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ECOSYSTEMS

Tree Harvest in an Experimental Sand Ecosystem: Plant Effects on Nutrient Dynamics and Solute Generation

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ABSTRACT

The hydrochemical signatures of forested ecosystems are known to be determined by a time-variant combination of physical-hydrologic, geochemical, and biologic processes. We studied subsurface potassium (K), calcium (Ca), and nitrate (NO_3) in an experimental red -pine mesocosm to determine how trees affect the behavior of these nutrients in soil water, both during growth and after a harvest disturbance. Solution chemistry was monitored for 2 years at the end of a 15-year period of tree growth, and then for 3 more years after harvest and removal of aboveground biomass. Concentrations were characterized by three distinct temporal patterns that we ascribe to changes in solute generation mechanisms. Prior to harvest, K soil-water concentrations were relatively uniform with depth, whereas Ca soil-water concentrations doubled with depth. Nitrate concentrations were below detection in soil water and discharge (drainage) water. Plant uptake and water/nutrient cycling exerted strong control during this interval. During the 1st year after harvest, K concentrations tripled in shallow soil water, relative to preharvest levels, and showed a strong seasonal peak in discharge that mimicked soil temperature. Summer soil temperatures and annual water flux also increased. Decomposition of labile litter, with complete nitrogen (N) immobilization, characterized this interval. In the third interval (years 2 and 3 after harvest), decomposition shifted from N to carbon (C) limitation, and Ca and NO_3 concentrations in discharge spiked to nearly 200 and 400 μM, respectively. Relatively stable ionic strength and carbonate chemistry in discharge, throughout the study period, indicate that carbonic-acid weathering was sustained by belowground decomposition long after the harvest. This stable chemical weathering regime, along with the persistence of N limitation for a long period after disturbance, may be characteristic of early-phase primary-successional systems.

Key words: biocycling; nutrient cycling; ecosystem disturbance; ecosystem regulation; mesocosm; calcium; potassium.

INTRODUCTION

Bormann and Likens (1967) described the use of small monitored watersheds to study nutrient cycling of intact and experimentally manipulated

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forested ecosystems through time. They proposed a nutrient flux and cycling model focused on biologic, geologic, and meterologic processes, both internal and external to the system, that govern ecosystem nutrient status as it responds to development or to disturbance (Likens and Bormann 1995; Bormann and Likens 1979). Application of the nutrient flux and cycling model to studies of ecosystem disturbance has borne fruit at the Hubbard Brook Experimental Forest (HBEF) (Bormann and others 1974; Hornbeck and others 1986) and elsewhere (for example, Jewett and others 1995). There is now broad recognition that nutrient losses associated with disturbance are due to combinations of changes in water and nutrient uptake, chemical weathering, and decomposition processes that together constitute transient loss of ecosystem control over internal nutrient pools (for example, Likens and others 1970; Dahlgren and Driscoll 1994; Schlesinger 1997). However, watershed-scale mass balance models are limited in their ability to test ideas about how specific sources and/or processes contribute to the nutrient losses, and how these contributions vary with stage of ecosystem development (for example, Vitousek and Reiners 1975; Gorham and others 1979).

The Hubbard Brook sandbox experiment was established in 1982 to reapply the small-watershed technique to outdoor mesocosms characterized by carefully documented construction and uniform initial conditions in the subsurface (Bormann and others 1987). Three sandboxes have water samplers along soil-water flowpaths and are plumbed to measure water drainage from the system. With this experimental control, researchers have isolated and examined processes obscured by complexity and heterogeneity in larger natural systems such as sources of nitrogen (N) to plants (Bormann and others 1993, 2002), chemical weathering and cation exchange (Berner and Rao 1997; Berner and others 1998), hydrology (O'Brien and others 2004), and weathering rates and consequences for nutrient availability (Bormann and others 1998; Kauffman and others 2003).

More recently, we conducted a tree harvest experiment in one of the sandboxes. Our goal was to further elucidate the mechanisms of ecosystem control that result from the interaction of biota and their resources (energy, nutrients, water, space). In this work, we observe how vascular plants affect potassium (K), calcium (Ca), and nitrate (NO_3) in soil water, both during growth and after a harvest, and we identify the processes generating these solutes. By harvesting only the aboveground biomass and minimizing physical disturbance to the soil, we examined compensatory ecosystem processes when root uptake and photosynthesis are abruptly terminated. We also compared growth and harvest effects to baseline changes in an adjacent undisturbed, nonvascular sandbox.

Our objective was to address the following research questions: (a) How do the distributions and dynamics of K, Ca, and NO_3 change in response to aboveground biomass removal and what causes these changes? (b) How does the degree of soil development influence the response to such a disturbance? We hypothesized that immediate increases in soil temperature, soil moisture, decomposition rates, and water discharge would cause large and immediate increases in all nutrient concentrations and fluxes (for example, Bormann and Likens 1979). However, due to small amounts of organic matter and weak soil development in the sandbox, we also hypothesized that our observed concentration changes would be smaller, and of shorter duration, than changes reported from an analogous harvest of a forested watershed with a well-developed soil.

BACKGROUND AND METHODS

Study Location

The HBEF is located in the White Mountains of north-central New Hampshire, USA, and encompasses an area of 3,160 ha. In 1982, 18 sandboxes were constructed and planted with various tree species to study N cycling (Bormann and others 1987). The sandboxes are located approximately 200 m east of HBEF weather station 22, where daily temperature, precipitation amount, and wet/dry deposition data are collected. Mean daily air temperatures at HBEF range from 19°C in July to −9°C in January (Federer 1973). Precipitation averages nearly 130 cm/y for the Hubbard Brook area, averaging 70% as rain and 30% as snow (Bormann and Likens 1979).

Forest floor soil was removed to facilitate the mechanical excavation of square holes for the sandboxes in the underlying well-drained glacial deposits (Bormann and others 1993; details in Ingersoll and others 1987). Three of the larger sandboxes, measuring 7.5 × 7.5 × 1.5 m, were fully lined with impermeable Hypalon geomembrane. Slotted polyvinylchloride (PVC) pipe was placed in a 15-cm layer of 1.9–3.8 cm–diameter gravel in the bottom of these boxes to collect drainage water. The pipes drain into tipping buckets to enable volumetric discharge measurements. The boxes were filled to ground level with 1.3 m of granitic glaciofluvial sand (no more than 0.95 cm). Then 5 cm of native topsoil was rototilled into the top 20 cm of the sand. Beneath this depth, the average grain-size distribution of the sandboxes was 94% sand, 4.5% silt, and 1.5 % clay particles (O'Brien and others 2004).

Two of these sandboxes were studied for this work. One sandbox, referred to as the ''nonvascular'' box, was actively weeded of vascular plants until it was eventually colonized by a lichen (*Cladonia cristatella* Tuck.) and moss (*Polytricum* spp.). Another sandbox, called the ''red pine'' box, was planted with 196 red pine (*Pinus resinosa* Ait.) seedlings in a 0.5-m nodal grid, providing each tree with 0.25 m^2 of growing space. The sandboxes have been as undisturbed as possible, with minimal intrusions including occasional weeding, soil sampling, installation of sampling equipment, and one-time replanting of failed red pine seedlings (Ingersoll, and others 1987). Statistical inference is limited to changes through time in the red pine and nonvascular sandboxes. Standard deviations are provided to describe sample variation within the boxes.

On 1 May 1998, the trees in the red pine box were carefully harvested by hand and all aboveground biomass was removed from the box, leaving only the stumps, roots, and a 5–8 cm-thick layer of twigs, branches, and needles (referred to hereafter as the ''litter layer'') in place. Physical disturbance of the box during the harvest was minimized by the use of wood planks placed upon the stumps to stand and walk on.

Data Collection

Precipitation amounts and samples for chemical analysis were collected from US Department of Agriculture Forest Service weather station 22. Bulk precipitation samples were analyzed at the Institute of Ecosystem Studies, Millbrook, NY for major cations and anions (Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+, NO_3^-, Cl^-, and SO_4^{2-}) (O'Brien 2000). In 1995, soil-water samplers consisting of a fritted glass plate on a cylindrical collection chamber (approximately 50 cm^3), connected to a vacuum pump maintaining a negative pressure equivalent to 255 cm H_2O, were installed laterally in both boxes at depths of 15, 35, and 95 cm below ground surface, with three replicate samplers at each depth (O'Brien 2000; O'Brien and others 2004). Samplers were flushed of any resident liquid prior to each 24-h sampling period.

Soil-water samples were filtered through a 0.2-µm nylon filter in the field, with one aliquot frozen for anion analysis and a second aliquot acidified to below pH 2.0 with HCl for cation analysis. Anions were quantitatively determined by ion chromatography (IC), and cations by either IC (1996–1997) (O'Brien 2000) or inductively coupled plasma spectroscopy (ICP) (1998–2000) (Havig 2002). Discharge-water samples were collected from both sandboxes, volume-weighted, and analyzed at Yale University for major cations using ICP and anions using IC. All ICP and IC analyses had a standard deviation of <5% (Berner and others 1998). Dissolved organic carbon (DOC) and total dissolved N (TDN) were measured by high-temperature catalytic oxidation; dissolved organic N (DON) was determined by the difference between TDN and dissolved inorganic N.

When the trees were removed, aboveground living biomass was separated into foliage, stem, and branches for analysis of biomass weight and nutrient content. Soil cores were collected in each sandbox at multiple locations and at three different times for cation extraction using a conventional ammonium-acetate procedure (Havig 2002). Extractable concentrations reported here correspond to ''exchangeable'' pools in much of the literature (for example, Jobbagy and Jackson 2001).

RESULTS

Data are presented in the context of the three distinct periods that emerged: preharvest, 1 year after harvest, and 2–3 years after harvest.

Preharvest Period

For the 2 years prior to harvest, there were large differences in sandbox discharge and soil temperature between the red pine and nonvascular sandboxes. Water discharge from the red pine sandbox was less than one-half of the discharge from the nonvascular box in water year 1996 and one-fourth of the nonvascular discharge in water year 1997 (Figure 1). The difference in maximum summer soil temperature in the upper 35 cm between the sandboxes was approximately 10°C, with the red pine sandbox having a lower temperature.

Clear patterns in red pine subsurface concentrations of K (Figure 2a) were difficult to discern prior to harvest; red pine ranges were similar to those observed in the nonvascular sandbox (Figure 2d). At some times, the K concentration was greater in shallow red pine soil water than in discharge. However, Ca concentration during the same time period was distinctly different between the boxes.

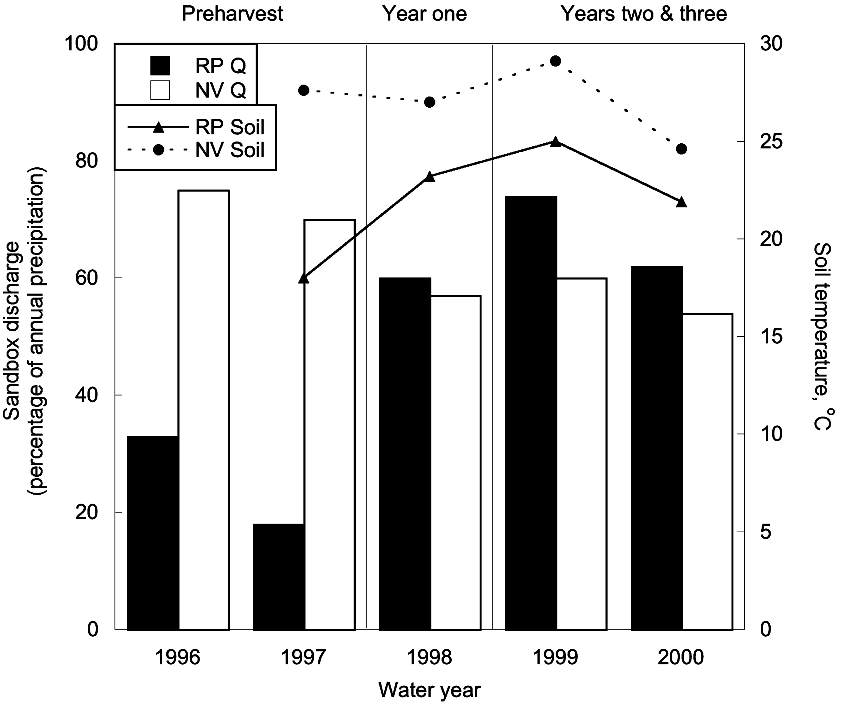

Figure 1. Discharge and soil temperature patterns over time for the red pine (RP) and nonvascular (NV) sandbox ecosystems. Discharge is reported as the percentage of total precipitation for each water year. Soil temperature is mean maximum for the upper 35 cm in each sandbox.

Soil-water concentrations in the red pine sandbox increased with depth, with mean concentrations at 95 cm more than twice as large as concentrations at 15 cm (Figure 2b). In the nonvascular sandbox, no such increase was evident (Figure 2e). While trees were growing, there was also a difference between the two sandboxes in NO_3 patterns. Preharvest NO_3 concentrations in the red pine sandbox (both soil water and discharge) were almost always below the detection level of 2 μM (Figure 2c). Shallow NO_3 concentrations in the nonvascular sandbox (15-cm depth) were as large as 50–100 μM, but concentrations in deeper soil-water and discharge never exceeded 40 μM (Figure 2f).

Soil-extractable cation concentration profiles (Figure 3) reflect 1998 conditions immediately before red pine harvest. At many depths, the differences between the sandboxes were not statistically significant, but the consistencies of the differences over substantial depth intervals are important. The red pine extractable-K profile showed enrichment relative to the nonvascular profile, particularly in the upper 15 cm. The Ca profile, by contrast, showed general depletion in the upper part of the sandbox relative to the nonvascular profile, with slight enrichment in the top 15 cm. The red pine patterns are similar to the patterns shown by the depth profiles of red pine soil-water concentrations described above: little change in K with depth below 15 cm and large increases in Ca with depth below 15 cm.

Year 1 after Harvest

After removal of the trees, water discharge from the red pine box increased significantly during the first year and was equivalent to nonvascular discharge (Figure 1). Loss of tree canopy increased the maximum summer red pine soil temperature by approximately 5°C in the upper 35 cm of the sandbox (Figure 1).

In shallow red pine soil water (15-cm depth), K concentrations more than doubled during the first growing season after harvest (Figure 2a). Concentrations of K in red pine discharge began to show a clear seasonal pattern with a strong correlation to soil temperature; red pine discharge concentrations were two to three times larger than those from the nonvascular sandbox (compare Figures 2a, d). In contrast, the range of subsurface Ca concentrations in the red pine sandbox did not deviate from the preharvest period (Figure 2b). Nitrate concentrations in the red pine sandbox also remained unchanged through out the first growing season, but they increased slightly during the first winter (Figure 2c). The observed stability of Ca and NO_3 is contrary to our hypothesis of rapid increases in all nutrient concentrations after harvest.

Years 2 and 3 after Harvest

Water discharge from the red pine sandbox exceeded discharge from the nonvascular sandbox by

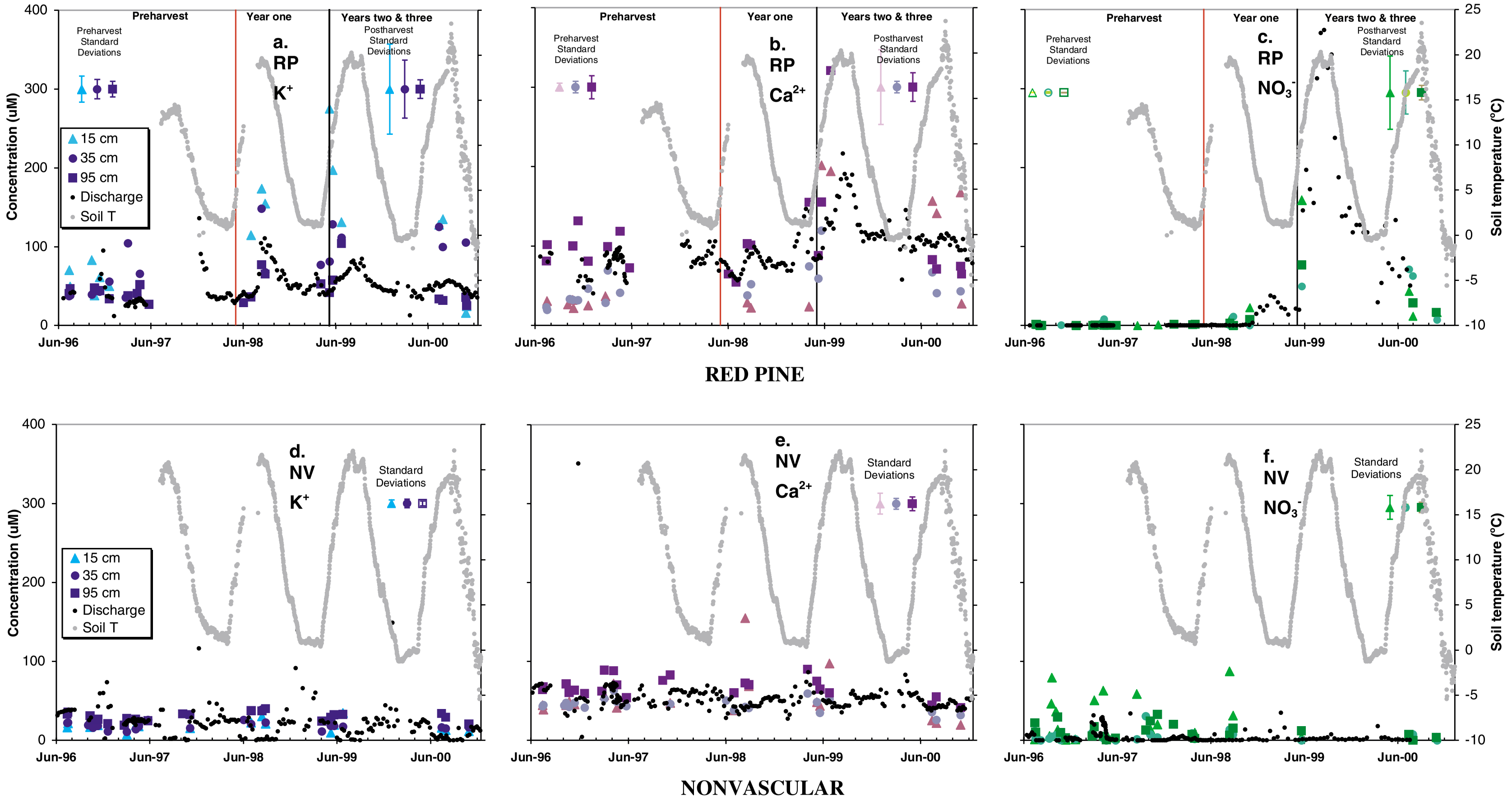

Figure 2. Nutrient concentrations over 5 years in *RP* and *NV* sandbox ecosystems. Red vertical line indicates harvest. *Black dots* represent sandbox discharge samples; *color symbols* represent soil-water samples at various depths (*triangles*: 15 cm; *circles*: 35 cm; *squares*: 95 cm). Standard deviations are reported among replicates. Soil temperature (*grayscale*) is at 95-cm depth. *K*, potassium, *Ca*, calcium, NO_3 nitrate.