

11-1-2008

# TB200: Carbon and Nutrients in Maine Forest Soils

Ivan J. Fernandez

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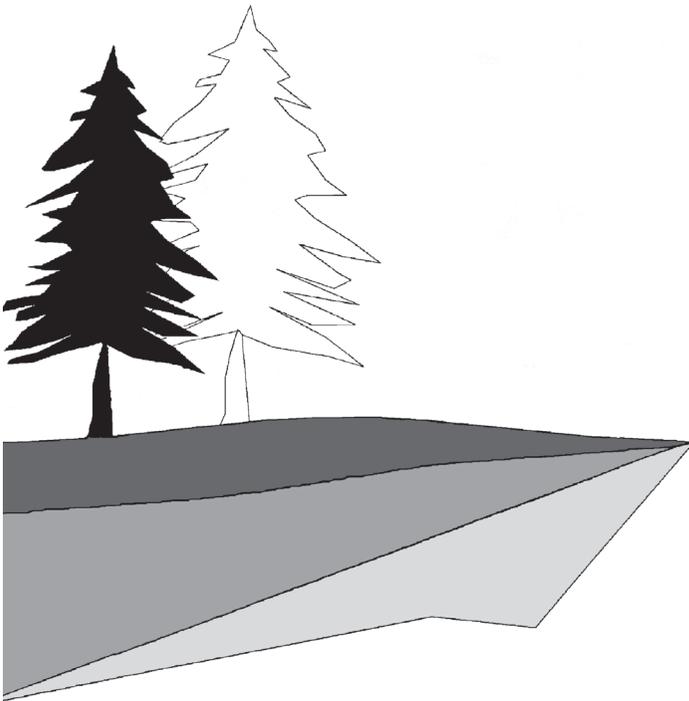
## Recommended Citation

Fernandez, I.J. 2008. Carbon and nutrients in Maine forest soils. Maine Agricultural and Forest Experiment Station Technical Bulletin 200.

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# Carbon and Nutrients in Maine Forest Soils

Ivan J. Fernandez



Technical Bulletin 200

November 2008

MAINE AGRICULTURAL AND FOREST EXPERIMENT STATION  
THE UNIVERSITY OF MAINE

# Carbon and Nutrients in Maine Forest Soils

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## ACKNOWLEDGMENTS

The author wishes to acknowledge the support of the Maine Agricultural and Forest Experiment Station and various additional agencies for their support of projects included in this analysis such as the USDA Forest Service, the US Environmental Protection Agency, the National Park Service, and the National Science Foundation. The author is also grateful to all the colleagues, staff, and students who made possible the various research projects used in this analysis. Special appreciation is extended to Cheryl Spencer for her contributions to most of the projects used in this analysis as well as her direct contributions in working with these data. The author also appreciates the assistance of Charles Hobie Perry for assistance with the USDA Forest Service Maine FIA data, and Stephen A. Norton, Lindsey E. Rustad, and Aaron R. Weiskittel for their helpful reviews of the manuscript.

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## INTRODUCTION

Recent public concerns surrounding climate change and greenhouse gas emissions have resulted in a lively debate about approaches to fossil fuel offsets and carbon (C) sequestration in forests. The forest community sees opportunities for the intensification of the use of forests for markets ranging from forest products, such as fuel (e.g., wood, wood pellets) or fuel feedstock (e.g., ethanol), to a range of new bioproducts (e.g., plastics). The dialogue often is about more intensive harvesting and more complete forest use. This era is reminiscent of the emergence of whole-tree clearcut harvesting practices in North America and Europe more than 25 years ago (e.g., Hornbeck et al. 1990; Kimmins et al. 1985a, 1985b; Mann et al. 1988; Smith et al. 1986). In both cases, the consequences for ecosystems of various strategies to extract C have important impacts on nutrient cycling, notably for nitrogen (N), phosphorus (P) and calcium (Ca). The intensification of forest harvesting can have varied consequences for the forest including risks of nutrient depletion, opportunities for sustainable intensified use, and the potential for site improvement through C sequestration.

Maine has established a progressive reputation in the climate change and greenhouse gas debate. In 2003, Maine passed the first law in the nation (ME Public Law 237) to set specific goals and a timeline for CO<sub>2</sub> emission reductions and in 2005 Maine joined other states in the northeastern U.S. to form the Regional Greenhouse Gas Initiative (RGGI). With ~90% of its land base in forests, Maine is moving to determine how forest management will help meet these C goals. In Governor Baldacci's 2008 State of the State address he announced a "Wood-to-Energy Initiative" to further the goal of using Maine's renewable resources to meet the energy challenge. A recent report on the biofuel potential of Maine's forests stated "If the residues are retrieved based only on the recovery estimates outlined in this report, 2.6 million dry tons of forest residues could potentially contribute up to one-third of Maine's transportation fuel supply through its conversion into ethanol, or three-quarters of Maine's fuel supply for diesel with F-T diesel" (Dickerson et al. 2007). This is just one example of analyses that point to the potential value of Maine's forest resources in meeting the challenges of the 21st century, and the importance of maintaining sustainability objectives while embracing opportunity.

In recent decades, we have learned a great deal about C and biogeochemical cycling of critical nutrients in forests. We need to take full advantage of what we have learned about these pro-

cesses, and use the extensive data that already exist, to help us to solve our energy and climate-change challenges in a timely and informed manner. Maine's rich terrestrial and offshore wind resources, coupled with its forest biomass potential, hydro, tidal, and solar resources represent exciting and realistic renewable energy alternatives.

This report provides initial insights from an ongoing effort to synthesize forest soils data for Maine. The specific objectives presented here were

1. to develop descriptive statistics for C and measures of available forms of the essential nutrients N, P, and Ca in Maine forest soils;
2. to evaluate the ecological stoichiometry of forest soil C relative to available N, P, and Ca; and
3. to highlight information needs to address the simultaneous goals of forest use, C sequestration, and forest sustainability.

## METHODS

This assessment focused on measurements of forest soil total C, total N, and labile phases of P (extractable P) and Ca (exchangeable Ca). These parameters were selected because they are typically available in most forest soils data sets because of their relevance to management, and they represent potentially important indices of nutrient availability in forests. This initial assessment focused on data developed through various studies in the forest soils program at the University of Maine, as well as several federal programs (Table 1). Most of the forest sites from the studies used here have undergone one or more cycles of forest harvesting, fire, and other major disturbance at some point in the past. For all data sets, 1 N  $\text{NH}_4\text{Cl}$  was used for extractable P and exchangeable Ca. Soil horizons were named by taxonomic convention as O, A, B, BC and C, typically named in the field during sampling. A few samples of mineral soil material, generally defined as having <20% organic C (NRCS 1999), were classified as an O horizon and vice versa in the field. The original field labels were retained in this analysis. The "B1" increment, as used here, is not a formal taxonomic designation but represents a soil-sampling-depth increment commonly employed in research where the upper 5 or 10 cm of the B horizon is sampled separately. This is done because the uppermost portion of the mineral subsoil is commonly more sensitive to environmental

Table 1. Data sources for this provisional analysis.

Data Name	Project Name	Project Objectives	Sample Date	Location	Reference
Acadia	US EPA PRIMENet Watershed Project	Biogeochemistry of burned and unburned watersheds in Acadia National Park	1999	Acadia National Park, Maine	Kahl et al. (2007)
BBWM	Bear Brook Watershed in Maine (BBWM)	Whole-watershed N and S acidification	1998	Two watersheds near Beddington, Maine	Norton and Fernandez (1999)
DDRP	US EPA Direct-Delayed Response Program (DDRP)	National Acid Rain Watershed Survey	1985	Throughout Maine	Lee et al. (1989)
DDRP-Pilot	Pilot Project in Maine for National DDRP	Pilot Watershed Survey in Maine	1984	Throughout Maine	Fernandez (1984)
FIA	USDA Forest Inventory and Analysis (FIA)	Forest Vegetation and Soil Monitoring	2001–2005	Throughout Maine	O'Neill et al. (2005)
HELM	High Elevation Lake Monitoring Project (HELM)	Evaluate watershed-lake linkages for lakes >600 m	1998	High elevations western Maine	Fernandez et al. (2001)
HIFS	Howland Integrated Forest Study (HIFS)	Biogeochemistry of a commercial spruce-fir forest	1987–1988	Howland, Maine	Fernandez et al. (1993)
MEGS	Maine Gradient Study	Forest C and N cycling across four climate zones in Maine	1993	Throughout Maine	Fernandez et al. (2000)
Reinman	Agenda 2020 Harvest Intensity Project	The effect of harvesting intensity on soil and site	2003–2004	Spruce-fir forests of northern Maine	Reinman (2006)

change than bulk samples of the whole B horizon. Sample sizes for each horizon varied and included instances of the uncommon A horizon and smaller sample sizes for E horizons because the E was typically not included in the analysis of research pedons for practical reasons (e.g., the E horizon is often thin and chemically somewhat inert). Smaller sample sizes in the deeper BC and C horizons resulted from deep soils not being sampled, depending on the research objectives. The results presented here are simple

descriptive statistics for this provisional data set for the O (n = 1,187), A (n = 28), E (n = 85), B1 (n = 630), B (n = 531), BC (n = 110), and C (n = 197) horizons. Box plots show the 25th and 75th percentiles, whiskers are the 10th and 90th percentiles; outliers are the 5th and 95th percentiles. The median is a solid line and the mean is dashed. Transformations failed to achieve constant variance and therefore Spearman correlation coefficients were used to examine correlations among selected data.

## RESULTS AND DISCUSSION

### **How Much Carbon Is in Maine Forest Soils?**

The data presented here do not attempt to comprehensively answer that question because this would require a rigorous program of sampling and analysis with due consideration to the range in landscape characteristics of Maine. Rather, here we focus on insights from the data sets assembled, which are biased towards the criteria for site selection of the various studies included. Undoubtedly, for example, hydric soils, montane soils, and organic soils are underrepresented. Many of these studies focused largely on upland, forested ecosystems. Evaluations of data through systematic spatially distributed inventories of forests, such as the USDA Forest Service Forest Inventory and Analysis Program (FIA), provide one of the few statewide measurement programs on forests, although these estimates also have limitations in their use. Birdsey and Lewis (2003) used FIA data and reported total C storage in Maine forests for 1995 to be 1,685,808,000 metric tons (MT), broken down as ~77% in soils, with the rest in trees, understory, and products. This averaged to 223,325 kg C ha<sup>-1</sup> in forests, with ~80% in the soil and forest floor. Figure 1 shows estimates of forest floor and mineral soil total C from this study compared to estimates from Birdsey and Lewis (2003) and two intensive forest ecosystem studies in Maine that used quantitative soil pits to directly measure forest soil C content. The quantitative pit approach (Hamburg 1984) is probably the most accurate available direct measurement of soil C. One Maine quantitative pit study was from the Howland Forest (Fernandez et al. 1993), a low-elevation spruce-hemlock-fir stand in Howland, Maine. This site has a history of biogeochemical, climate, and C research. The other site was the Bear Brook Watershed in Maine (Norton and Fernandez 1999), the site of long-term, whole forested watershed biogeochemical and climate research consisting of both spruce-fir and northern hardwood stands.

Despite the varied sources of these estimates, the results were relatively similar in magnitude for both the O and mineral soils. In general, the estimates were between 110,00 and 210,00 kg C ha<sup>-1</sup> in forest soils. These can be considered underestimates of soil C because, in most instances, these estimates exclude soil C below 1 m depth, organic and inorganic C bound in rocks and minerals, some portions of root C, and sometimes coarse particles of organic C that are lost to sieving if only the fine fraction (typically <6 mm in organic soils and <2 mm in mineral soils) is analyzed. These data also focus on only those sites included in the research studies or surveys noted, and may not be representative of specific forest types or soil conditions, such as at high elevation soils, poorly drained soils, or organic soils (i.e., Histosols).

It is important to recognize the difference between “concentration” (e.g., mg kg<sup>-1</sup>, %) and “content” (e.g., kg ha<sup>-1</sup>) in discussions of forest soil C. Figure 1 shows estimates of C content in forest soils, highlighting the large pool of C stored in the mineral subsoils.

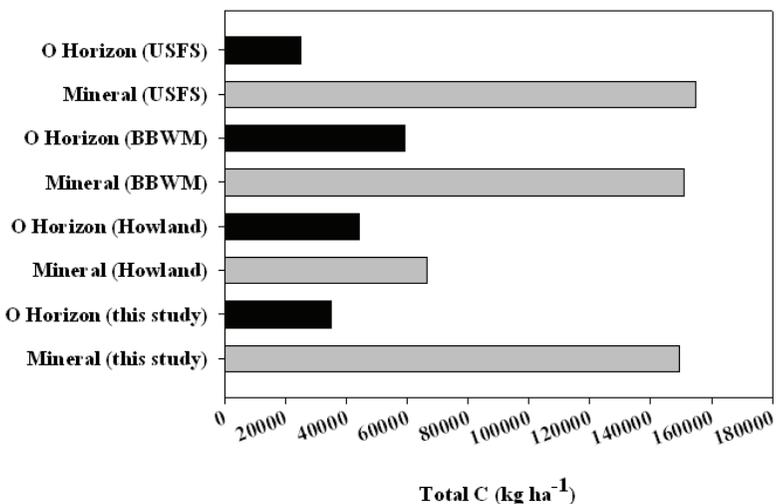


Figure 1. Comparison of estimates for forest floor and mineral soil total. Data are for the USDA Forest Service estimates (USFS) from Birdsey and Lewis (2002), the Howland Research site (Fernandez et al. 1993), the Bear Brook Watershed in Maine (BBWM) (Norton and Fernandez 1999), and this study. For USFS the O horizon includes estimates of the O horizon, fresh litter, and coarse woody debris. For the other studies coarse woody debris and fresh litter not mechanically attached to the morphological O horizon are not included.

This depth distribution can be counter to what casual observers might expect given the high concentration of C in the surface O horizon. Figure 2 shows major horizons and an implied depth profile for descriptive statistics of forest soil C concentrations from this study. In these figures, not all horizons are always present in soil profiles, and typically in Maine forests one (e.g., A) or more are not common. The mean total C concentrations ranged from 41.9% in the O horizon to 1.1% in the C horizon. Even in the B horizon, mean total organic C was only 4.0%, yet the large mass of the mineral soil resulted in a large organic C content in the mineral soil (Figure 1). There were notably higher C concentrations in the B1 increment, with a mean of 6.8%. This can be attributed to several factors. The B1 increment is an artificially defined depth increment used in research to sample the upper mineral soil, typically 5 or 10 cm in thickness. This zone is immediately beneath the O horizon (i.e., when the E horizon is absent) and the higher organic C concentration could reflect the influence of O horizon materials in these samples due to natural mixing processes (which are typically minimal) or as a sampling artifact. However, it is more likely that higher organic C in the B1 depth increment reflects natural processes. The acidic character of Maine soils results in few macro-invertebrates (e.g., earthworms), so mechanical mixing of horizons by biota is highly suppressed, allowing the development of distinct,

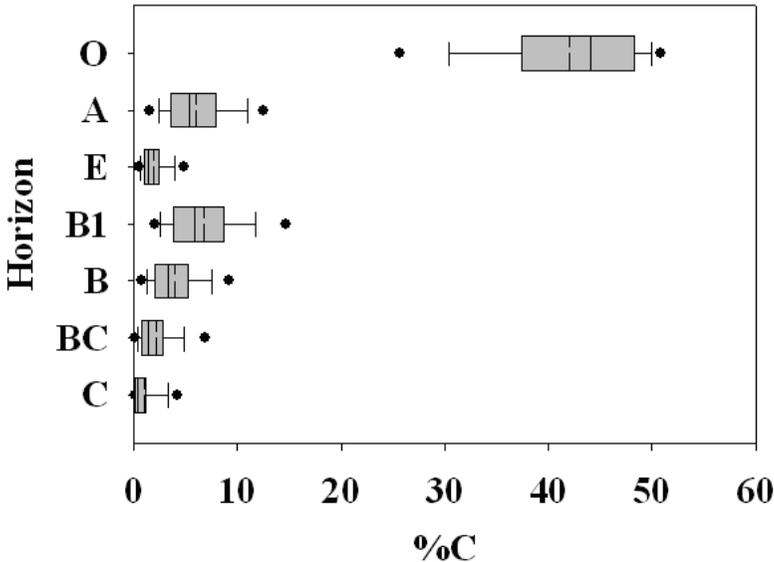


Figure 2. Box plot for descriptive statistics of total soil C for this study.

abrupt boundaries for the upper horizons. Maine's dominant soils are Spodosols, although Maine mineral soils can be technically classified as Entisols, Inceptisols, or Spodosols, depending on the degree of soil development or pedogenesis (Ferwerda et al. 1997). Regardless of their taxonomy, a process of illuviation is taking place in these soils that causes the precipitation of organic matter in the B horizon along with metals dominated by aluminum (Al) and iron (Fe). Organic matter leaches from the O horizons in soil solution as dissolved organic C (i.e., DOC) and typically precipitates rapidly with soil depth leaving the greatest concentrations near the top of the B horizon. When this illuviated organic matter results in a dark-colored band at the top of the B (which might otherwise be a Bw, Bs, or Bg horizon for Maine soils), it can be referred to as a Bh horizon (or in combination with other subordinate distinctions, such as a Bhs horizon), denoting visual evidence of this organic matter accumulation by the "h." Thus, the higher organic C concentrations in the B1 increments in this study were likely due, at least in part, to this natural soil forming process. The A horizons in these data could be abandoned farm fields (i.e., old Ap horizons) or conditions that allowed the incorporation of organic matter into the upper mineral soil through natural processes. These could occur in some imperfectly drained sites that were included in these data, or sites with high-quality litter and rapid decomposition at the surface allowing mineral soil incorporation. Most closed-canopy Maine forests would not result in conditions that would be conducive to the formation of A horizons. Nevertheless, where they occur, they commonly have higher organic C concentrations than underlying mineral soils.

### **What Is the Relationship between C and Nutrients in Maine Forest Soils?**

Carbon can be considered the currency of energy in forested ecosystems. Fixed by plants through photosynthesis into organic matter from atmospheric carbon dioxide (CO<sub>2</sub>), organic matter stores the sun's energy as organic chemically reduced C. As organic C moves through the ecosystem, stored energy is used by organisms from wildlife to bacteria through respiration, a process of oxidation. Organic matter also contains the mineral nutrition required by living organisms, or what we refer to as the mineral nutrients (e.g., N, P, potassium [K]). The rate at which organic matter decomposes and releases mineral nutrients is a function of many factors including the quality of organic matter and its nutrient concentration. There is a well-developed scientific literature

on the biogeochemistry of C and mineral nutrients that interested readers should consult for insights on these topics (e.g., Aber and Melillo 1991; Brady and Weil 2008; Schlesinger 1997).

The availability of nutrients to higher plants, such as trees, depends on many factors including the rate of nutrient transformation into biologically available forms. In the case of N in Maine forests, the most biologically available forms are the inorganic ions ammonium ( $\text{NH}_4^+$ ) and nitrate ( $\text{NO}_3^-$ ). Some studies have reported that plants use dissolved organic N (DON) (e.g., Lipson et al. 2001; Schimel and Chapin 1996), but in the largely N-limited landscape of boreal and temperate forests (Tamm 1991), microbial communities would more successfully compete for organic N in contrast to tree roots. Therefore, the rate at which N in organic matter is transformed into inorganic N (i.e.,  $\text{NH}_4^+ + \text{NO}_3^-$ ) largely determines the availability of N to forests. Because of the ephemeral nature of these ions, and the perennial nature of the forest, a soil extraction at any one time to measure their concentrations is of limited use in predicting the ongoing supply of N in forests. Likewise, the total N concentration gives us information about a large N pool of which only a small component is labile and available to biota. Jefts et al. (2004) reported ~0.1% of total soil N at the BBWM watershed occurred as extractable inorganic N. Therefore, total N by itself is not a good indicator of the rate at which organic N will be mineralized to inorganic N. It is for this reason that we often use the ratio of C to N (i.e., C/N ratio) as an indicator of inorganic N availability in soils. Figure 3 shows both the N concentration depth pattern and the C/N depth pattern in Maine forest soils based on this data analysis. What is evident is that total N concentrations follow similar patterns to total C, which is logical given the central role both elements play as building blocks of living organisms. As organic matter decreases with depth in these forest soils, so too does the concentration of N.

There is a critical difference between the organic matter in the O horizon of forest soils, strongly influenced by fresh litter and partially decomposed organic materials, and the relatively humified organic matter found in the mineral subsoils. Aber and Melillo (1980) defined litter as material exhibiting net N immobilization and soil as material exhibiting net N mineralization. Most morphologically defined O horizons are a mixture of both. David et al. (1995) noted that the forest floor is made up of plant and root litter, partially decomposed plant and microbial products, and humic substances. They stated organic matter in the mineral subsoils was comprised of (a) illuviated DOC that is leached from

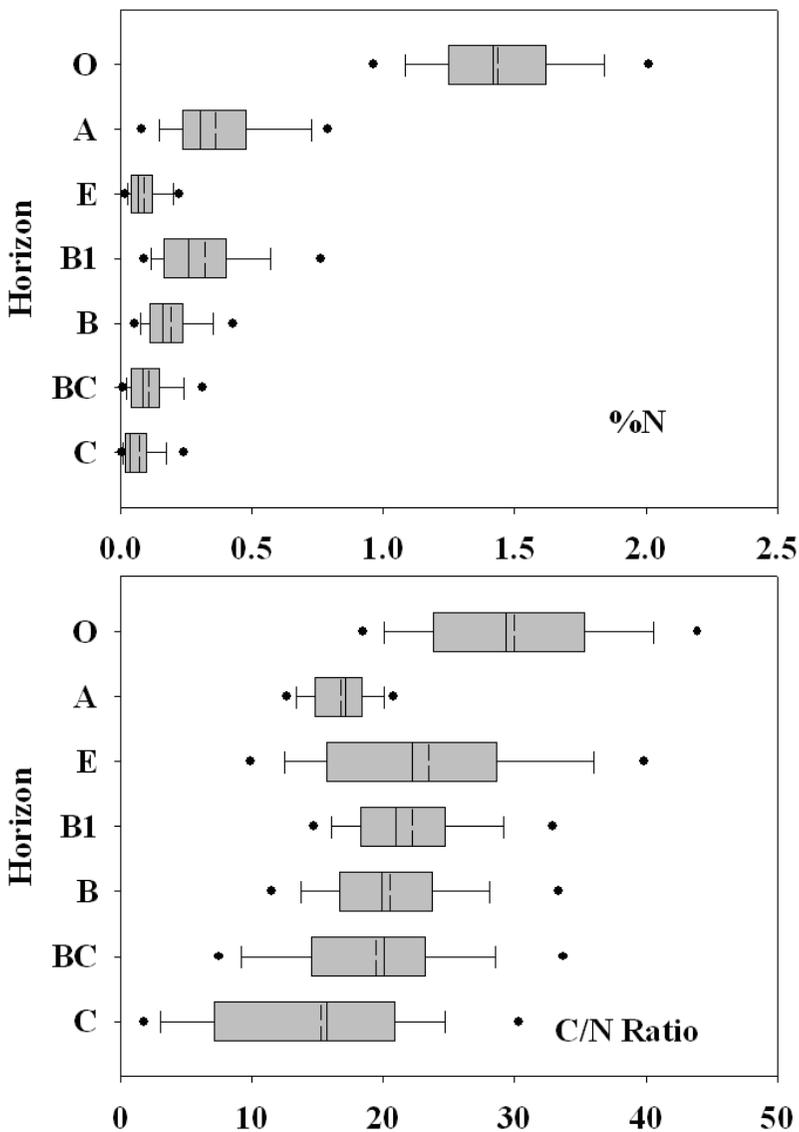


Figure 3. Box plot for descriptive statistics of total soil N and C/N ratio by depth for this study.

surface soils and precipitated lower in the soil profile, (b) the decomposition of roots and microbial biomass in the soil, and (c) the transport of organic matter by soil animals (e.g., macroinvertebrates such as earthworms and insects). In Maine's relatively

acidic forest soils, macroinvertebrate activity is generally limited and the illuviation of humic materials dominates the character of organic C in the B horizon. Therefore, when we use data on soil C/N ratio in forest soils to assess N availability, this index of N availability from decomposing organic matter best applies to the O horizon, but is poorly suited to predicting N availability in the mineral soil. Generally, the higher the C/N ratio for fresh organic matter such as forest litter, the slower the rate of decomposition and therefore N mineralization (Brady and Weil 2008), and thus the lower the availability of N to growing forests. Figure 3 shows that the O horizon mean C/N ratio was ~30, perhaps a representative value for forest soil O horizons in Maine across all forest types. The B horizon mean C/N ratio was ~20, but this lower C/N ratio does not mean that there is a higher rate of N mineralization and availability in the B horizon because of the dominance of humified organic materials composed of high molecular weight organic compounds that are difficult to decompose. Melillo et al. (1989) provides a good discussion of the complexities of lignin, cellulose, and N in soil organic matter decomposition along the soil organic matter decay continuum.

We know enough about C/N ratios in soil organic matter to know that an O horizon with a C/N ratio of 30 will mineralize N much faster than, for example, sawdust (C/N ~400–600), and much slower than finished household compost (C/N ~15), but it is more difficult to determine relative N availability in forests from differences in O horizon C/N ratios among forest sites. In general, the higher the C/N ratio in the O horizon, the lower the rate of N cycling and thus N availability. One index of relative availability that can be applied across aggregated data to accommodate differences in analytical techniques is the percentage of total net N mineralization represented by net nitrification. This was applied to forest soil data by Aber et al. (2003) to evaluate the effects of atmospheric N deposition on forest soil N status in the northeastern U.S. Some of the Maine data in this report were also part of the Aber et al. (2003) analysis. Figure 4 shows this relationship for the Maine data reported here. What is evident from this figure is that higher C/N ratios result in little or no net nitrification, and it appears that below a C/N ratio of ~25 we see a dramatic increase at many sites in the rates of net nitrification. This is similar to the regional findings of Aber et al. (2003). Chapin et al. (2002) described a “critical C/N ratio” of ~25, above which microbes must scavenge additional N from the soil to meet their growth requirements thereby reducing N availability to higher plants.

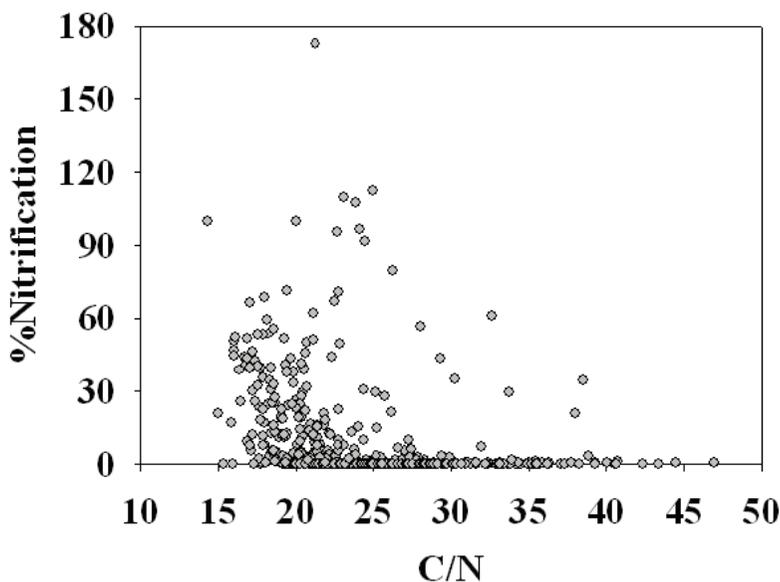


Figure 4. Net nitrification as a percentage of net N mineralization versus C/N ratio, from N dynamics data available for O horizons in this analysis.

Below this C/N ratio, available N in organic materials exceeds microbial growth requirements and excess N is secreted into the soil making it available for higher plants. Gunderson et al. (1998) found that conifer stands in temperate forest ecosystems in Europe having a C/N ratio below 25 leached  $\text{NO}_3^-$  or had elevated surface water  $\text{NO}_3^-$  concentrations. They suggested a C/N ratio continuum where the potential for  $\text{NO}_3^-$  leaching is low with O horizon C/N ratios above 30, moderate for sites with C/N ratios between 25 and 30, and high for those with C/N ratios below 25. Changes in the composition of the forest through succession or management that alters the quality of organic matter or the balance between C and N have the potential to shift N availability in these largely N-limited New England forests.

Unlike N, both P and Ca availability in soils is frequently characterized by soil extraction procedures that measure a small portion of the total nutrient in the soil. Although these measurements are operationally defined, the portion of the soil nutrient measured is considered to be biologically relevant or "available." In soil testing laboratories the method used to determine the biologically available concentrations of nutrients is usually based on experience in various geographic regions after evaluating available methodolo-

gies. These methods are relatively standardized in soil testing for the broadly defined area of agriculture (to include soil testing for agronomic, horticultural, forest, and environmental purposes) for the base cationic nutrients in soils (i.e., Ca, magnesium [Mg], and K). These available soil forms are defined as the “exchangeable” phases of these base cationic nutrients. Soil P has a much more complex chemistry in soils, and no single chemical phase clearly represents an available P pool. Particularly with soil P, chemical extractants react differently with different soils leading to specific regions in the U.S. often favoring different P testing methods. In all cases, available P is considered the amount extracted by some operationally defined procedure that has proven useful for soils in a particular geographic area and is predictive of P availability to higher plants. For forest soil testing in the region of this research, 1 N  $\text{NH}_4\text{Cl}$  has been frequently used for available P testing and thus the same extractant is employed to measure “exchangeable Ca” and “extractable P,” as used in this study.

Figure 5 shows the soil horizon and depth trends for both extractable P and exchangeable Ca in these soils. The concentration of these operationally defined available phases of P and Ca largely parallel the soil organic C and N depth patterns, with the highest concentrations in the O horizon and much lower concentrations in the mineral soils. Phosphorus is often considered a potentially limiting nutrient in soils after N, although little empirical data exist at this time demonstrating P deficiencies in forest soils in Maine. It is possible that P limitations could be of increasing concern in the future for intensively managed forests, or under conditions where elevated atmospheric N deposition or climate warming increases N availability (Aber et al. 2003; Ollinger et al. 2008) that can lead to changes in P cycling with possible effects on forests (Elser et al. 2007; McGroddy et al. 2004; Perring et al. 2008). One of the unique characteristics of P is that it is strongly “fixed,” or chemically combined in a relatively unavailable form in acidic mineral soils (Wood et al. 1984). The largest pool of mineral soil P has been shown to be chemically combined with Al (Sherman et al. 2006; SanClements et al. 2008), and this phase of P is considered to be relatively unavailable to higher plants. Because of the high concentrations of both Al and Fe in these soils, the capacity for P fixation is high. This is particularly true in acid soil environments, which encompasses nearly all Maine forest soils.

Exchangeable Ca, on the other hand, is a divalent cation adsorbed to the effective cation exchange capacity (CEC) of soils and this form of Ca is considered to be relatively available to plant

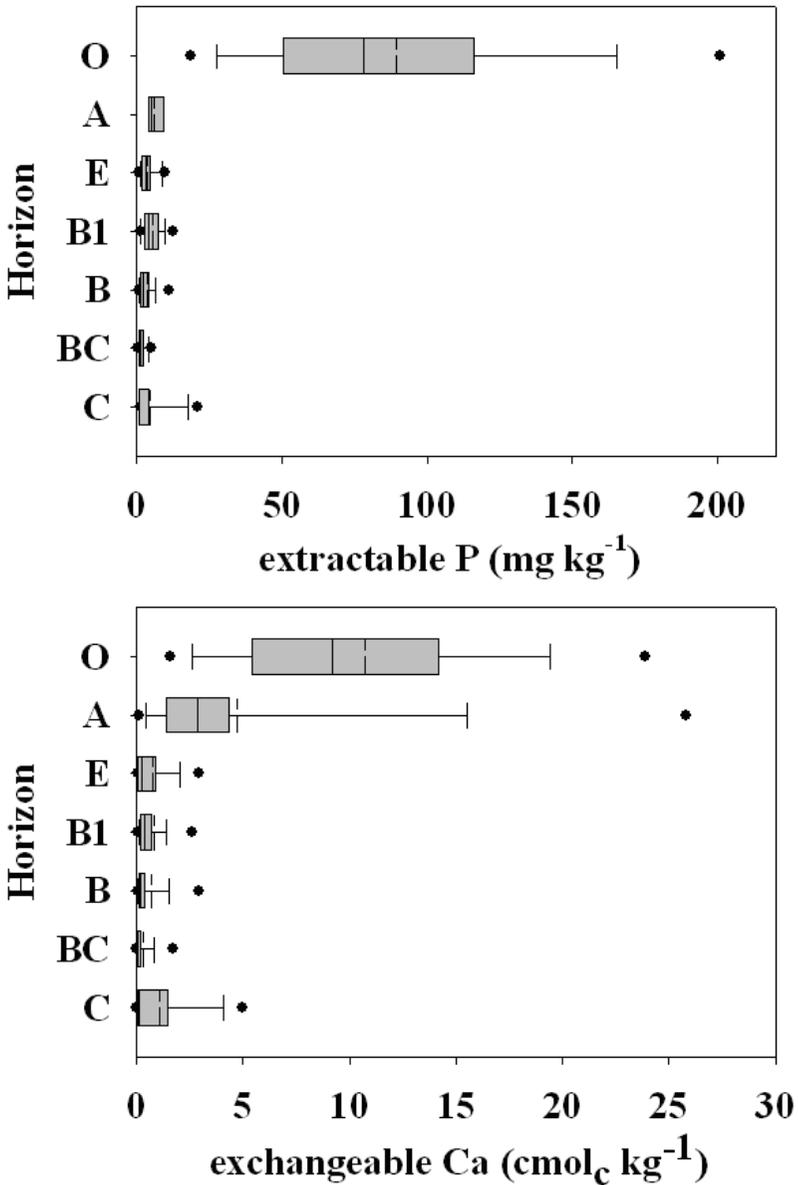


Figure 5. Box plot for descriptive statistics for extractable P and exchangeable Ca by horizon and depth for this study.

roots and soil biota. Our ability to chemically identify the available phase of Ca is more accurate than our ability to define available P. Because of the typically coarse textured character of Maine's upland and interior young forest soils, they have a low clay mineral content and most of the  $CEC_e$  in the mineral soil horizons is associated with organic matter. The exception to this would be the finer-textured soils derived from marine sediments found mostly in coastal Maine and along major river basins (Ferwerda et al. 1997) that can have higher clay-sized particle contents and  $CEC_e$  attributable to mineral colloids. Because Maine soils are young, there are few true secondary clay minerals and most of the clays are clay-sized particles of the primary minerals of parent materials. The majority of soils in these data were from interior Maine, and therefore the depth and distribution pattern of exchangeable Ca was strongly influenced by the distribution of organic C. As with P, an increase in the intensity of harvesting in forests raises the possibility of Ca depletion if other ecosystem processes (e.g., mineral weathering, atmospheric deposition) do not replenish the nutrients removed in biomass at a rate that equals or exceeds the long-term nutrient removal. In addition, a more recent concern over the past several decades has emerged for Ca depletion in forest soils due to long-term acid deposition (Fernandez et al. 2003; Lawrence et al. 1997; Watmough et al. 2004) and the intensification of harvesting might add to this pressure on Ca availability (Huntington 2005; Smith et al. 1986; Thiffault et al. 2008). To date, little experimental research has been done to address these issues, and no direct evidence of significant P or Ca limitations has been shown by fertilization or other studies in Maine. Yet research on the biogeochemistry of forested ecosystems continues to point to the need for us to better understand ecosystem processes governing nutrient supply in our forests. As with most properties and processes in forests, soils are characterized by a high degree of variability, resulting in a range of susceptibilities to nutrient depletion, from high susceptibility at vulnerable, low-nutrient sites to low susceptibility at well-buffered, high-nutrient sites.

The focus of this discussion is on forest soil nutrients, but we have already noted the importance of  $CEC_e$  in governing base cationic nutrient availability. Similarly, soil pH, a measure of soil acidity, has long been recognized as a master variable controlling nutrient availability in soils. Generally, as soils become more acidic, nutrient availability decreases (Brady and Weil 2008). Therefore, it is instructive to include here observations of pH and CEC from the soils studied. Figure 6 is a scatter plot of  $pH_{Ca}$  (pH measured in a

dilute  $\text{CaCl}_2$ -soil suspension) and  $\text{CEC}_e$  as a function of organic C. These plots show little evidence for a strong relationship between mineral soil C and  $\text{pH}_{\text{Ca}}$ . It appears that soils with very low C concentrations can be highly acidic or near neutral. The O horizon data suggest a decreasing  $\text{pH}_{\text{Ca}}$  as C concentration increases. This

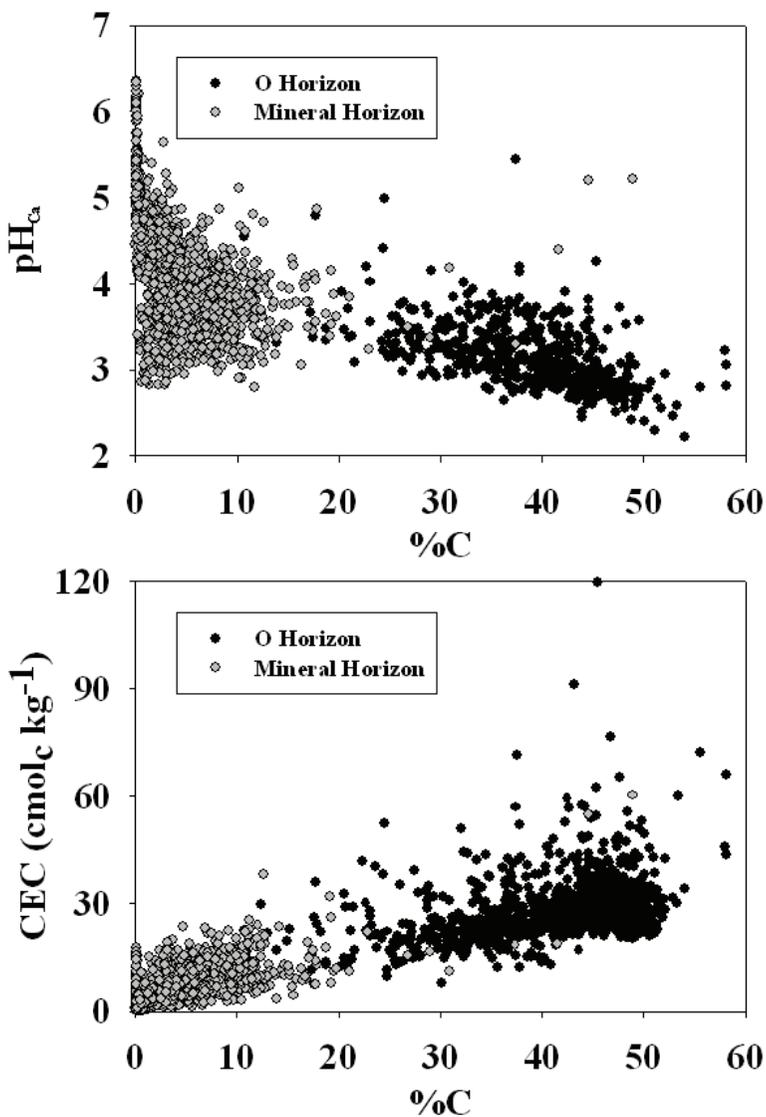


Figure 6. Scatter plots for O horizon and mineral soil pH and CEC with soil % C.

likely reflects a gradient of multiple factors, one of which would be forest type. Softwoods tend to accumulate more organic matter in the forest floor and mineral soils, but the ecological quality of that organic matter is lower than hardwoods resulting in the generation of greater weak organic acidity in soils. There also tends to be less mixing of mineral soil in the O horizon because of the greater C accumulation and lower biological activity in softwoods compared to hardwoods, resulting in higher C concentrations in the O horizon and lower  $\text{pH}_{\text{Ca}}$ . The pattern of generally increasing  $\text{CEC}_e$  with C concentration is expected because organic matter in soils has a higher surface area and  $\text{CEC}_e$  compared to mineral soil materials on a mass basis.

One objective of this analysis was to determine if differences in soil C were associated with differences in the essential nutrients N, P, and Ca. Because these nutrients can be found in essentially all soil organic materials at some concentration, an increase in total soil C content will inevitably increase total soil mass of N, P, and Ca. However, forest site productivity and sustainability are more directly influenced by the availability of these and other nutrients, and therefore measures of available nutrient concentrations or other availability indices are often a more appropriate framework to evaluate forest sustainability over time. Figure 7 shows a series of scatter plots for the O and mineral soil horizons (note changes in scale among panels). Table 2 shows the correlation coefficients for these variable pairs. The plots show the relationship in these data between total N, extractable P, and exchangeable Ca with C concentration in forest soils. As expected, increasing C concentration results in increasing N concentration because in this case, we are looking at total nutrient measurements. In the O horizon, there is a great deal of variability at the higher C concentrations attributable to the broad range of litter quality possible, ranging from high C, low N peaty coniferous sites to high C, high N mixed forest types on more minerotrophic soils. Because of the high dispersion of the data at higher C concentration values, there is no statistical correlation evident. In the mineral soil, the relationship between C concentration and N concentration is highly correlated. The stronger correlation results from the convergence of C concentration and N concentration as fresh organic matter is transformed by humification in the soil to a more stable material resistant to decomposition. As discussed earlier, the humification process results in a convergence of the C/N and is therefore typically not a good indicator of inorganic N availability in the subsoil compared to the less humified surficial organic materials.

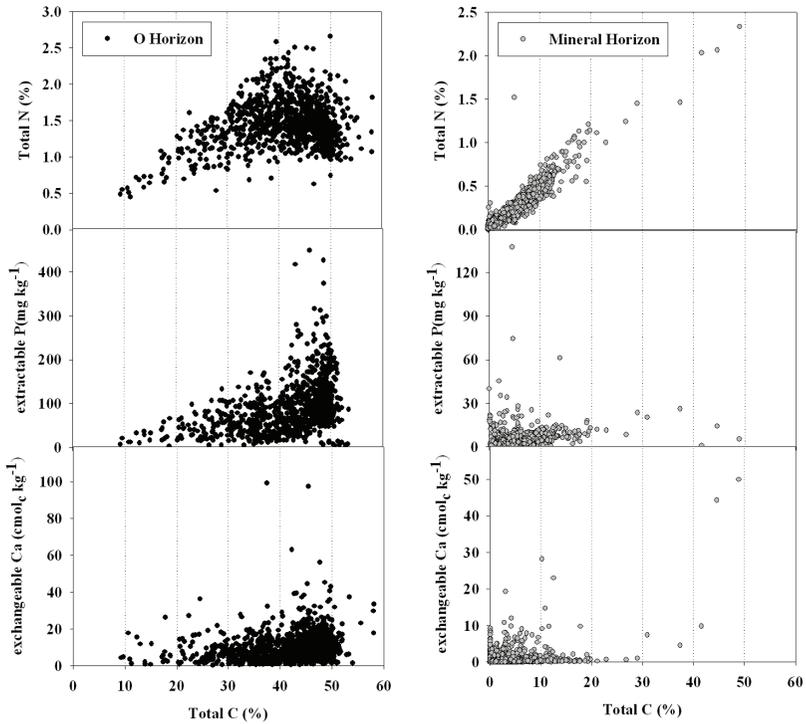


Figure 7. Scatter plots for O horizons and mineral soils between total N, extractable P, and exchangeable Ca with soil % C.

Table 2. Correlations between total soil C and N, P, and Ca. Spearman correlation coefficients for total C, total N, extractable P, and exchangeable Ca by horizon type.

	O Horizons	Mineral Horizons
	C	C
N	-0.03	0.94
P	0.49	0.46
Ca	0.29	0.20

The trends for extractable P and exchangeable Ca with C concentration are not as clear in Figure 7 as with total N. There is a tendency for both extractable P and exchangeable Ca to increase with increasing C concentration in both the O and mineral horizons. In the case of extractable P, a higher C concentration reflects more organic matter in various phases of decomposition that release labile P to the extraction process. In addition, as C concentration increases there is less mineral soil in the O horizon resulting in lower Al and Fe fixation of P. While there is a suggestion in these patterns of higher exchangeable Ca with C concentration in the O horizon, these relationships are weak. As already noted, the sites with a higher concentration of C are more likely associated with softwoods, and the greater acidity of softwoods could result in greater leaching losses of Ca and thus lower available Ca, despite the higher CEC<sub>e</sub> associated with higher C concentration. In the mineral soils, neither extractable P nor exchangeable Ca appears to be strongly correlated with C concentration. It is likely that the strong fixation of P by Al and Fe, abundant in the mineral subsoil (SanClements et al. 2008), dominates P availability and explains the relatively low available P. Similarly, Al abundance in these mineral soils means that in these acid soil environments we expect labile exchangeable Al to effectively dominate exchange sites and displace exchangeable Ca (Fernandez et al. 2003). In particular, the reactive Al in these acid subsoils would displace exchangeable Ca from organic and mineral exchange sites leading to Al-dominated exchange sites on organic and mineral colloids in the mineral horizons, with Ca leaching losses and depletion over time. This is a natural process of acidification during soil development that can be accelerated due to other disturbances such as acid deposition.

### **What Are the Influences of Forest Composition on C and Nutrients in Maine Forest Soils?**

Forest composition has a strong influence on the ecological stoichiometry of C, N, P, and Ca distribution and accumulation in forest soils because of tree species differences in (a) the bioaccumulation of C and nutrients and (b) the characteristic litter quality of different species that influences rates of decomposition and nutrient release. Forest composition effects on nutrient dynamics have been widely recognized in the scientific literature (e.g., Cole and Rapp 1981; Lovett et al. 2004). Table 3 shows concentrations and amounts for the data presented with means calculated by major forest type as hardwoods and softwoods. These data represent primarily northern hardwoods (i.e., birch-beech-maple) and spruce-fir forest types.

Table 3. Forest composition influences on C and nutrients. Means (and Standard Errors) for total C, total N, exchangeable Ca, and extractable P by forest type and horizon type from the aggregated Maine forest soil data.

		Hardwood		Softwood	
		Mean	SE	Mean	SE
<b>O Horizons</b>					
		concentrations			
C	%	37.4	0.66	43.4	0.24
N	%	1.50	0.03	1.40	0.01
C/N	-	25.1	0.32	31.0	0.28
P	mg kg <sup>-1</sup>	70	5.7	93	2.0
Ca	cmol kg <sup>-1</sup>	10.7	1.0	9.9	0.2
		mass per unit area			
C	kg ha <sup>-1</sup>	17,490	1,059	42,338	1,549
N	kg ha <sup>-1</sup>	555	61	1,633	58
P	kg ha <sup>-1</sup>	2	0	7	0
Ca	kg ha <sup>-1</sup>	66	10	196	12
<b>Mineral Horizons (excluding A horizons)</b>					
		concentrations			
C	%	4.9	0.20	5.4	0.15
N	%	0.30	0.01	0.30	0.01
C/N	-	19.6	0.29	22.0	0.24
P	mg kg <sup>-1</sup>	4.3	0.4	5.0	0.2
Ca	cmol kg <sup>-1</sup>	0.8	0.1	0.4	0.0
		mass per unit area			
C	kg ha <sup>-1</sup>	147,381	-	153,674	-
N	kg ha <sup>-1</sup>	7,205	-	6,565	-
P	kg ha <sup>-1</sup>	12	-	15	-
Ca	kg ha <sup>-1</sup>	333	-	147	-

As already discussed, softwood soils typically accumulate more C. Despite the parallel trends in C and N accumulation in these soils, the tendency for a higher C/N ratio with higher C concentration results in lower N pools in softwood soils compared with hardwood soils. Differences between forest types for extractable P were unremarkable in these data. Exchangeable Ca concentrations were also unremarkable in the O horizon, but the higher O horizon mass

in softwoods resulted in higher exchangeable Ca content in softwood O horizons. The opposite appeared to be true in the mineral subsoils, where both higher concentrations and mass existed in hardwoods compared to softwoods. Despite these differences, Ca concentrations were generally low in these soils.

### **What Do We Need to Know?**

There is always a need for us to better understand the form and function of ecosystems, a need that forms the basis for research in the natural sciences. This discussion about C in Maine forest soils helps frame important fundamental and practical information needs surrounding forest C and forest sustainability. These needs include

1. Development of scientifically appropriate and practical methods to measure soil C that allows us to quantify and track changes in soil C that result from ambient natural processes, altered land-use management, and environmental change.
2. More extensive data on the influence of site factors, most notably parent materials and soil drainage, on forest soil C and nutrient dynamics.
3. Improved inventories of forest C using standardized measures over time that include coarse fraction C in soil, coarse woody debris, better estimates of roots, and deep soil C pools.
4. A better understanding of the biogeochemical processes that govern both C and mineral nutrients in forests that will allow us to define “sustainability” in an era of accelerated forest use and a changing chemical and physical climate.

These needs can be addressed by a combination of intensive long-term studies of ecosystem function and targeted research of shorter duration addressing questions about rapid response processes or discrete problems. Because of the costs for intensive, ecosystem-scale long-term research, the most intensive studies will be few and should build on existing sites with a history of data wherever possible. An important component of an overall research agenda is research performed in collaboration with, and on lands managed by, forest managers and landowners.

## CONCLUSIONS

Changes in forest soil C concentration and content due to stand development, environmental factors, or management will also result in changes in mineral nutrient concentrations and content. If efforts are made to increase forest C through on-site C sequestration, then we will also increase sequestration of mineral nutrients in the accumulating organic matter. The nutrients can come from mineral weathering, atmospheric deposition and fixation, or fertilization. Similarly, when organic C is removed from the forest site through harvesting, so too are the associated nutrients. But simple measurements of total soil nutrient concentrations are typically not good measures of the availability of mineral nutrients to forests. Soil science offers numerous examples where we can increase the total amount of a nutrient in soil yet nutrients become less available. The data shown here indicate that differences in total soil C do not necessarily reflect parallel differences in the availability of the nutrients studied. Rocks and minerals, along with soil organic matter, typically contain a great deal of the mineral nutrients needed for forest growth, but most of them are not available for uptake by tree roots. Our far greater challenge lies in understanding the biogeochemical mechanisms that govern coupled C and mineral nutrient cycles in forests on both short and long time scales. It is within this knowledge base that we can best prescribe management policies to assure healthy and sustainable Maine forests for the future.

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