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Long-term soil nutrient dynamics and lateral nutrient movement in fertilized and unfertilized red pine plantations

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Abstract. In this study, we use a repeated-measures analysis to test the hypothesis that soil fertility under potassium-limited red pine (*Pinus resinosa* Ait.) stands at the Charles Lathrop Pack Demonstration Forest in Warrensburg, New York is increasing toward a steady state that was artificially induced in fertilized stands by K-fertilization over 50 years ago. We measured soil K by horizon and added new data to a 53-year database. We examine one mechanism that explains the higher rate of K accumulation in unfertilized stands compared with fertilized – lateral movement of fertilizer K from treated plots to untreated – using the rubidium/potassium reverse tracer method. Over the past five decades, soil K concentrations under both fertilized and unfertilized red pine have increased significantly. The trends under fertilized and unfertilized plots demonstrate the gradual convergence of soil K under unfertilized plots toward concentrations in fertilized plots. Five decades after fertilization, treated soils still contain greater concentrations of exchangeable K and lower bulk densities than unfertilized plots. Analysis of Rb/K ratios in the forest floor of fertilized and unfertilized plots confirms the hypothesis that lateral transport of surface broadcast fertilizer, applied over 50 years ago, extends approximately 11–16 m from the edges of fertilized plots. The four unfertilized plots closest to fertilized plots have been significantly affected by inputs of fertilizer K, while the remaining five plots are relatively unimpacted. Approximately 36% of the K in fertilized plots, and 23% of the K in unfertilized plots affected by fertilizer migration were derived directly from the fertilizer applied 5 decades ago, demonstrating the highly conservative nature of mineral nutrient cycling in aggrading forests.

Introduction

Fifty-three years of measurements under red pine (*Pinus resinosa* Ait.) plantations at the Charles Lathrop Pack Demonstration Forest in Warrensburg, New York record the amelioration of poor soil by aggrading forest stands. Comparison of the trends in soil nutrients in stands that were fertilized five decades ago with unfertilized stands shows the long-term effects of fertilization on soil sustainability, stand development, and biomass accumulation. In this study, we test the hypothesis that soil fertility under unfertilized red pine is increasing toward a steady state that was induced in fertilized stands by fertilization over 50 years ago; and we examine a mechanism that explains the higher rate of K accumulation in unfertilized stands compared with fertilized.

We update the five decade database and use more conservative statistical analyses to reconfirm the findings of Nowak et al. (1991) that exchangeable soil K pools increased in both unfertilized and K-fertilized red pine soils on the K-deficient glaciofluvial outwash sands of the Pack Forest. Soil K dynamics are emphasized, since low soil K limits tree growth on the site and K fertilization of stands in the 1940s allows a comparison of unaltered plots with artificially improved stands on an otherwise homogeneous site (Heiberg et al. 1964). In addition to changes in soil K, trends in soil pH over the past 5 decades are compared between fertilized and unfertilized stands.

Significant nutrient uptake from 3 m below the soil surface suggests that the overall K increase in surface soils of both fertilized and unfertilized plots is due to the mobilization of K from the entire rooting zone and subsequent concentration into the upper soil horizons by sequential processes of nutrient uptake, litterfall and throughfall, mineralization, and cation exchange (Buxbaum 1994). However, the difference in rates of K accrual between fertilized and unfertilized plots cannot be explained by deep subsoil uptake, nor by any other inherent species or site characteristics, since the sampled trees were all planted at the same time and of the same provenance, and the sampling sites are relatively homogeneous in terms of past use and soil characteristics (Leaf 1970). We test the hypothesis that significant lateral flux of K from fertilized to unfertilized plots has occurred over the past five decades and that contamination of unfertilized plots with K from adjacent fertilized sites accounts for higher rates of K accretion in the unfertilized stands.

We measure the conservation of K fertilizer that was applied five decades earlier and determine the extent to which fertilizer has been transported laterally within the ecosystem using the Rb/K reverse tracer technique (Hafez & Stout 1973; Stone & Kzystyniak 1977). Rb/K concentration ratios in the forest floor litter (O1 horizon) in unfertilized plots are compared with respect to distance between unfertilized and fertilized plots. If the Rb/K ratio diminishes with proximity of unfertilized to the nearest fertilized stands, then our hypothesis that fertilizer-applied K has been transported laterally into the unfertilized plots is supported. Quantifying the long-term lateral component of nutrient flux in forest ecosystems has implications for several concerns including: the width of buffer zones to protect aquatic and wetland habitats from fertilizer pollution and to maintain the integrity of future long-term nutrient manipulation studies; and the duration of windrow effects and similar nutrient-concentrating phenomena.

History of nutrient cycling research on the Pack Forest Plain

Few long-term studies allow an analysis of soil response during soil development. In North America, the longest ongoing study of trends in forest soil fertility is found in plantations of red pine and other conifer species at Pack Forest (Leaf 1970). Researchers began monitoring soil chemical characteristics under various conifer species on the outwash sand plain at Pack Forest in 1939, over 50 years prior to the current study. Sampling of the 25 red pine stands used in the current historic analysis of soil trends at Pack Forest was repeated several times throughout the 1940s and 1950s. Many of the plots were resampled in the 1960s. A lull in the 1970s was followed by intensive renewed soil sampling and analysis throughout the 1980s and into the early 1990s.

The Pack Forest Plain was donated by Charles Lathrop Pack to the New York State College of Forestry in 1921. "The Plain", as the outwash terrace is commonly called, was planted in the 1920s and 1930s primarily to various conifer species. Research initiatives at the time of planting included studies on spacing, provenance, species mixtures, and planting methods (Leaf 1970). However, soon after the plantations were established, researchers noted symptoms of severe nutrient deficiency, varying among species, but generally characterized by chlorosis, shortened needle length, early needle abscission, very poor growth, and tree death in some species (Heiberg et al. 1959).

Early research on The Plain aimed primarily to determine growth limiting factors and optimum fertilizer requirements of the conifer plantations. In the earliest studies, a pronounced growth response was observed upon addition of various organic mulches (Heiberg & White 1951; Heiberg & Leaf 1961). To demonstrate that the response was not due to improved soil water retention by the mulch, researchers added a glass wool mulch treatment to test the effects of increased soil moisture without additional nutrients. Lack of response to the glass wool indicated a mineral nutrient, rather than water, deficiency. Subsequent trials with various pure chemical salts revealed that potassium was the sole nutrient to which the trees responded (Heiberg & White 1951). Fertilizer application rate tests demonstrated that 112 kg/ha K produced optimum growth (Heiberg et al. 1959).

Other investigators in the first decades of research on the Pack Forest Plain discovered that prior land use and depth to discontinuous fine subsoil horizons influenced tree growth and vigor. Relatively vigorous growth rates were observed in red pine stands at the southern end of The Plain (White & Wood 1958; Heiberg & Lowenstein 1958). The boundary between poor and healthier stands coincided roughly with an old farm fence-line. South of the fence-line, a discontinuous, but extensive, fine-textured horizon was present at a depth of approximately 2 m, while north of the fence-line, the upper limit of the fine stratum was about 3 m deep. The fine subsoil horizon was later shown to contain higher CEC and more extractable K than overlying B and C horizons (White & Leaf 1964, 1965). It was hypothesized that, if trees have active roots in the fine subsoil lenses, then they may be able to mobilize K that would not otherwise be available (White & Wood 1958). Debate focused on whether the differential growth was attributable to the shallower depth to the fine layer, and consequent greater root accessibility to potential nutrient and moisture stores south of the fence-line (White & Wood 1958); or to antecedent nutrient conditions caused by differing prior farming impacts on either side of the fence (Heiberg & Lowenstein 1958). Ultimately, a combination of the two may be true, since agricultural land-use was likely influenced by original forest vegetation, which, in turn, may have been affected by the shallow fine layer.

Work on the Pack Forest Plain in the 1960s emphasized quantification of plant response to fertilization (Madgwick et al. 1970; Heiberg et al. 1964), along with further study of factors affecting the availability of potassium to roots (Leaf et al. 1971; Hart et al. 1969; White & Leaf 1964). The difference between fertilized and unfertilized red pine growth remained pronounced 20 years after fertilizer application (Madgwick et al. 1970). In addition to biomass, the concentrations of nutrients in various tissues of fertilized trees and their underlying soils were higher than in unfertilized trees (White & Leaf 1965).

Heiberg et al. (1964) suggested that the nutrient status of the unfertilized stands would gradually converge toward the steady state achieved in the treated sites: "... reforestation following severe site degradation, as by exploitative agriculture, would tend to cause a gradual return to inherent site conditions. In this case, successful fertilization would be expected to increase the rate of regression towards a stable forest-soil relationship and so give a longer lasting response in growth."

In the 1980s biogeochemical research at Pack Forest diverged in three directions: (1) distinguishing effects of atmospheric acid deposition from the effects of different tree species on soil development (LeBlanc et al. 1987; Nowak et al. 1989); (2) formulating an ecosystem nutrient budget to account for influxes and losses of nutrients in fertilized and unfertilized red pine stands (Shepard & Mitchell 1991; Shepard et al. 1990); and (3) testing the hypothesis of Heiberg et al. (1964) that the K status of unfertilized stands is gradually improving toward the steady state achieved in fertilized stands (Nowak et al. 1991).

Nowak et al. (1991) resampled soil from all of the K fertilized and unfertilized red pine plots that had been sampled in the previous four decades. They confirmed the hypothesis that the unfertilized red pine stands were improving toward a steady state achieved by the fertilized stands. They suggested that the deep subsoil nutrient reserves from the fine-textured substratum was the source of the relatively higher rate of K accrual in the unfertilized soils than in the fertilized soil (cf. Buxbaum 1994).

The Rb/K reverse tracer method

Root preference for one ion species over another was first demonstrated by Collander (1941) in a series of experiments on 22 plant species grown in solutions containing varying concentrations of cations. Collander showed, for all species examined, that Rb is absorbed and translocated as readily as K. The inability of plant roots to distinguish between Rb and K, both monovalent cations of similar atomic radius, serves as the basis for the Rb/K reverse tracer method.

Soils and plants contain both K and Rb in locally distinct, but constant proportions. Noting this, Hafez and Stout (1973) devised a study that relied on the fraction of naturally occurring Rb in soils as a tracer to determine the source and fate of soil and plant K. Commercial fertilizers have negligible Rb/K ratios compared with natural soils. Thus, Hafez and Stout were able to measure the amount of K derived from a fertilizer application by comparing the Rb/K ratio in the fertilized barley foliage with the Rb/K ratio in an unfertilized foliage from plants grown on the same soil. If the plant absorbs fertilizer, then the Rb/K ratio is proportionally lower than in the control.

Two later studies applied the Rb/K reverse tracer technique to examine forest nutrient cycling (Stone & Kszystyniak 1977; Stone 1981). In the 1977 study, the researchers estimated the amount of K remaining in two red pine stands from single applications of K fertilizer 23 and 9 years earlier. They determined the percent of potassium derived from fertilizer as:

$$\%\text{K from fertilizer} = \frac{100 * (\text{Rb/K})\text{control} - (\text{Rb/K})\text{fertilized}}{(\text{Rb/K})\text{control}}$$

Much of the K cycling in fertilized red pine stands was directly attributable to fertilizer added decades earlier. Stone (1981) used the Rb/K reverse tracer method to examine forest nutrient cycling in various other conifer and deciduous forest tree species, and reaffirmed the axiom that conifer forest systems tend to be more conservative that hardwoods.

Materials and methods

Site description

The study site has been described in detail in numerous publications over the past five decades (Heiberg & White 1951; Heiberg & Leaf 1961; Leaf 1970; Nowak 1986; Shepard et al. 1990). The Pack Forest Plain is a 48.5-ha glacio-fluvial outwash sand-plain, located 7 km north of Warrensburg, New York. The climate is cool continental, with mean January temperatures of –7 °C, and July temperatures of 22 °C. The growing season lasts from early May to late September. Total precipitation averages approximately 1000 mm annually. The soil is classified as a Plainfield loamy sand (Mesic Agriudipsamment) up to 9m deep (SCS 1989). The mineral soil is uniformly textured coarse sand to a depth of 1 meter, but is highly stratified with very fine sand and silt lenses below 2 m depth in the southern end of the site and below 3 meters depth in the northern end.

After clearing the wild shrub vegetation on The Plain, the New York State College of Forestry planted experimental stands of red pine and various other conifer species from 1928 to 1932. In a series of fertilizer studies, from 1942 to 1951, pure potassium salts (primarily KCl and K_2SO_4) were applied directly to 16 red pine plots ranging in size from 0.04 to 0.2 ha, at elemental K rates varying from 56 to 336 kg/ha. Nine control plots, ranging in size from 0.02 to 0.2 ha were not treated with any type of fertilizer.

Historic soil sampling and analysis

The long-term database used in this study was compiled by Nowak et al. (1991). From 1949 to 1956, 15 random soil cores from 0 to 15 cm depth were composited from each plot (Heiberg & White 1951; Anonymous 1957). From 1959 to 1961, five subsamples were composited by depth from each of three randomly located soil pits in each plot, from depths of 0 to 10 cm and 10 to 20 cm (Madgwick 1962). In 1962, one large soil pit was excavated at the center of each plot and four samples taken from each soil horizon from each side of the pit (White 1964). In 1984 and 1985, samples were obtained from 4 to 10 small soil pits in each plot, from depths of 0 to 7.5 cm and 7.5 to 15.0 cm (Nowak 1986; Downard 1988). Samples from 1987 were composited from 5 subsamples collected using a 3-cm diameter sampling tube from 0 to 8, 8 to 15, and 15 to 45 cm depths (Shepard & Mitchell 1990). In developing the historical database, Nowak et al. (1991) formulated depth-weighted averages to standardize all collected soil sample data to a 0 to 15 cm depth, defining the Ap horizon.

Soil samples were collected in the summer in all years. Mineral soil samples were air-dried and sieved through a 1-mm mesh (1949 to 1957) or 2-mm mesh (1959 to present). Oven-dried (105 °C) subsamples were washed with 1N ammonium acetate, pH 7.0 buffered, to extract exchangeable cations. Prior to 1965, cations in the extractant were determined using flame emission spectrophotometry; while after 1965, atomic absorption spectrophotometry was used to measure concentrations of extracted cations. Soil pH was measured from a glass electrode immersed in a 1:1 or 1:2 soil/water paste (Downard 1988).

Current soil sampling and analysis

Twenty-five red pine plots that had each been sampled at least twice previously, beginning at least 30 years prior to 1992, were resampled in July and August of 1992. Composite forest floor samples were collected by cutting seven to ten 0.3-m^2 squares randomly from the forest floor. Samples from horizons O1 and O2 were collected and analyzed separately. In each plot, composite mineral soil samples were gathered using a 2.5-cm diameter punch tube. Samples were divided into three depth classes, which were composited from 25 to 45 cores per plot from the Ap horizon (0 to 15 cm) and B horizon. While depth classes were selected to conform to available data, they also approximate the horizon depths for a Plainfield loamy sand, 0 to 3 percent slope (SCS 1989). All soil samples were collected at least 2 m from the boundaries of any of the plots. All 1992 mineral soil samples were air-dried and sieved through a 2-mm screen. Forest floor samples were dried to constant weight at 65 °C and ground in a Wiley mill to pass a 2-mm sieve. Exchangeable cations were extracted from the mineral soils using 1N ammonium acetate (pH 7 buffered) and extractant cation concentrations were determined using a Perkin-Elmer 3038B atomic absorption spectrophotometer. Soil cation content was corrected for soil moisture content. Soil pH was measured in a 1:2 soil and water suspension using an Orion Research Model 601A. Ten gram forest floor samples were ashed at 470 °C for 48 hours and the ash dissolved in HCl. Litter K and Rb concentrations were determined by atomic absorption spectrophotometry (Perkin-Elmer 3038B).

Long-term trend analysis

In earlier analyses of long-term soil data from Pack Forest, K and pH data were grouped into year or decade classes (Downard 1988; Shepard et al. 1990; Nowak et al. 1991). The earlier statistical analyses did not account for temporal autocorrelation between repeated measurements from the same sites. This problem was amplified by the fact that some plots were sampled more frequently than others and therefore contributed more weight to the analysis. The parameter of interest in the historic analysis is the mean per-plot trend in soil K, therefore plots are the true experimental units. Analyzing trends based on the number of plots in which measurements were made results in a more conservative means comparison (Meredith & Stehman 1991).

The slope of the linear regression describing soil K concentrations and pH by horizon as a function of time in each plot was determined; and the mean slopes of the fertilized and unfertilized treatments were compared with a one-tailed t-test ($\alpha = 0.05$). Two hypotheses were tested for each parameter of interest: (a) do the slopes significantly differ? (H_0: $\mu_{\text{fertilized}} = \mu_{\text{control}}$); and (b) are the slopes significantly non-zero? (H_0: $\mu_{\text{fertilized}} = 0$; $\mu_{\text{control}} = 0$). In analyzing trends in the Ap horizon, 16 fertilized and 8 control plots each with three or more data points distributed over at least 30 years of the 50-year sampling period were analyzed. One unfertilized plot was omitted from the long-term analysis because it was first sampled only in 1984. For Ap horizon pH and B horizon K, plots with two or more data points were accepted for analysis because fewer plots were available with three or more measurements. The inaccuracy of slopes determined by only two data points is contained within the high variance among the slopes of the response variables over time in each plot. Finally, a comparison of soil Ap Horizon K concentrations in 1984 and 1992 treated and untreated plots was conducted to examine whether or not soil K concentrations are becoming constant over time, which would indicate that the aggrading forest ecosystem was approaching Heiberg's hypothesized equilibrium.

In the case of Ap horizon pH, data from fertilized plots in the 1960s were never collected. The data from unfertilized plots that were collected in the 1960s were omitted from the analysis because Nowak et al. (1989) reported that soil pH across the sampling period from 1949 to 1985 was lowest in the early 1960s, (attributed, in part, to effects of high atmospheric sulfate and nitrate concentrations and consequent acid deposition). As such, including the 1960s data from only unfertilized plots in a comparison of pH trends between fertilized plots and unfertilized plots would bias the comparison.

Litter sampling and analysis

In July and August, 1992, composite forest floor samples were collected by cutting seven to ten 0.3-m^2 squares randomly from the forest floor of the 16 fertilized and 9 unfertilized plots. Samples from horizons O1 and O2 were collected and analyzed separately; (however, only O1 horizon results are reported because much of the K had leached from the O2 horizon). All samples were collected at least 2m within the boundaries of any of the plots. Forest floor samples were dried to constant weight at 65 °C and ground in a Wiley mill to pass a 2-mm sieve. Ten gram forest floor samples were ashed at 470 °C for 48 hours and the ash dissolved in 10N HCl. Litter Rb and K concentrations were determined using a Perkin-Elmer 3038B atomic absorption spectrophotometer.

Lateral fertilizer transport data analysis

The litter Rb/K ratios of unfertilized red pine plots were graphed with respect to the distance from the center of each unfertilized plot to the center of the nearest fertilized plot. The non-linear curve described by the data was then determined using the SIMPLEX algorithm (Caceci & Cacheris 1984) to calculate an exponential saturation equation of the form: $y = a(1 - e^{bx}) + c$.

The distance from the center of each of the nine unfertilized plots to the center of the respective nearest fertilized plot was measured in the field, and ranges from 19 to 245 m. In order to estimate the maximum distance to which fertilizer applied 50 years ago has been transported, the section of the curve that approaches horizontal was determined. The data were divided into sequential overlapping groups of 4 data points, based on distance (i.e. 19, 20, 20, and 23 m; 20–29 m; 20–32 m; 23–40 m; 29–60 m; and 32–245 m; named groups 1 to 6 respectively). A 1-way ANOVA and Fisher's protected least significant difference (FPLSD) comparison of means of the 6 sequential groups of four Rb/K data points was employed to distinguish the separation among the 9 unfertilized plots into 2 groupings: plots uninfluenced by K-fertilizer ("control"), and plots to which fertilizer has migrated ("affected"). Finally, by comparing the ratio of Rb to K in the O1 horizon of "control" unfertilized plots with "affected" unfertilized and "fertilized" plots, the proportion of K derived from fertilizer in the two classes of fertilizer impacted plots was determined.

Analyses of variance were examined among "control", "affected", and "fertilized" plots for mean O1 horizon Rb/K ratio, O1 horizon and Ap horizon K concentrations, and Ap horizon K long-term trends, to determine whether lateral transport of fertilizer from fertilized plots to unfertilized has influenced the total amount and dynamics of K in unfertilized plots.

Table 1. Summary results of statistical tests of mean long-term linear trends in Ap horizon (0–15 cm) and B horizon (15–30 cm) exchangeable K and other soil nutrient characteristics between K-fertilized and unfertilized red pine plots on the Pack Forest Plain. P-values show results of single sample t-tests (H_o: fertilized and unfertilized slope = 0), or two sample t-test (H_o: fertilized slope = unfertilized slope)

Variable	Single sample t-tests		Two sample t-test
	Fertilized trend	Unfertilized trend	Mean difference between trends
Ap Horizon Potassium ($cmol_c kg^{-1} yr^{-1}$)	0.00031 n = 16 p = 0.01	0.00058 n = 8 $p < 0.01$	fert. < unfert. p = 0.08
B horizon Potassium ($cmol_c kg^{-1} yr^{-1}$)	0.00043 n = 2 p = 0.07	0.00021 n = 6 $p < 0.01$	fert. > unfert. p = 0.02
Ap Horizon pH (pH units/yr)	–0.0099 n = 8 $p < 0.01$	–0.011 n = 4 $p < 0.01$	fert. = unfert. p = 0.30

Results

Effect of K fertilization on long-term soil characteristics under aggrading red pine plantations

Over the past five decades, exchangeable K concentrations in the Ap horizon of both fertilized and unfertilized red pine on the Pack Forest Plain have been increasing significantly (Table 1). The mean linear trends under fertilized and unfertilized plots demonstrate the gradual convergence of exchangeable K under unfertilized plots toward concentrations in fertilized plots. Although the p-value is slightly high (p = 0.08), we accept the inference that accrual of exchangeable K under unfertilized red pine is occurring at a greater rate than under fertilized plots. However, we believe that K fertilizer broadcast 50 years ago has spread laterally into several of the unfertilized plots.

In the B horizon, there has been a significant increase in exchangeable K under both fertilized and unfertilized plots (Table 1). But opposite Ap horizon trends, B horizon K concentrations under fertilized plots have increased at a significantly higher rate than under unfertilized plots.

Soil pH in the Ap horizon of fertilized and unfertilized red pine plots declined significantly from 1949 to 1992 (Table 1). Mean rates of pH

Table 2. Summary results of t-tests of mean 1992 mineral soil and forest floor characteristics under K fertilized and unfertilized red pine on the Pack Forest Plain. p-values show results of two-sample t-tests

Variable	Ap (0–15 cm)		(15–30 cm)		C (30–60 cm)	
	Fertilized	Unfertilized	Fertilized	Unfertilized	Fertilized	Unfertilized
a. Mineral soil horizons						
Exchangeable K	0.058	0.049	0.018	0.015	0.014	0.011
($cmol_c kg^{-1}$)	$p < 0.01$		$p = 0.02$		$p = 0.03$	
pH	4.90	4.92	5.27	5.32	5.35	5.38
	$p = 0.32$		$p = 0.20$		$p = 0.33$	
Bulk density	1.045	1.090	1.122	1.179		
($g\ cm^{-3}$)	$p = 0.03$		$p = 0.07$			

Variable	O1 (Oi)		O2 (Oa + Oe)	
	Fertilized	Unfertilized	Fertilized	Unfertilized
b. Forest floor horizons				
K concentration	0.61	0.57	0.60	0.58
($g\ kg^{-1}$)	$p = 0.07$		$p = 0.25$	

change between fertilized and unfertilized plots did not differ significantly. Inverse logarithmic transformation of the pH data into linear hydrogen ion concentration did not affect significance of statistical results.

1992 soil conditions

Five decades after K fertilization, treated plots contained significantly greater concentrations of exchangeable K than unfertilized plots in all mineral soil horizons (Table 2a). Mineral soils under fertilized red pine had significantly lower bulk densities than unfertilized plots, possibly reflecting greater root mass under fertilized sites. There was a higher concentration of K in the O1 horizon under fertilized plots than under unfertilized plots (Table 2b). However, this difference is less significant statistically than the differences in mineral soil K. Effects of K-fertilization are unapparent in the O2 horizon, where no significant difference between K concentrations in fertilized and unfertilized plots can be inferred.

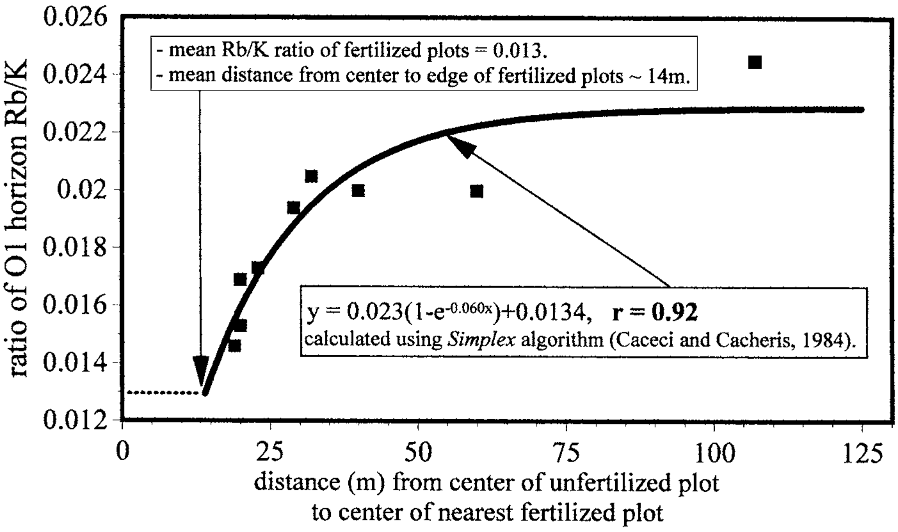

Figure 1. Exponential saturation regression of 1992 O1 horizon Rb/K ratio in unfertilized red pine plots with respect to distance from nearest potassium fertilized plot on the Pack Forest Plain.

Extent of K fertilizer transport

The Simplex algorithm (Caceci & Cacheris 1984), used to calculate the non-linear curve described by the litter Rb/K ratios of the nine unfertilized red pine plots with respect to the distance from the center of each plot to the center of the nearest fertilized plot, yielded the equation: $y = 0.023(1 - e^{-0.060x}) + 0.0134$, where x is the distance (meters) from unfertilized to fertilized plots and y is the O1 horizon Rb/K ratio (Figure 1). The calculated exponential saturation curve is very closely correlated with the observed Rb/K data ($r = 0.92$).

Six overlapping sequential groups of 4 data points were compared to estimate the mean distance from fertilized plots to unfertilized where effects of fertilizer transport on Rb/K ratios become negligible (Figure 2). Fisher's protected least significant difference comparison of means of the 6 groups of data are summarized in Table 3. The ANOVA of moving windows of Rb/K values facilitated the division of unfertilized plots into two classes: Unfertilized but "affected" by fertilizer migration ($n = 4$), and unfertilized "controls" ($n = 5$).

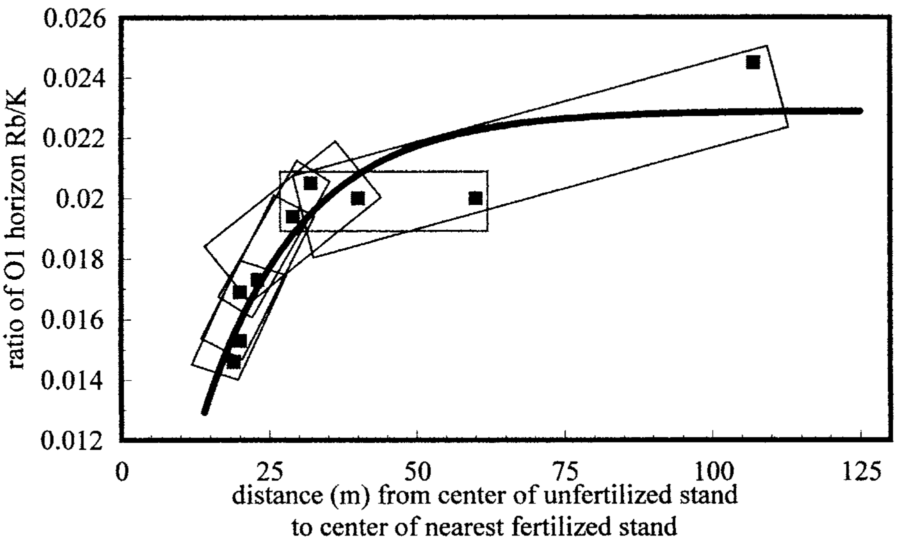

Figure 2. Six sequential sets of four consecutive experimental units along exponential saturation regression of 1992 O1 horizon Rb/K ratio in unfertilized red pine plots on the Pack Forest Plain.

Table 3. Results of ANOVA means comparisons of sequential "windows" of *four* experimental units along the curve delimited by unfertilized O1 horizon Rb/K with respect to distance from center of unfertilized plot to center of nearest fertilized plot

Group of 4 plots	Mean Rb/K ratio*	Mean distance
Group 1	0.0160 **A**	20.5 m
Group 2	0.0172 **AB**	23.0 m
Group 3	0.0185 **B**	26.0 m
Group 4	0.0193 **BC**	31.0 m
Group 5	0.0200 **C**	40.3 m
Group 6	0.0213 **C**	59.8 m

*group mean Rb/K ratios labeled with the same letter are not significantly different: FPLSD (α = 0.05).

Conservation of fertilizer K

The proportion of K derived from fertilizer in fertilized and affected plots was determined by comparing the Rb/K ratios in the O1 horizon with the Rb/K ratio of true "control" plots (Stone & Kzystyniak 1977). The results indicate that fertilizer applied five decades ago accounts for 36% of the potassium

Table 4. Proportion of litter K derived from single fertilizer applications 50 years prior to sampling under K-fertilized, fertilizer "affected", and control red pine plots on the Pack Forest Plain, determined using Rb/K reverse tracer method

	Fertilized	Affected	Control
Mean Rb/K ratio	0.0134	0.0160	0.0209
Standard error	0.0024	0.0013	0.0021
% K from fertilizer	35.8%	23.4%	

Table 5. Results of least significant difference (FPLSD) comparisons of means of K-Fertilizer related soil parameters in "fertilized", fertilizer "affected", and "control" red pine plots on the Pack Forest Plain

Parameter	Fertilized mean	Affected mean	Control mean
1992 O1 horizon Rb/K ratio	0.014 n = 16 **A***	0.016 n = 4 **A**	0.021 n = 5 **B**
1992 O1 horizon K (g/kg)	0.061 n = 16 **A**	0.061 n = 4 **A B**	0.053 n = 5 **B**
1992 Ap horizon K ($cmol_c kg^{-1}$)	0.058 n = 16 **A**	0.052 n = 4 **A B**	0.046 n = 5 **B**
50-year Ap K trend ($cmol_c kg^{-1} yr^{-1}$)	0.00031 n = 16 **A**	0.00047 n = 3 **A**	0.00064 n = 5 **A**

n = sample size.
*Treatment means *across rows* marked by different letters are statistically different (α = 0.05).

cycling in "fertilized" plots, and 23% of the K in nearby "affected" plots (Table 4).

Effect of lateral fertilizer transport on long-term K dynamics

Rb/K ratios are inversely proportional to relative influence of fertilizer K. ANOVA and means comparison of various soil characteristics related to K-fertilization also demonstrates a gradient from "fertilized" to "affected" to "control" plots (Tables 5 and 6).

Table 6. Results of single-sample t-tests of long-term linear trends in Ap horizon (0–15 cm) exchangeable under fertilized, fertilizer "affected", and control red pine plots on the Pack Forest Plain; p-values show results of single sample t-tests (H_o: slope = 0)

Variable	Fertilized trend	Affected trend	Control trend
Ap Horizon Potassium ($cmol_c kg^{-1} yr^{-1}$)	0.00031 n = 16 p = 0.01	0.00047 n = 3 p = 0.03	0.00064 n = 5 p < 0.01

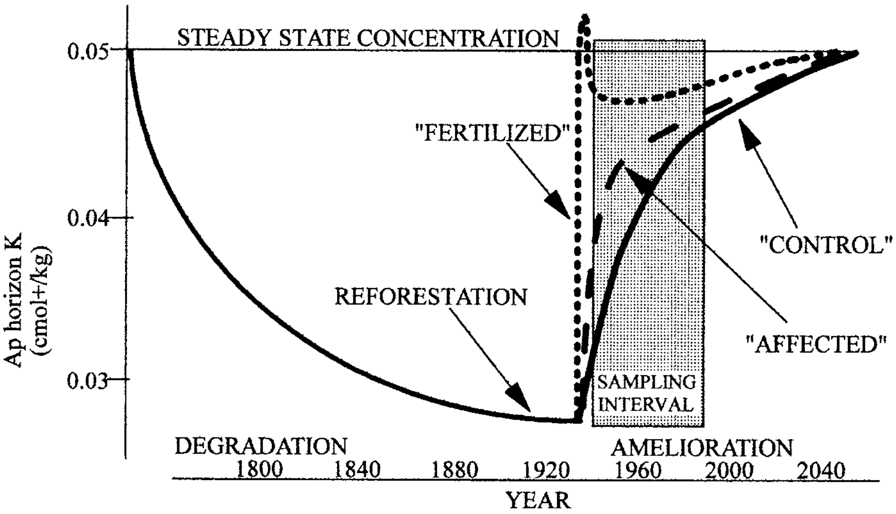

Figure 3. Hypothetical effects of degradation and amelioration on Ap horizon exchangeable K on the Pack Forest Plain, based on suggested treads among "fertilized", fertilizer "affected", and "control" plots (adapted from Nowak et al. 1991).

Discussion

Soil K trends

The portion of Figure 3 highlighted in a shaded box represents the sampling interval covered in the present study. The rates of K increase in the Ap horizon of fertilized and unfertilized plots suggest that K concentrations will converge in 2–3 decades, approximately 80 years after fertilization. The observation that B horizon soil exchangeable K concentrations are increasing more rapidly in fertilized plots than in unfertilized can be attributed to the effects of gradual illuviation of Ap horizon K to the lower B stratum. It would be anticipated that this process would occur at a greater rate under fertilized plots, where potassium concentrations in the Ap horizon exchange complex are higher than in unfertilized plots. Results from Crocker and Major (1955) suggest that the effects of surface cations leaching to the B horizon become observable after 30 to 70 years of soil development.

In 1992, significant effects of fertilization 5 decades earlier remained. This reflects the sustained and ongoing improvement elicited by K-fertilization on the nutrient status of the treated red pine. Forest floor layers (especially the O2 horizon) show no differences in K from past fertilizer treatment due to the rapid mineralization of K from litter and its subsequent transport to underlying mineral horizons.

The overall decrease in Ap horizon pH over the 50-year period is typical of conifer plantation development, caused by the accumulation of soil organic matter, increased rates of soil respiration; base cation removal via uptake, leaching or cation exchange; and possibly increased exchangeable aluminum (Reuss & Johnson 1986; Knoepp & Swank 1994). It was anticipated that fertilized plots would exhibit a greater decline in pH than unfertilized plots due to higher organic matter content related to increased root density and turnover, and higher rates of litter production resulting from more vigorous stand development. However, no significant differences in pH trends between unfertilized and fertilized plots were observed.

Downard (1988), examining only unfertilized plots, found that the trend in pH does not conform to a simple linear model. Ap horizon pH decreased dramatically from the 1940s to the 1960s and has increased slightly since then. Nowak et al. (1989) found that the pH increase from the 1960s to the 1980s was not significant. The significant pH decline over the first two decades accounts for the majority of change over the 50-year sampling interval, which is logical given the early change from sparse vegetation to dense pine plantations. While 1960s pH data are only available from unfertilized plots, it is probable that similar soil pH dynamics apply to fertilized plots as well.

Effects of aggrading forests on soil fertility

Nutrient loss can occur in forest soils if the combination of nutrient uptake by plants and leaching past the rooting zone exceeds influx of previously unavailable nutrients. A decrease in soil pH over 20 years in both mixed hardwood and white pine watersheds in North Carolina is due primarily to uptake of cations, evidenced by a corresponding decrease in base saturation (Knoepp & Swank 1994; Alban 1990). Johnson and Todd (1990) showed that accelerated Mg leaching from the Walker Branch watershed in Tennessee was due to atmospheric inputs of sulfate.

Most workers have found net accrual of nutrients in aggrading forest ecosystems. K increase in Hubbard Brook soils eight years after a 1984 whole-tree harvest was attributed to increased K mineralization and weathering (Romanowicz et al. 1996). Rolfe and Boggess (1973) found that aggrading pine and hardwood stands in southern Illinois exhibited increased soil Mg, Ca, and bulk density. Factors that contribute to soil nutrient amelioration include: increased cation exchange capacity (CEC) due to accumulation of soil organic matter (Fisher 1990); and concentration of nutrients from the soil rooting volume by plant nutrient uptake and return to the surface soil (Stone 1975).

In the analysis of 50-year trends of K in the Ap horizon (0–15 cm), both fertilized plots and unfertilized red pine plots show significant increases in exchangeable K. Potential sources of increasing K in the surface mineral soil horizons at Pack Forest include atmospheric deposition, weathering, and concentration of nutrients in the surface horizons by intrasystem cycling. Likens et al. (1994) showed that K deposition in the northeastern United States is a relatively insignificant factor in forest nutrient cycling, and Shepard and Mitchell (1990) determined that atmospheric inputs at Pack Forest are slightly lower than leaching losses as measured by 45-cm deep lysimeters. The significant uptake of nutrients from depths of 2 to 3 meters, and the presence of fine textured strata at these depths, suggest that the "bottom" of the Pack Forest Plain ecosystem is much deeper than 45-cm (Buxbaum 1994). Potassium leaching to depths of 3m cannot be considered lost from the system.

With a p-value of 0.08, analysis of the long-term trends suggests that exchangeable K concentrations in unfertilized plots have increased at a higher rate than in fertilized plots over the past 50 years (Table 1). The lateral migration of fertilizer outward from fertilized plots to unfertilized may explain this observed trend. In fertilized plots, the only sources of increasing K in the Ap horizon subsequent to fertilization are atmospheric deposition, weathering from the entire rooting volume, and concentration from deeper soil layers. However, in some unfertilized plots (i.e. fertilizer "affected" plots), an additional source of K is the movement of fertilizer from nearby fertilized plots.

Extent of K fertilizer transport

The K fertilizer broadcast five decades ago contained negligible amounts of Rb, whereas the natural K minerals in the ecosystem contain a relatively consistent proportion of weatherable Rb that is biogeochemically cycled along with soil K. The extent to which lateral migration of fertilizer K from nearby fertilized plots is the source of K in unfertilized plots is manifest in the lower Rb/K ratios of unfertilized plots next to fertilized plots. Visual examination of the Rb/K curve suggests that K fertilizer has influenced the Rb/K ratio of plots whose centers lie up to 25 to 30 meters from the nearest fertilized plot (Figure 1). The average distance from the center to edge of fertilized plots is approximately 14 meters; therefore the distance to which K fertilizer has dispersed beyond fertilized plot boundaries is estimated to be 11 to 16 meters.

Table 1 affirms the approximation based on visual examination of the curve delimited by the data. The one-way ANOVA and FPLSD means comparison distinguishes the nine unfertilized K plots into two groups: Plots apparently uninfluenced by fertilizer ("control"); and unfertilized plots to which fertilizer has been transported ("affected"). Among the six overlapping groups of four plots, group 3 demarcates a boundary between unfertilized plots affected by fertilizer and those uninfluenced by lateral K transport. Two clusters along the Rb/K gradient can be identified. The first four data points appear clustered about the value 0.016 Rb/K; while the more distant five data hover around the 0.020 Rb/K ratio; only group 1 (the first four data) and groups 5 and 6 (the subsequent five data) have means that are completely distinct from one another. The results of this analysis suggest that the 50-year lateral spread of K extends approximately 26 meters from the center of the nearest fertilized plot to respective unfertilized plots.

In sum, these results confirm the hypothesis that significant lateral transport of surface broadcast fertilizer, applied over 50 years ago, has occurred. Fertilizer flow extends approximately 11 to 16 meters from the edges of fertilized plots (i.e. 25 to 30 meters from the centers). The four unfertilized plots closest to fertilized plots have been significantly affected by inputs of fertilizer K, while the remaining five plots are relatively unimpacted. These results demonstrate the need for adequate buffer zones between experimental units in long-term biogeochemical experiments and to prevent contamination of wetlands and aquatic ecosystems.

Several factors probably contribute to the redistribution of nutrients in forested ecosystems. Red pine roots have been observed to grow laterally across distances of 9 m (Stone & Kalisz 1991; Leonard et al. 1971). In addition, red pine roots can undergo extensive root grafting (Klepzig et al. 1991). Lateral root redistribution of nutrients by dense surface roots and associated mycorrhizal fungi has been shown to concentrate nutrients in agroforestry systems (Tomlinson et al. 1995) and in forest soils in Poland (Pietrzak-Flis et al. 1996). Slope, wind direction, and the size and shape of leaves are factors that determine horizontal transport of leaf litter (Gaskin et al. 1989; Welbourn et al. 1981). Polglase et al. (1992) showed that fertilizer applied directly to the base of *Pinus elliottii* Engelm (slash pine) trees in a Florida plantation appeared in the inter-row forest floor one year later due to litterfall and throughfall. Finally, soil water does not only flow vertically, especially when downward flowing moisture encounters a textural discontinuity, as occurs along the upper boundary of the silt or fine-sand lenses in the subsoil of the Pack Forest Plain.

Conservation of fertilizer K

The tightness of forest nutrient cycling plays an important role in the amelioration of forest soil fertility (Xue 1996; Fisher 1990). The efficiency of root systems in mitigating nutrient loss has been suggested by Stone and Kzystyniak (1977) who found, using the Rb/K reverse tracer method, that 35–40% of K fertilizer applied to red pine plantations 23 years prior to sampling was still cycling in the ecosystem. The higher proportion of fertilizer K in plots that were fertilized over 50 years ago is within the range found by Stone (1981) to persist in fertilized red pine plantations on outwash sands after 23 years (Table 4). One explanation for the high persistence of fertilizer on the Pack Forest Plain is that the relative initial contribution of fertilizer K may have been proportionally higher than on many of the sites examined by Stone (1981) due to the extreme nature of the K deficiency at Pack Forest. Alternatively, it has been shown that significant uptake of K by red pine on the Pack Forest Plain occurs from deep subsoil fine-textured lenses which underlie the coarse surface soils at depths of 2 to 3 meters (Buxbaum 1994). These lenses may act as a secondary barrier to K loss from the ecosystem; any K that does leach past the surface soil horizons may be retained by this fine subsoil stratum and ultimately taken back up into the active cycling by root uptake.

Effect of lateral fertilizer transport on long-term K dynamics

Fertilized vs. affected vs. control treatment comparison. We divided the plots into three treatments (directly "fertilized", unfertilized but "affected" by fertilizer migration, and unfertilized "control"), and predicted that the Rb/K ratio would be inversely correlated with concentrations of K in the soil and litter. We applied ANOVAs to compare K concentrations in soil and litter between fertilized, affected, and control plots. K concentrations in the O1 horizon and Ap horizon show that concentrations of K in soil of affected plots are intermediate between fertilized and control plots (Table 5).

We also examined the rate of change in K in the Ap horizon the 50-year sampling interval (i.e. linear slope of K concentration) between fertilized, affected, and control plots. We predicted that the affected plots should have higher slopes than unfertilized, since they have higher K concentrations in

Table 7. 1984–1992 eight-year ANOVA comparison of Ap horizon soil Exchangeable-K concentrations under fertilized, fertilizer "affected", and control red pine plots on the Pack Forest Plain

Source of variance	p-value		
ANOVA			
Treatment	0.0021		
Year	0.0001		
Treatment ∗ year interaction	0.5533		
Treatment	**Fertilized**	**Affected**	**Control**
LSD Contrasts			
Mean Ap horizon K ($cmol_c kg^{-1}$)	0.0532 **A**∗	0.0447 **B**	0.0455 **B**
Year	**1984**	**1992**	
Mean Ap horizon K ($cmol_c kg^{-1}$)	0.0433 **A**∗	0.0555 **B**	

∗Treatment means *across rows* marked by different letters are statistically different (α = 0.05).

their soils and have an additional source of K from adjacent fertilized plots. Yet there were no significant differences in mean 50-year trends between fertilized, affected and control plots (Table 5). This may be due to low power in the analysis, or it may be that much of the increase in K observed in affected plots occurred soon after fertilization, and may have preceded the sampling period (Figure 3).

Finally, we performed single sample t-tests on the fertilized, affected, and control Ap horizon K trends to determine if all treatments still exhibit significant increases in exchangeable K over the five decade sampling interval. The results show that all three treatments demonstrate highly significant increases in soil K (Table 6). This result lends strong support to our overall hypothesis that forests ameliorate soil fertility.

1984 vs. 1992 comparison. Between 1984 and 1992, there were not significant differences in soil K trends between fertilized, affected, and control plots, evidenced by the lack of treatment ∗ year interaction (Table 7). Furthermore, there has been a significant overall increase in soil K from 1984 to 1992. The rate of increase over the recent 8-year sampling interval in the control plots also supports the forest amelioration hypothesis: In 1984, the control plots contained 0.041 $cmol_c kg^{-1}$, while in 1992, the concentration of K had increased to 0.046 $cmol_c kg^{-1}$. The difference, 0.005 $cmol_c kg^{-1}$ very closely corresponds to the overall observed rate of K accrual in these plots, 0.00064 $cmol_c kg^{-1} yr^{-1}$ ($0.046 \approx 0.041 + 0.00064 * 8$yrs). These findings suggest that the Pack Forest Plain fertilized and unfertilized plots have not yet approached the convergence suggested in Figure 3; and are still actively accumulating K. The similarity over the 1984–1992 sampling period between K concentrations in control plots and affected plots reinforces the idea that most of the lateral fertilizer movement occurred in the early decades after fertilization.

Conclusion

Ap horizon (0–15 cm) exchangeable K concentrations were shown to have significantly increased over the 50-year sampling period in both fertilized and unfertilized red pine plots. Sources of increasing Ap horizon K include atmospheric deposition, mineral weathering, and uptake from the entire rooting zone, demonstrated to include subsoil strata at depths up to 3 meters below grade. Higher rates of K accumulation in the Ap horizon of unfertilized plots relative to fertilized plots may be due to the transport of fertilizer K from nearby fertilized plots.

The significant lateral redistribution of fertilizer from treated to untreated red pine plots on the Pack Forest Plain suggests that forest plant communities are able to share unevenly available resources over time. This has broad implications for the design of future long-term nutrient manipulation studies. Adequate buffer zones must be instituted to maintain the integrity of an experiment. In the case of The Pack Forest Plain (a sandy, well-drained soil), over the past five decades, fertilizer has moved outward approximately 11 to 16 meters from the edges of fertilized plots. Analysis of litter Rb/K ratios demonstrates that approximately 36% of the potassium in fertilized plots, and 23% of the K in unfertilized plots affected by fertilizer migration are derived directly from the fertilizer applied 5 decades ago, demonstrating the extreme biogeochemical conservativeness of aggrading forests.

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