Spatial Variability in Arid Soils: Sampling and Characterization Issues

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ABSTRACT

A central feature of arid soils is their spatial variability. In particular, the “islands of fertility” phenomenon characterizes these systems, causing regular patterns in carbon and nutrient concentrations in soils on both a horizontal and vertical scale. This paper reviews sampling techniques and associated problems associated with characterizing soils in general and addresses some issues that are particularly important to arid soils. For the purposes of soil inventories where quantitative, aerial estimates of soil pools (i.e., kg ha^{-1}) we generally advocate simple random sampling rather than stratified random sampling or systematic sampling because it avoids errors related to indistinct strata boundaries for the former and problems in characterizing variability for the latter. In stony soils, it is vital to measure the volume and mass of rock fragments in order to obtain accurate estimates of soil pools. We provide case studies of soil samplings that have been conducted in semi-arid forests of the eastern Sierra Nevada which illustrate some of the spatial patterns discussed.

INTRODUCTION

All soils are inherently variable over time and space, presenting significant problems for both sampling and characterization. One of the fundamental features of soils is horizonation, which represents systematic spatial variation in the vertical direction as a result of soil development. Horizontal variation can also be very large and systematic, relating to slope position, vegetation cover, management history, and parent material. Arid soils are often characterized by a finer scale, systematic variation in the horizontal direction related to the “islands of fertility” phenomenon, wherein soil organic matter and nutrient concentrations are higher beneath shrubs and trees than in interspaces (Garner and Steinberger, 1989; Wikeem and Pitt, 1982; Charley and Wext, 1975; Tiedemann and Klemmedson, 1973, 1986; Halvorson et al., 1994, 1997; Klemmedson and Tiedemann 1986; Virginia and Jarrell, 1983; Everett et al., 1986; Schlesinger et al., 1996). These islands of fertility are thought to be caused by a combination of wind-blown topsoil and other debris blown from interspaces and trapped by the shrub or tree (often on the leeward side), uptake of nutrients taken up from surrounding soils and recycling them via litterfall to soils beneath the shrubs, and excreta from animals taking shelter beneath trees and shrubs. This regular spatial pattern of soil organic matter and nutrients has also been used as an index of desertification: Schlesinger et al (1990) propose a conceptual model for desertification of grasslands whereby the relatively uniform distribution of soil organic matter and nutrients in native grasslands is disrupted (for example, by overgrazing), facilitating the invasion of shrubs which in turn exacerbate the spatial heterogeneity through the processes described above. Thus, it is important to properly characterize the spatial patterns in arid soils for a number of reasons. Schlesinger et al (1996) used semi-variograms to quantify the spatial patterns of soil nutrients in several desert ecosystems and found this to be a very useful approach. The average variance, or semi-variance of samples taken at increasing distance from one another are plotted against this distance which is termed the lag interval. Plots of this nature can be used to interpret both the degree and scale of spatial variability of soil nutrients. Details of the statistical methodology are given by Schlesinger et al (1996) and Rossi et al (1992).

The presence of islands of fertility in arid soils present significant sampling problems when calculating soil pool sizes (i.e., kg ha^{-1} or g m^{-2}) of organic matter and nutrients which are not addressed by the semi-variogram approach and are not easily solved by soil sampling protocols typical of more mesic systems. Characterization of pool sizes of soil C in particular is rapidly becoming a necessity in view of the potential role of soils in the global C cycle. Even a cursory review of published global carbon budgets reveals that soils could be either a major source or sink for carbon. Schimel (1995) estimated that soils contain approximately twice as much C (1580 x 10^{15}g) as the atmosphere (750 x 10^{15}g) or terrestrial vegetation (610 x 10^{15}g). Less than 1% of the terrestrial C reservoir (1.9 x 10^{15}g C yr^{-1}) is emitted to the atmosphere through changing land use each year, whereas amounts of C entering soil as detritus (61.4 x 10^{15}g C yr^{-1}) and leaving by respiration (60 x 10^{15}g C yr^{-1}) are far greater (Schimel, 1995). In light of these observations, reliable information is needed on soil C pool sizes as well as the effects of management practices on these pools. The latter will require measuring changes in soil C pools, a task that is challenging even in relatively uniform soils and especially daunting in arid soils with their inherent spatial variability.

Many detailed reviews and analyses have been written on the nature of arid soils and the important role of fertility islands in them (West, 1991; Charley and Wext, 1975; Tiedemann and Klemmedson, 1973, 1986; Halvorson et al., 1994, 1997; Klemmedson and Tiedemann 1986; Virginia and Jarrell, 1983; Everett et al., 1986; Schlesinger et al., 1996). The reader is referred to these references for more detail about this subject. What is often lacking, however, is a full discussion of the inherent problems encountered in sampling soils in the field and an analysis of potential solutions to these problems. Thus, the primary purpose of this paper is to review sampling and characterization problems in arid soils and potential solutions to them.

SAMPLING LITTER AND SOILS IN A SPATIALLY HETEROGENEOUS ENVIRONMENT

Accounting for Horizontal Variation

Peterson and Calvin (1986) note that there are three sources of error in soil sampling: 1) sampling error, or that error associated with the fact that only a selected subsample of the entire population of samples is taken; 2) selection error, where some sample types are not adequately represented (i.e., rocky areas), and 3) measurement error, where the value measured is not the true value for the unit. Although the authors do not so state, we believe that sampling error and especially selection error are generally much more important than measurement error in sampling of non-agricultural soils. Peterson and Calvin (1986) also discuss the advantages and disadvantages three methods of sampling in the horizontal scale: simple random sampling, stratified random sampling, and systematic sampling (i.e., a regular grid with established sampling points). Their review of the literature indicated that systematic sampling is the preferred method in nearly all cases where the three methods have been compared. They note however, that exceptions occur where the variation is periodic, such as where there are with rows of crops, and in cases where there is a fertility gradient along rows of a field. They also note that one of the major problems with systematic sampling is the estimation of sampling error from the sample itself, and they offer three alternative methods: 1) assume that the population of soil samples was in random order before the grid was laid out; 2) stratify the sample such that the variation within each stratum can be considered random; or 3) take a number of systematic samples, each drawn from a randomly selected sampling point.

We have concluded that neither stratified nor systematic sampling is appropriate for soils in semi-arid forests of the Sierra Nevada Mountains. Stratified sampling was rejected because the boundaries of the strata (the borders between the islands of fertility and interspaces) are diffuse, leading to arbitrary and inconsistent delineations of strata boundaries among individual investigators and between sites and over time. We judged that the definitions of strata boundaries was sufficiently unclear and inconsistent as to overwhelm any possible advantage to stratification when sampling either soils or litter for the purposes of measuring pools sizes. Systematic sampling is judged inappropriate for several reasons. First of all, the population of samples is not random but varies systematically, both over the landscape as a whole and within strata (e.g., within the islands of fertility), thus violating the premises alternatives 1 and 2 above for defining sample variability. Alternative 3 is considered to be too expensive in time, labor, and analytical costs for most cases. We find is most convenient to plot random coordinates on a Cartesian system and then convert these to polar coordinate so that random sampling points can be easily determined in the field from distance and azimuth measurements from the plot center. When sampling for the purpose of determining pool sizes, we avoid selection error if at all possible. If a sample point lies directly beneath a tree, it must be discarded; however, if a sample point lands on a large boulder, it is included: the fine earth fraction is 0, and the bulk density is defined as mineral density (2.65 g cm^{-3} or a density determined from rock samples taken nearby).

Accounting for Vertical Variation: Soil Horizons

A fundamental feature of soils is horizonation, and this must be taken into account when sampling soils, either for pool sizes or for chemical concentrations. The first and usually most distinct soil horizon is the organic (O) horizons, which consist of organic matter. The three major organic horizons are Oi, consisting of slightly decomposed plant litter, Oe, moderately decomposed plant litter (still recognizable as to species), and Oa highly decomposed organic matter (not recognizable as to species). The distinctions between these horizons are often arbitrary and therefore will vary with investigator and field conditions such as moisture (Federer, 1982). Furthermore, separation of the Oa horizons from underlying A horizons (mineral soils high in organic matter) can be very difficult: soil particle and even rocks can be intermingled with Oa horizons are invariably included in

Oa samples. In the case of small particles, this can be corrected for by determining ash content (combustion); in the case of rocks and larger particles, it is often necessary to separate the organic from mineral phase by floating. Unfortunately, soil profiles are in actuality continuous chromatographs and the definition of horizons and boundaries are often arbitrary and the boundaries between are often indistinct. Figure 1 illustrates a typical distribution of soil organic matter concentration with depth in a given profile. When sampling for pool sizes, it is important to sample horizons proportionately, that is, to take samples from each horizon within a constant horizontal area, as in a core, so as not to bias the samples with more or less of one depth or another within the horizon. Thus, if soil samples are to be taken by shovel or trowel, it is important to keep the sampling hole proportional and avoid the natural tendency to narrow the hole area with depth, as illustrated by the biased sample in Figure 1.

To complicate matters further, horizon depths are often quite variable in the horizontal direction, especially in disturbed landscapes. Figure 2 illustrates this, and the sampling problems that could be encountered if soils are sampled by depth rather than by horizon. A constant depth of sampling will not include all of the A horizon in sample points where the horizon is thick and will include some amount of the underlying horizon in sample points where the horizon is thin. It would seem ideal, then, to sample soils by horizon rather than by depth at each sampling point. Unfortunately, this is only possible if pits are dug at each sampling point or in the event that the soil is very friable and free of stones so that an open-faced punch auger can be used to determine depths while coring. In the event that pits are dug, the possibilities for resampling in the future near the same location are greatly diminished. In practice, the usual procedure is to dig a pit in the general area of the sampling to determine the nominal depths of the major horizons and use that to establish sampling depths to be used subsequently with a coring device. Thus, the sampling problems illustrated in Figure 2 are often a major factor in soil variability on the horizontal scale. A further problem may occur in soils subject to expansion and contraction (i.e., those containing smectite clays or those which accumulate or lose considerable amounts of organic matter). If it is desired to measure changes in soil properties over time in such cases (as will be the case for soil C sequestration), the shrinking and swelling of soils will cause changes in horizon depths that must be taken into account. Such changes can be calculated if bulk density is measured at each sampling date. Although it is generally preferable to sample soils by horizon, it is often the case that samples must be taken to a constant lowest depth, unless total soil depth is dictated by the presence of bedrock. This is because soil depth is one of the major variables affecting total soil mass and therefore total soil pools of a given nutrient. Even in the cases of soil C and N, where the highest concentrations occur in surface horizons, total depth of soil considered is often a major factor in total soil pools because deeper horizons are often more dense and make up considerable mass.

Estimating Soil Mass

Obtaining representative soil element concentrations over the landscape and by horizon is adequate for some purposes (relating to plant fertilizer needs or water quality only), but it is less than half of the battle in terms of estimating soil nutrient pool sizes. Measurements of soil mass are all fraught with sampling problems and errors, and can be far more tedious than taking samples for chemical analysis. Three fundamental things are needed in order to obtain estimates of soil mass: bulk density of the soil, percent coarse fragments (mineral material, rocks, stones, boulders greater than 2 mm diameter), and depth. Bulk density can be measured using various methods (clod, core, excavation, and radiation) which are fully reviewed by Blake and Hartge (1986). These methods have been developed largely for agricultural soils which are low in large coarse fragments; wildland soils in forests and arid lands often contain substantial amounts of large coarse fragments, but these are seldom measured accurately because of the difficulties involved. Indeed, large coarse fragments are often simply estimated by eye or from very sparse and general data sets, and then liberally used in detailed calculations of soil C and nutrient content. We feel that improper and inaccurate measurements of large coarse fragments is the major source of error in estimation of soil C and nutrient pools in many wildland soils.

Measurements of large coarse fragments are usually made by excavation methods and are difficult, time consuming, and destructive to the site being sampled. Hamburg (1984) outlined a quantitative pit procedure for measurement of bulk density and large coarse fragments in very stony soils in Hubbard Brook, New Hampshire. The method involves digging a very straight-walled pit, 1 m^2 in area, and removing and weighing all material from it, by horizon. The volume of the hole is then estimated using a template which subdivided the area into a 25-cell grid and measuring the perpendicular distance to the soil surface at each grid point. Problems were encountered with large boulders protruding from the pit walls, and their volume and mass had to be measured separately. Bulk density of the soil fraction was then estimated by coring in the pit walls.

CASE STUDIES OF SOIL SAMPLING IN SEMI-ARID FORESTS

Little Valley, Nevada

A case study of the results of litter and soil sampling in a semi-arid forest in the eastern Sierra Nevada Mountains (Little Valley, Nevada) is shown in Figure 3 (Johnson et al., 1997, Susfalk, 2000). The study site is at an elevation of 2015 m, with a slope of less than 3% and with an overstory vegetation is dominated by widely-spaced110-120-year-old lodgepole pine *Pinus contorta* Dougl.) With occasional jeffrey pine jeffrey pine (*Pinus jeffreyii* [Grev. and Balf.]). Understory vegetation consists of bitterbrush (*Purshia tridentata* D.C.), and various grasses and forbs. Soils at the study site are the Marla soil series, sandy, mixed Aquic Cryumbrepts derived from colluvium of decomposed granite. The site is characterized by pronounced islands of fertility associated with the overstory trees. Sampling points were established in a completely random fashion and both litter and soils were sampled by horizon rather than depth using large sample pits (Johnson et al., 1997, Susfalk, 2000). The depth of sampling for the A horizons varied from 3 to 10 cm, the depths for the B horizons varied from 20 to 22 cm, and BC horizons were all sampled to 50 cm. In pits 1 through 4, we were able to get samples below 50 cm and determined that the soil was at least 1 m deep. Figure 3A shows that C concentrations vary most in the surface horizons, and Figure 3B shows the depth distribution of C content (kg ha^{-1}) for each individual pit. In Figure 3B, total O horizon C content is shown above the 0 line and soil C contents by horizon (as negative numbers) below the 0 line. The first, second, third, and (where present) fourth bars below the 0 line in Figure 3B represent the C contents in the A, B, BC, and C horizons, respectively, and are coded so that the depth of sampling is indicted.

The island of fertility effect is clearly shown here, with extreme variability in O and A horizon C contents. However, the relationship between O horizon C content (the best index of inputs via litterfall) and soil C concentrations or content is not straightforward. It clear that pit 4 had the greatest C contents in both O horizons and mineral soils as well as the greatest A horizon C concentration, but A horizon depth was among the lowest. Also, there were no statistically significant correlations between O horizon C content and A horizon C concentration, A horizon C content or A horizon depth, however. Nor were there any significant correlations in C concentrations between A and B, B and BC, or BC and C horizons.

It is generally assumed that most soil C is contained in the A horizon. In this site, O horizon C contents rival those in the mineral soil (to a depth of 50 cm) in some cases, however (pits 4 and 6). In some cases, total soil C content is dominated by the A horizon: (A horizon C content accounts for half or more of total soil C in pits 4, 5, and 6). In other cases, however, (pits 1, 2, and 3), the C contents of the lower horizons are relatively important even though the concentrations are very low. Where the data is available (pits 1 through 4), it is clear that the C content of the C horizon (50-100 cm depth) contributes significantly (20 to 33%) to the total soil C content even if concentrations in that horizon are low. This is because of the large mass of the soil in the C horizon, which is a result of mostly of its thickness. Coarse fragment (> 2mm) contents are low in this particular soil (< 3%), but coarse fragment content has a substantial effect on soil C pools in stonier soils. The subject of coarse fragments and their measurement is discussed in more detail below.

Truckee, California

We used a variation on the quantitative pit method of Hamburg (1984) to sample stony soils in the eastern Sierra Nevada Mountains. The site is dominated by Jeffrey pine in the overstory and has a somewhat sparse understory consisting of bitterbrush, occasional manzanita (*Arcostaphylos patula* Greene), snowbush (*Ceanothus velutinus* Dougl.), and squawcarpet (*Ceanothus prostratus*). Soils are the Kyburz series, fine-loamy, mixed, frigid Ultic Haploxeralfs derived from andesite.
In our variation of the Hamburg (1984) method, 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. Unlike Hamburg (1984) who established plots arbitrarily away from large boulders and trees, we established pits in a simple random fashion over a series of 24 plots covering three landscape positions: upper and lower slope in one location (which had been thinned and later received prescribed fire) and another location which had never been thinned but later received prescribed fire. We also measured litter and coarse woody debris mass on each plot.

The results show considerable amounts of coarse fragments (which were classified mainly as cobbles, being rocks 7.5 to 25 cm diameter) within all soils (Figure 4). The US classification system calls for a mention of coarse fragments if they constitute over 15% of the whole soil volume. If rock fragments constitute over 35% in the control section (soil from the top of the Bt horizon down to a depth of 50 cm), the term skeletal is uses in the particle size descriptor. Thus, the soil in this site may be classified as in all cases and in the case of location 1, upslope, it would be cobbly, loamy-skeletal, mixed, frigid Ultic Haploxeralf. The system also calls for the word *very* to precede the cobbly adjective in cases where coarse fragments constitute 35 to 60% by volume, and the upslope set of plots in location 1 nearly qualify for that. Perhaps most importantly, the carbon concentrations in these soils differ significantly from one another, the rock fragment contents in these soils differ significantly from one another, and yet the carbon contents do not differ significantly because the variations in carbon concentration are offset by those in rock fragments (Figure 4). This example illustrates the importance of obtaining accurate measurements of rock fragments when estimating soil C pools, and this cannot be made without tedious and time-consuming measurements.

CONCLUSIONS

For quantification of carbon and nutrient pools (kg ha^{-1}) in arid environments, completely random sampling is recommended. Stratification according to islands of fertility requires defining strata boundaries, and this is subject to considerable error with investigator and over time with a single investigator. Definition of soil horizons is problematic in many cases, and will very considerably among investigator and over time with one investigator. In general, it is recommended that mineral soils be sampled by depth after determining the nominal depths corresponding to major horizons. Depth sampling will inevitably lead to sampling across horizons in situations where horizons vary in thickness, but as depths are easier to control for and replicate than horizon definitions. In the case of O horizon – mineral soil boundaries, a measure of mineral fraction in the laboratory (such as loss on ignition) is desirable as a control measure for horizon definition. It is vital to take proportional samples with depth when quantifying carbon and nutrient pools – soil carbon and nutrient concentrations vary continuously with depth, and taking non-proportional samples can lead to significant bias in estimates. If coarse fragment are small enough to fit within soil cores, soil bulk density and %>2mm fractions should be obtained by taking cores at each depth, as this is the most accurate method in such circumstances. If large rocks, cobbles, and boulders are present, some form of quantitative pit should be used – so-called "ocular" estimates of rock content lead to too much error in soil mass estimation to be acceptable.

REFERENCES

Blake, G.R., and K.H. Hartge. 1986. Peterson, R.G., and L.D. Calvin. 1986. Bulk density Chapter 13 pp. 363-376 *In:*Klute, A. Methods of soil analysis. Part 1. Physical and mineralogical methods. Second Edition. Number 9 in theseries, Agronomy. Soil Science Society of America, Madison, Wisconsin.

Burke, I.C., W.A. Reiners, D.L. Sturges, and P.A. Matson. 1987. Herbicide treatment effects on properties of mountain big sagebrush soils after fourteen years. Soil Sci. Soc. Amer. J. 51: 1337-1343.

Charley, J.L., and N.E. West. 1975. Plant-induced soil chemical patterns in some shrub-dominated semi-desert ecosystems of Utah. J. Ecol. 63: 945-963.

Everett, R., S. Sharrow, and D. Thran. 1986. Soil nutrient distributionj under and adjacent to singleaf pinyon crowns. Sci. Soc. Amer. J.50: 788-792.

Federer, C.A. 1982. Subjectivity in separation of organic horizons of the forest floor. Soil Sci. Soc. Amer. J. 46: 1090-1093.

Garner, W., and Y. Steinberger. 1989. A proposed mechanism for the formation of "Fertile islands' in the desert ecosystem. J. Arid. Env. 16: 257-262.

Halvorson, J.J., J. Bolton, Jr, and J.L. Smith. 1997. The pattern of soil variables related to *Artemesia tridentata* in a burned shrub-steppe. Soil Sci. Soc. Amer. J. 61: 287-294.

Halvorson, J.J., J. Bolton, Jr, J.L. Smith, and R.E. Rossi. 1994. Geostatistical analysis of resource islands under *Artemesia tridentata* in the shrub-steppe. Great Basin Naturalist 54: 313-328.

Hamburg, S.P. 1984. Effects of forest growth on soil nitrogen and organic matter pools following release from subsistence farming, in Forest Soils and Treatment Impacts, Proceedings of the Sixth North American Forest Soils Conference, edited by E.L. Stone, pp. 135-158, University of Tennessee, Knoxville, 1984.

Klemmedson, J.O., and A.R. Tiedeman. 1986. Long-term effects of mesquite removal on soil characteristics: II. Nutrient availability. Soil Sci. Soc. Amer. J. 50: 476-480

Peterson, R.G., and L.D. Calvin. 1986. Sampling. Chapter 2 pp. 33-52 *In:*Klute, A. Methods of soil analysis. Part 1. Physical and mineralogical methods. Second Edition. Number 9 in theseries, Agronomy. Soil Science Society of America, Madison, Wisconsin.

Rossi, R.E., D.J. Mulla, A.G. Journel, and E.H. Franz. 1992. Geostatistical tools for modeling and interpreting spatial dependence. Ecol. Mon. 62: 277-314.

Schlesinger, W.H., and A. Pilmanis. 1998. Plant-soil interactions in deserts. Biogeochemisty 42: 169-187.

Schlesinger, W.H., J.A. Raikes, and A.F. Cross. 1996. On the spatial pattern of soil nutrients in desert ecosystems. Ecology 77: 364-374.

Schlesinger, W.H., J.F. Reynolds, G.L. Cunningham, L.F. Huenneke, W.M. Jarrell, R.A. Virginia, and W.G. Whitford. 1990. Biological feedbacks in global desertification. Science 247: 1043-1048.

Tiedemann, A.R., and J.O. Klemmedson. 1973.Nutrient availability in desert grassland soils under Mesquite (*Prosopis juliflora*) trees and adjacent open areas. Soil Sci. Soc. Amer. J. 37: 107-111.

Tiedemann, A.R., and J.O. Klemmedson. 1986.Long-term effects of mesquite removal on soil characteristics: I. Nutrients and bulk density. Soil Sci. Soc. Amer. J. 50: 472-475.

Virginia, R.A., and W.M. Jarrell. 1983. Soil properties in a mesquite-dominated Sonoran desert ecosystem. Sci. Soc. Amer. J. 47: 138-144.

West, N.E. 1991. Nutrient cycling in soils of semiarid and arid regions. pp. 295-332 *In*: J. Skujins (ed). Semiarid lands and deserts: Soil resource and reclamation. Marcel Dekker, New York.

Wilkeem, S.J., and M.D. Pitt. 1982. Soil nitrogen gradients as influenced by sagebrush in southern British Columbia. Northwest Sci. 56: 276-286.

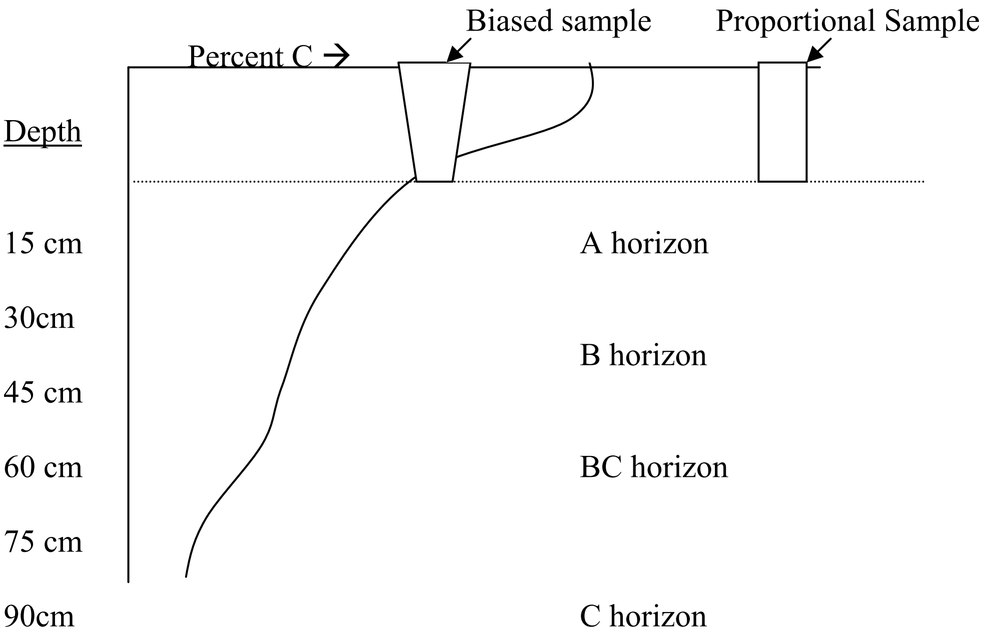

Figure 1. Schematic of typical carbon concentrations with soil depth. The biased sample will give an inflated value for carbon in the A horizon because it takes a disproportionate amount of soil from the upper part of the A horizon, whereas the proportional sample is not biased and will properly represent the average value for the horizon.

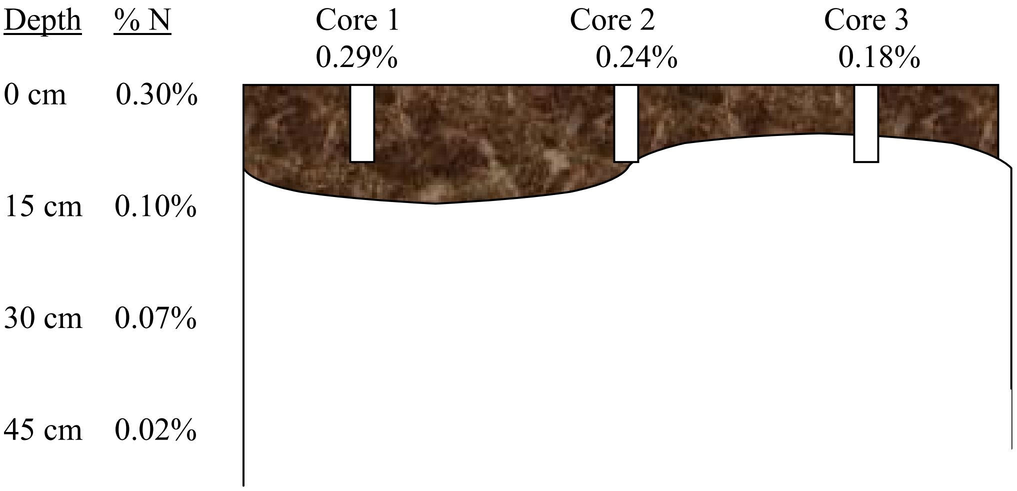

Figure 2. Schematic representation of sampling by depth in a soil with variable A horizon thickness. Numbers are arbitrary and for the purposes of illustration only.

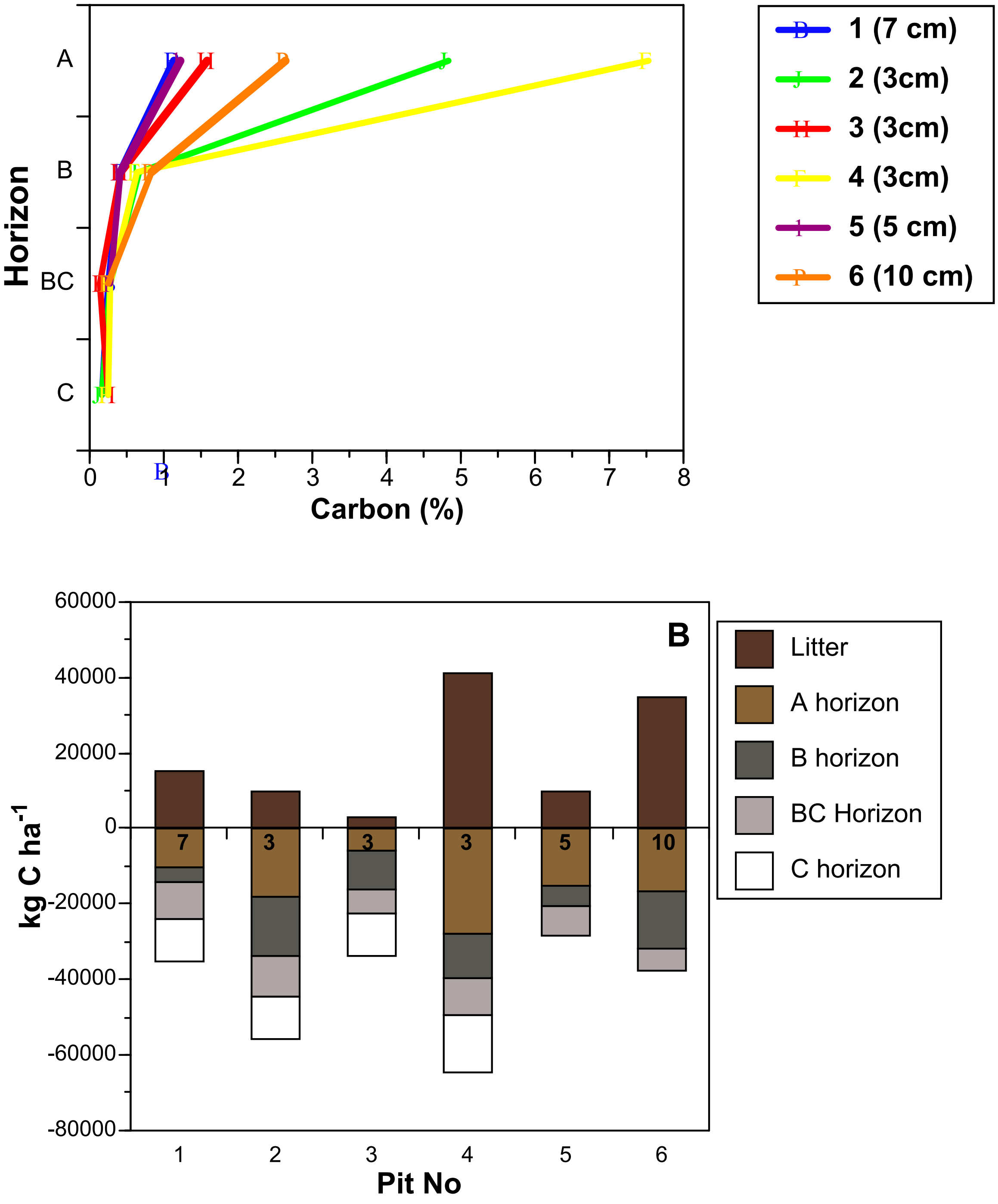

Figure 3. Carbon concentration in soils (A) and carbon content in litter and soils (B) in a lodgepole pine forest in Little Valley, Nevada. Depths of A horizon sampling in cm are shown in the legend in A and within each bar in 3B. (After Johnson et al., 1997 and Susfalk, 2000).

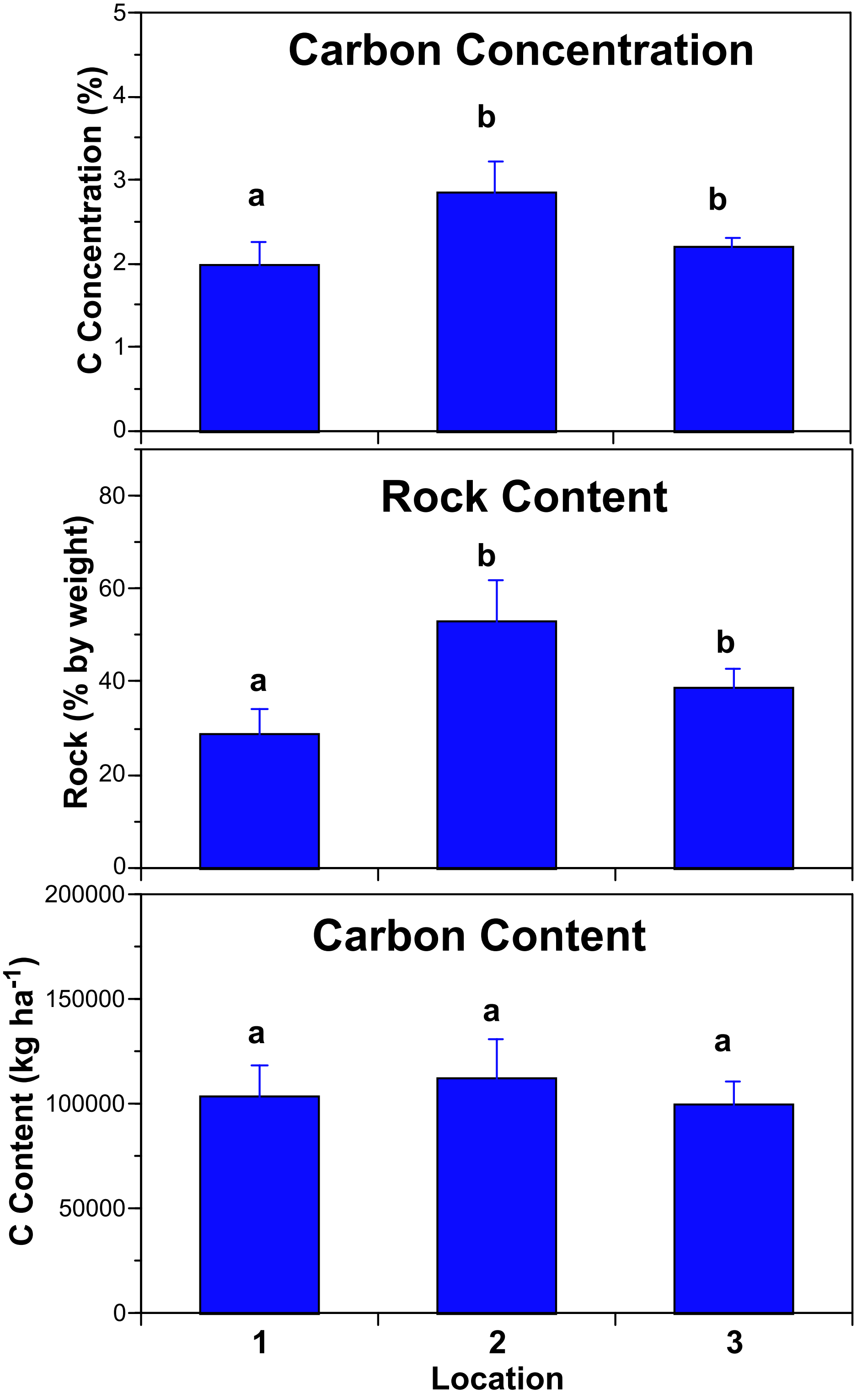

Figure 4. Carbon concentrations, rock contents, and carbon contents in soils from the Truckee prescribed fire site. Letters denote statistically significant differences, ANOVA with Bonferroni post-hoc tests.