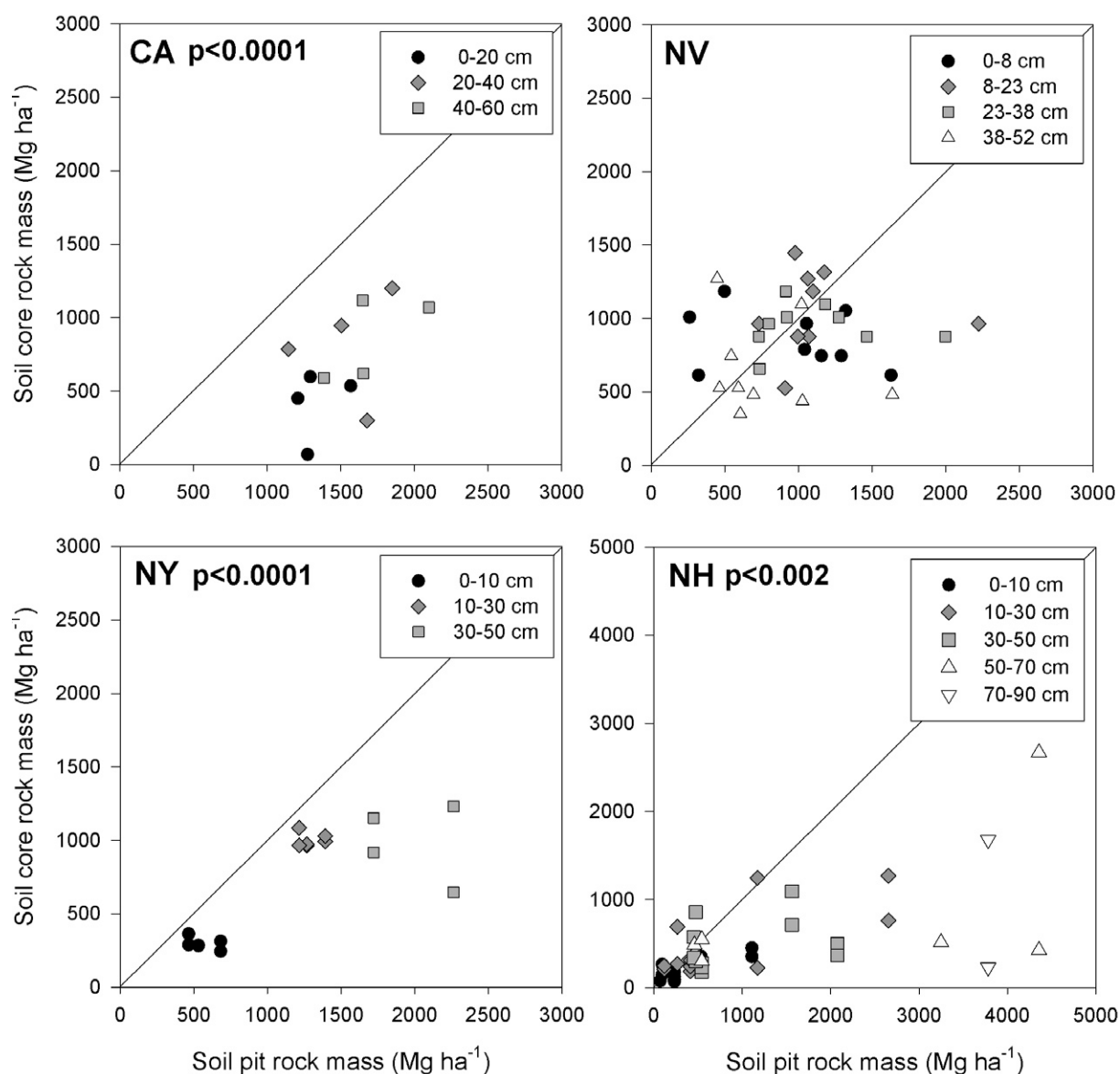


Fig. 4. Rock mass ( $\text{Mg ha}^{-1}$ ) in quantitative soil pits compared to rotary cores at the four sites. The lines represent a 1:1 relationship. The California (CA) site has four pit-core pairs; the Nevada (NV) site has nine pit-core pairs; the New York (NY) site has two cores for each of three pits; and the NH site has two cores paired with each of four pits and four cores paired with one pit. The  $p$  values show the significance of the mixed model comparing pits and cores.

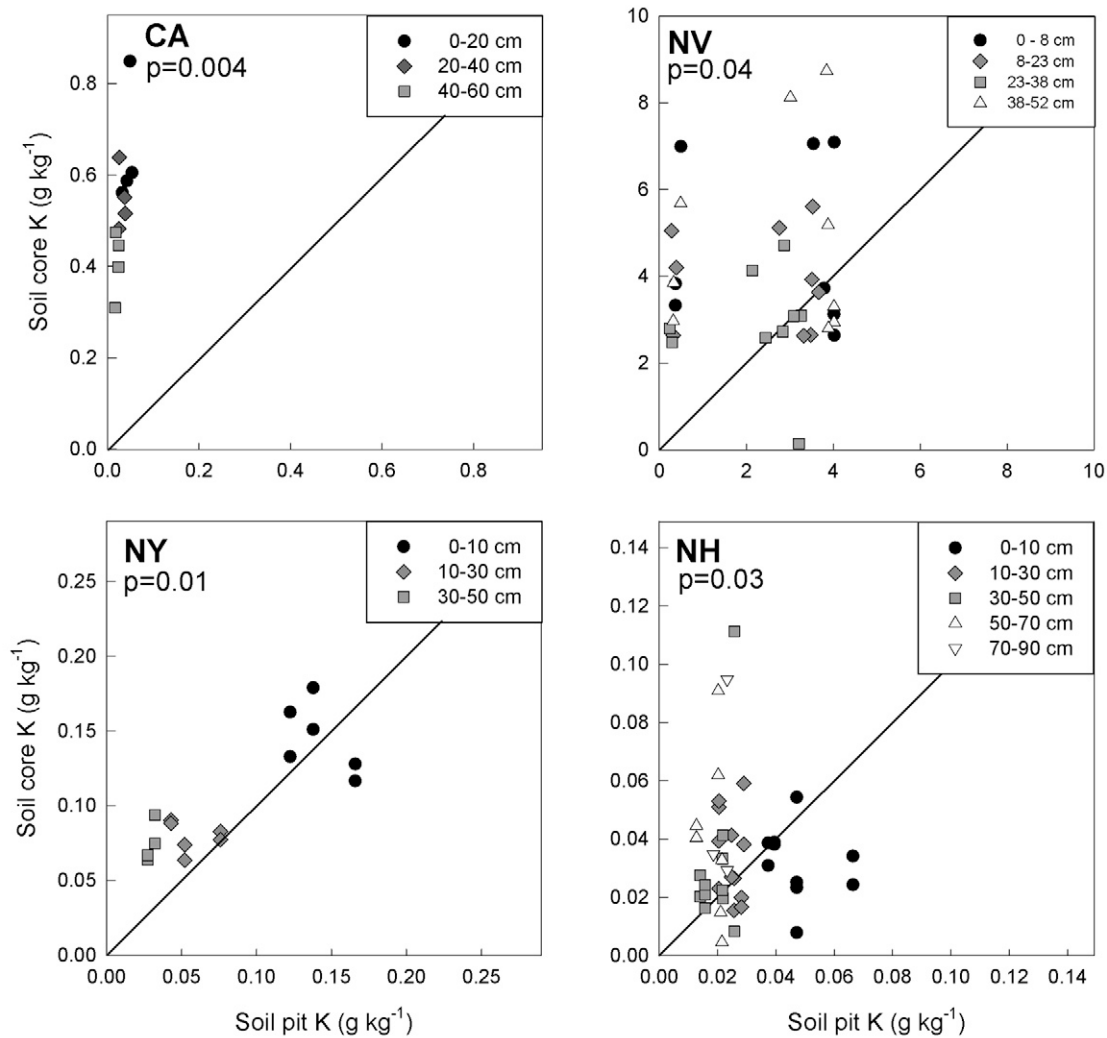


Fig. 5. Exchangeable K concentrations ( $\text{g kg}^{-1}$  dry soil) in quantitative soil pits as compared to rotary cores at the four sites. The lines represent a 1:1 relationship. The California (CA) site has four pit-core pairs; the Nevada (NV) site has nine pit-core pairs; the New York (NY) site has two cores for each of three pits; and the New Hampshire (NH) site has two cores paired with each of four pits and four cores paired with one pit. The  $p$  values show the significance of the mixed model comparing pits and cores.

2% to the core mass at the NY site and 9% at the NH site. Due to the small mass of contamination relative to the total mass of the core, concentrations of exchangeable cations, C, and N in the total core were not significantly increased as a result of including the removal and insertion contamination sources.

## DISCUSSION

### Soil Mass and Rock Mass

Only at the NY site was soil mass significantly elevated by rotary coring (Figure 3). We wondered whether the shale at the NY site was more susceptible to crumbling than the igneous rock types present at the other three sites, creating an increase in the  $<2$  mm fraction at the expense of the  $>2$  mm fraction during grinding. However, the core samples with highest soil mass relative to the corresponding pit samples were not the same as those with relatively low rock mass ( $P = 0.48$ ; linear regression). In general, there was a poor relationship between rock mass and soil mass for both pits and cores, likely due to inaccuracies in estimates of sample volume. The comparison of pits and cores is also

necessarily imprecise, since the same point cannot be measured by both methods, and rocks are not homogeneously distributed at this spatial scale.

Both quantitative soil pits and rotary cores likely underestimate rock mass. In the NH site, which had granite cobbles and boulders, sampling locations were rejected if rocks covered more than half the pit area, because the pit frame could not be secured (Vadeboncoeur et al., 2012). Similarly, coring locations were rejected if the area to be cored was entirely in rock. In the NV and NY sites, on volcanic tuff or shale, rocks did not prevent sampling, and there was not a significant difference between pits and cores in estimates of rock mass. The systematic error incurred by rejecting sampling locations for either pits or cores could be partially accounted for, either by recording zero soil depth when rocks prevent sampling or by surveying the rock area at the soil surface (Johnson et al., 2011), but the amount of soil underneath these rocks is unknown.



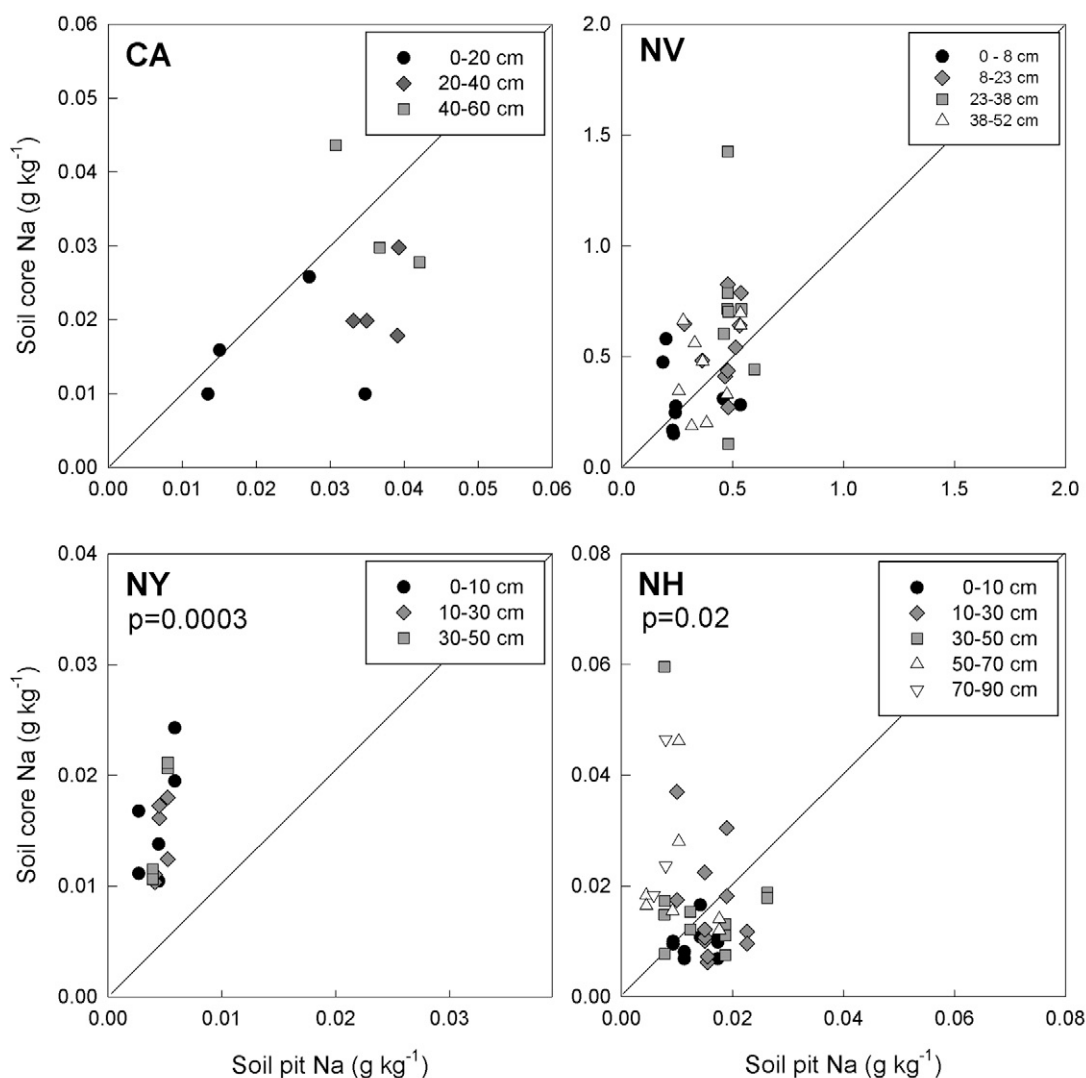


Fig. 6. Exchangeable Na concentrations ( $\text{g kg}^{-1}$  dry soil) in quantitative soil pits as compared to rotary cores at the four sites. The lines represent a 1:1 relationship. The California (CA) site has four pit-core pairs; the Nevada (NV) site has nine pit-core pairs; the New York (NY) site has two cores for each of three pits; and the New Hampshire (NH) site has two cores paired with each of four pits and four cores paired with one pit. The  $p$  values show the significance of the mixed model comparing pits and cores.

### Exchangeable Cation Concentrations

Accurate assessment of soil cation availability is important to understanding forest health and nutrient dynamics (Marschner, 1995; Juice et al., 2006; Hawley et al., 2006). In this study, we found that samples collected by coring generally had higher exchangeable cations than samples collected from pits, although the differences were consistent across all sites only in the case of K. Of nine significant differences for concentration (Fig. 5–8) and 10 for content (Table 2), all but one were in the direction of higher values in cores than pits. We had expected that a greater coarse fraction at depth might lead to an increased effect of contamination from grinding at depth, but we did not observe an interaction between depth and sampling method for any of the elements.

Differences by site in the cations that showed elevated concentrations due to coring (Table 3) are largely explained by differences in the rock composition of the four sites. Calcium was significantly elevated in cores at the CA site, which had the

highest percentage of Ca in the parent material (3.5%) (B.M. Rau et al., unpublished data, 2012); the other three sites had concentrations ranging from 0.5 to 3.2% (Billings and Wilson, 1965; Van Tyne, 1993; Rau et al., in prep.). Magnesium was elevated in cores at the CA and NV sites. Concentrations of Mg (1.5%) in the parent material at the CA site were highest of the four sites, but the NV site had the lowest Mg concentrations (0.08%). The NV site had the lowest Ca in the parent material, and this was the site at which coring reduced Ca concentrations. Potassium was elevated by coring at all four sites, and K was prevalent in all four parent materials (1.3–4.2% of rock mass). Sodium was elevated by coring at two of the four sites, one of which had high Na concentrations in rocks (2.9% in NH); in NY, there was lower Na in rocks (0.5%) but still a significant increase with coring. At the NH and NY sites, the greater handling of soil required when coring may have contributed to Na contamination as well; we did not wear gloves when handling these samples in the field.

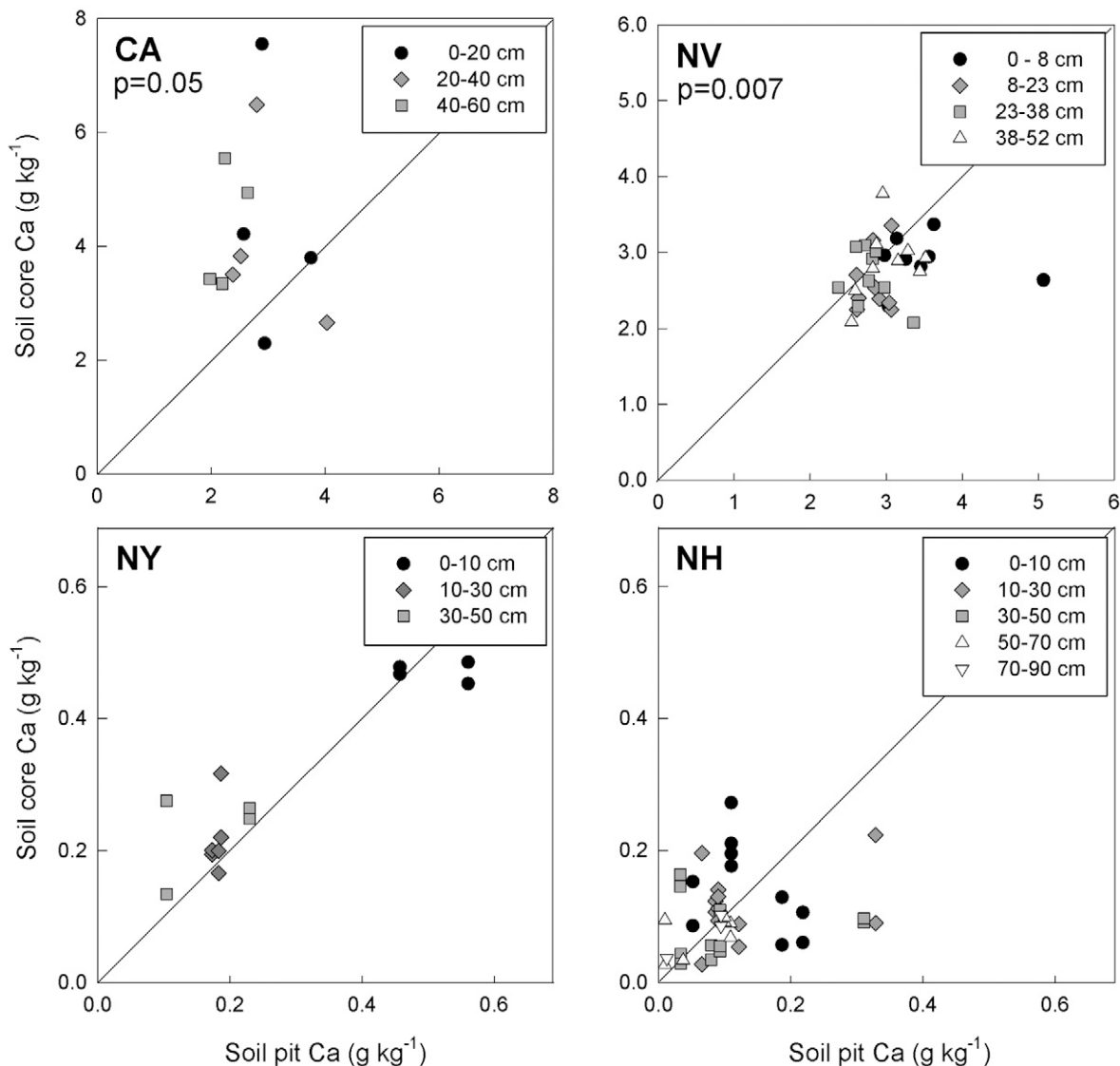


Fig. 7. Exchangeable Ca concentrations ( $\text{g kg}^{-1}$  dry soil) in quantitative soil pits as compared to rotary cores at the four sites. The lines represent a 1:1 relationship. The California (CA) site has four pit-core pairs; the Nevada (NV) site has nine pit-core pairs; the New York (NY) site has two cores for each of three pits; and the New Hampshire (NH) site has two cores paired with each of four pits and four cores paired with one pit. The  $p$  values show the significance of the mixed model comparing pits and cores.

### Attempts to Minimize Contamination in Samples Collected by Coring

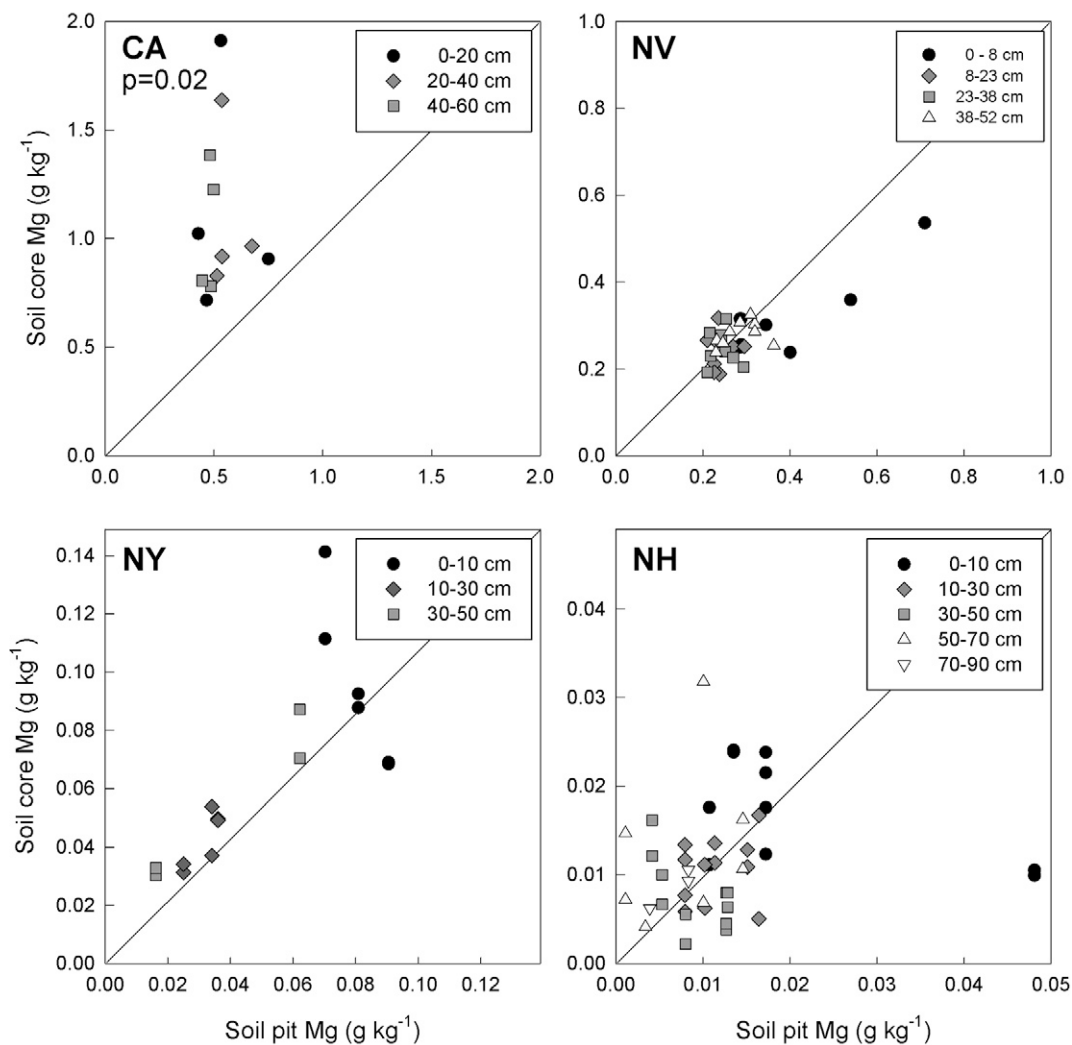
Our effort to avoid exchangeable cation contamination by subsampling the inner portion of the core was not entirely successful. At the NY and NH sites, where we tested the technique, the whole cores did have higher concentrations of some exchangeable cations than the inner portions of the core. Unfortunately, even the inner core had higher concentrations of some exchangeable cations than the soil pits, suggesting that contamination was not limited to the margins of the core. At these sites, we noted that the soil cores were not undisturbed, even at the center. The core rotated in the bit while coring, which was clear from the difficulty in removing the soil from the bit. Thus cross-sectional shearing must have occurred at some depth, if not throughout the core. We have used rotary coring at many other sites than those reported here. In some sites, the soil mixes in the core, but in others, where there are fewer rocks and better soil

structure, the soil is less disturbed. In those conditions, it seems more likely that an inner core sample might not show evidence of contamination from grinding, and this subsampling technique could be attractive.

We quantified the systematic overestimation of soil C, N, and exchangeable cation content as a result of the material introduced to the sample during the insertion and removal of the drill bit, and found it to be small (2% of core mass in NY and 9% in NH). This effort is probably not warranted, and carries a risk of introducing additional contamination from the sides of the core hole when removing material from the bottom of the hole.

### Recommendations for Rotary Coring in Rocky Soils

Rotary coring may have drawbacks for characterizing soils in some soil types. In site with rocks that obstructed coring (NH), the cores underestimated rock mass relative to the soil



**Fig. 8.** Exchangeable Mg concentrations ( $\text{g kg}^{-1}$  dry soil) in quantitative soil pits as compared to rotary cores at the four sites. The lines represent a 1:1 relationship. The California (CA) site has four pit-core pairs; the Nevada (NV) site has nine pit-core pairs; the New York (NY) site has two cores for each of three pits; and the New Hampshire (NH) site has two cores paired with each of four pits and four cores paired with 1 pit. The  $p$  values show the significance of the mixed model comparing pits and cores.

pits. Cores also overestimated cation concentrations relative to pits, consistently so for K across the study sites. For other base cations, elevated concentrations in cores were sometimes related to high concentrations in the parent material.

Coring does, however, have several advantages relative to the excavation of quantitative soil pits. The coring equipment is portable and weighs less than the equipment needed for excavating quantitative pits. Coring also takes much less time to reach deep samples, compared to quantitative pits (Rau et al., 2011). If a greater number of cores can be collected with less effort than a small number of soil pits, they may provide a more precise estimate of site-level soil properties, particularly in the spatially heterogeneous sites typical of forests and wildlands. Thus, the possibility of systematic overestimation of exchangeable cation concentrations might be acceptable in a tradeoff for precision, for example in studies aimed at detecting changes in soil nutrient concentrations over time.

#### ACKNOWLEDGMENTS:

We thank Joel Blum for the initial suggestion that grinding rocks and soil during coring might affect the cation concentrations in our samples. We thank Tyler Refsland, Kikang Bae, and Braulio Quintero for assistance with the collection of soil cores in New Hampshire and New York, and Guin Fredriksen for pit excavation at the New York sites. Steve Stehman and Eddie Bevilacqua provided statistical expertise, and Brendan Finney assisted with graphics. This study was supported by grants to RDY from the National Science Foundation and the Northeastern States Research Cooperative of the USDA Forest Service, to CLG from the McIntire-Stennis and Hatch programs, to BMR from the Joint Fire Sciences Program, and to DWJ from the Nevada Agricultural Experiment Station.

#### REFERENCES

- Billings, M.P., and J.R. Wilson. 1965. Chemical analyses of rocks and rock-minerals from New Hampshire. New Hampshire Department of Resources and Economic Development, Concord.
- Boone, R.D., D.F. Grigal, P. Sollins, R.J. Ahrens, and D.E. Armstrong. 1999. Soil sampling, preparation, archiving, and quality control. In: G.P. Robertson et al., editors, Standard soil methods for long-term ecological research. Oxford Univ. Press, New York. p. 3–28.
- Fatemi, F.R., R.D. Yanai, S.P. Hamburg, M.A. Vadeboncoeur, M.A. Arthur, R.D. Briggs, and C.R. Levine. 2011. Allometric equations for young northern hardwoods: The importance of age-specific equations for estimating

- aboveground biomass. *Can. J. For. Res.* 41:881–891. doi:10.1139/x10-248
- Hamburg, S.P. 1984. Effects of forest growth on soil nitrogen and organic matter pools following release from subsistence agriculture. In: E.L. Stone (ed.) *Forest soils and treatment impacts. Proceedings of the Sixth North American Forest Soils Conference*, Knoxville, TN. June 1983. Univ. of Tennessee, Knoxville. p. 145–158.
- Hawley, G.J., P.G. Schaberg, C. Eagar, and C.H. Borer. 2006. Calcium addition at the Hubbard Brook Experimental Forest reduced winter injury to red spruce in a high-injury year. *Can. J. For. Res.* 36(10):2544–2549. doi:10.1139/x06-221
- Johnson, D.W., C.T. Hunsaker, D.W. Glass, B.M. B.M Rau, and B.A. Roath. 2011. Carbon and nutrient contents in soils from the Kings River Experimental Watersheds, Sierra Nevada Mountains, California. *Geoderma* 160:490–502.
- Juice, S.M., T.J. Fahey, T.G. Siccama, C.T. Driscoll, E.G. Denny, C. Eagar, N.L. Cleavitt, R. Minocha, and A.D. Richardson. 2006. Response of sugar maple to calcium addition to northern hardwood forest. *Ecology* 87(5):1267–1280. doi:10.1890/0012-9658(2006)87[1267:ROSMTC]2.0.CO;2
- Jurgensen, M.F., M.J. Larsen, and A.E. Harvey. 1977. A soil sampler for steep, rocky sites. Res. Note INT-217. USDA, Forest Serv., Intermountain Forest and Range Exp. Stn., Ogden, UT.
- Kulmatiski, A., D.J. Vogt, T.G. Siccama, and K.H. Beard. 2003. Detecting nutrient pool changes in rocky soils. *Soil Sci. Soc. Am. J.* 67(4):1282–1286. doi:10.2136/sssaj2003.1282
- Marschner, H. 1995. *Mineral nutrition of higher plants*. 2nd ed. Academic Press, San Diego, CA.
- Murphy, J.D., D.W. Johnson, W.W. Miller, R.F. Walker, E.F. Carroll, and R.R. Blank. 2006. Wildfire effects on soil nutrients and leaching in a Tahoe Basin Watershed. *J. Environ. Qual.* 35:479–489. doi:10.2134/jeq2005.0144
- Neeley, J.A. 1965. Soil survey: Tompkins County, New York. Series 1961, no. 25. USDA, Soil Conserv. Serv., Gov. Print. Office, Washington, DC.
- Park, B.B., R.D. Yanai, M.A. Vadeboncoeur, and S.P. Hamburg. 2007. Estimating root biomass in rocky soils using pits, cores, and allometric equations. *Soil Sci. Soc. Am. J.* 71:206–213. doi:10.2136/sssaj2005.0329
- Ponder, F., and D.E. Alley. 1997. Soil sampler for rocky soils. Res. Note NC-371. USDA, Forest Service, North Central Forest Exp. Stn., St. Paul, MN.
- Rau, B.M., D.W. Johnson, J.C. Chambers, R.R. Blank, and A. Lucchesi. 2009. Estimating root biomass and distribution after fire in a Great Basin woodland using cores and pits. *West. N. Am. Nat.* 69(4):459–468. doi:10.3398/064.069.0405
- Rau, B.M., A.M. Melvin, D.W. Johnson, C.L. Goodale, D.E. Todd, and R.R. Blank. 2011. Revisiting soil carbon and nitrogen sampling: Quantitative pits vs. rotary cores soil science. *Soil Sci.* 176(6):273–279. doi:10.1097/SS.0b013e31821d6d4a
- Vadeboncoeur, M.A., S.P. Hamburg, J.D. Blum, M.J. Pennino, R.D. Yanai and Chris E. Johnson. 2012. The quantitative soil pit method for measuring belowground carbon and nitrogen stocks. *Soil Sci. Soc. Am. J.* 76: doi:10.2136/sssaj2012.0111 (In Press).
- Vadeboncoeur, M.A., S.P. Hamburg, and R.D. Yanai. 2007. Validation and refinement of allometric equations for roots of northern hardwoods. *Can. J. For. Res.* 37:1777–1783. doi:10.1139/X07-032
- Van Tyne, A.M. 1993. Detailed study of Devonian black shales encountered in Nine Wells, in western New York State, petroleum geology of the Devonian and Mississippian Black shale of eastern North America. U.S. Geological Survey Bull. 1909:M1–M16.