

# Contrasts in Carbon and Nitrogen Ecosystem Budgets in Adjacent Norway Spruce and Appalachian Hardwood Watersheds in the Fernow Experimental Forest, West Virginia

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## Abstract

We constructed watershed mass-balance budgets of carbon (C) and nitrogen (N) and measured seasonal net N mineralization in an attempt to account for nearly 40 years of large discrepancies in stream  $\text{NO}_3\text{-N}$  export in two adjacent, gauged watersheds at the U.S.

Department of Agriculture Forest Service's Fernow Experimental Forest, WV. These watersheds have similar management histories, varying primarily by vegetation cover, where one watershed is a monoculture of Norway spruce (*Picea abies*) and the other has regenerated to native Appalachian hardwoods. Long-term stream chemistry indicates that the hardwood watershed has approached N-saturation, with relatively high stream export of nitrate-N (15 kg  $\text{NO}_3\text{-N/ha/yr}$ ), whereas the spruce watershed exports virtually no nitrate-N. We estimated the pool size of C and N within the mineral soil, forest floor, litter, above- and below-ground tree biomass, and stream dissolved organic N. We were unable to account for long-term differences in  $\text{NO}_3\text{-N}$  export via streamflow by estimating these pools. Total C and N pools were 28 percent and 35 percent lower in the spruce watershed, respectively. Though historic organic C and N were never measured in the long-term stream chemistry, the discrepancy in C and N budgets between the two watersheds suggests that the spruce watershed may have been subjected to a period of large losses of C and organic N from deeper subsurface soils. Such large losses suggest that species conversion has the potential

to significantly alter ecosystem C and N budgets, with implications for long-term productivity, C sequestration, and water quality.

**Keywords:** Fernow Experimental Forest, Norway spruce, carbon, nitrogen

## Introduction

Stream chemistry at watershed outlet weirs integrates ecosystem functions (chemical, biological, and physical) and displays responses of the total watershed to alteration. Studies of nutrient mass-balance budgets have been utilized to account for differences in stream chemistry (e.g., lower stream nitrate export) and to identify effects of management regimes on ecosystem processes influencing such differences (e.g., Triska et al. 1984). Conversion of native vegetation to monocultures of conifer may disrupt biogeochemical cycling of carbon (C) and nitrogen (N) (Guo and Gifford 2002).

Two adjacent watersheds within the U.S. Department of Agriculture (USDA) Forest Service's Fernow Experimental Forest (FEF) in West Virginia provide an excellent opportunity to investigate the specific role of tree species in ecosystem N cycling and retention. Long-term stream chemistry of these watersheds indicates divergent export of stream  $\text{NO}_3\text{-N}$  at the outlets. Mean annual stream  $\text{NO}_3\text{-N}$  exported from an experimental 39-yr-old hardwood stand (watershed 7) is nearly 15 kg/ha, whereas stream  $\text{NO}_3\text{-N}$  exported from a nearby experimental 37-yr-old Norway spruce stand (watershed 6) has been nearly zero for 20 years (mean = 0.18 kg/ha/yr).

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The present work is an attempt to account for nearly 40 years of large discrepancies in stream  $\text{NO}_3\text{-N}$  export in two nearly adjacent, gauged watersheds at the FEF using estimates and comparisons of key components of ecosystem C and N budgets. It was hypothesized that because  $\text{NO}_3\text{-N}$  export has been negligible from the spruce watershed, and because inputs to the two watersheds from atmospheric deposition are equal, then C and N pools will have accumulated to a greater extent in vegetation, forest floor, and soil horizons in the spruce watershed because of slower decomposition of organic material and slower nutrient cycling, resulting in low  $\text{NO}_3\text{-N}$  export to the stream.

Specific objectives were to (1) measure selected pool sizes of C and N within each watershed to ascertain if significant differences in these pools occur after nearly 40 years of influences from contrasting forest vegetation and (2) measure rates of net N mineralization to determine if this measure of current N flux was associated with differences in size of selected C and N pools in the two watersheds.

## Methods

### Description of the Watersheds

The watersheds used in this study are located within the USDA Forest Service FEF near Parsons, WV (USA). See Kochenderfer (2006) and Kelly (2010) for complete site descriptions. Both watersheds 6 and 7 (WS6 and WS7) were clearcut-logged in sections (1964–1967) and maintained barren with herbicides until 1969. Watershed 6 (22 ha) was planted with Norway spruce in 1973, but WS7 (24 ha) was allowed to regenerate naturally beginning in 1970. After nearly 40 years of growth, the spruce has a closed canopy and dense stand structure with mean basal area of 23  $\text{m}^2/\text{ha}$ .

Soils in WS6 are mapped as Calvin series (Soil Survey staff, USDA Natural Resources Conservation Service) derived from shale, siltstone, and sandstone parent material. Soils in WS7 are mapped as both Calvin and Dekalb series derived from acidic sandstone parent material. This watershed is dominated by yellow-poplar, red oak, and sugar maple, with mean basal of 17  $\text{m}^2/\text{ha}$ .

Historic  $\text{NO}_3\text{-N}$  export and specific conductivity data from the spruce and hardwood streams indicate close similarity in ecosystem biogeochemical activity at the time of conversion to a Norway spruce stand (Kelly 2010).

### Atmospheric Deposition and Stream Export

Data for wet and dry deposition of  $\text{NO}_3\text{-N}$  were attained from annual records from the National Atmospheric Deposition Program monitoring site WV18 and the CASTnet monitoring site PAR107. Streamflow and weekly  $\text{NO}_3\text{-N}$  concentration data were attained from the USDA Forest Service Timber and Watershed Lab, Parsons, WV. These data were used to calculate total inputs and exports of  $\text{NO}_3\text{-N}$  from the two watersheds for 1973–2009. Total dissolved N was analyzed from 2007–2009 in monthly stream samples from both watersheds in order to determine export values of dissolved organic N (DON) that had not previously been measured in these watersheds.

To determine the potential flux of inorganic N resulting from N mineralization, intact soil cores (0–10 cm) were collected at 12 sampling sites in each watershed. Incubations were performed seasonally for two years to determine temporal differences in net ammonification, nitrification, or immobilization.

### Soil C and N Pools

To estimate C and N pool sizes within surface soil horizons and the forest floor, soil samples were collected in July 2007 from 30 sampling sites within each watershed at each horizon. Soil horizons are defined in these watersheds as A (0–10 cm) and B (10–46 cm).

Forest floor samples were collected in October 2007 and 2009 to characterize depth, oven-dry weight, and total C and N at each sampling location. Freshly deposited litter materials were collected monthly from 2008 to 2009.

### Biomass C and N Pools

Diameters of trees were measured by the USDA Forest Service in 2003. Each individual tree was converted to biomass (kg) using allometric equations for both above- and below-ground (see Kelly 2010 for description of equations). From total above- and below-ground biomass estimates, tree compartment mass and percent C and N were estimated using values published by Whittaker et al. (1974) for the hardwood watershed and by Feng et al. (2008) for the spruce watershed.

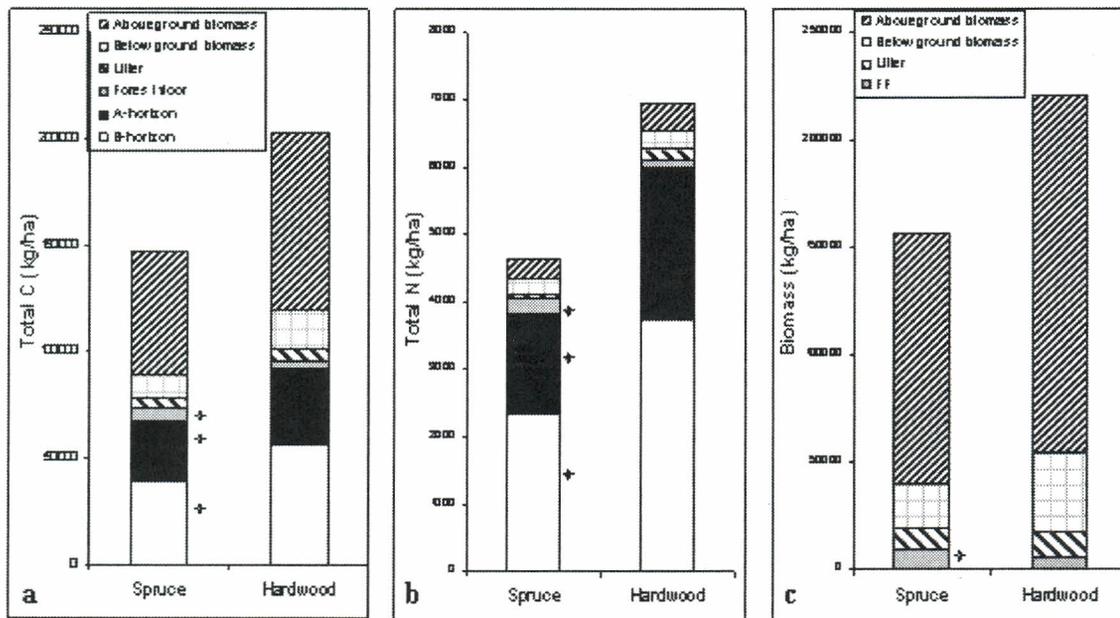


Figure 1. Watershed budgets depicting the mass of (A) carbon, C; (B) nitrogen, N; and (C) biomass contained within each soil and biomass compartment in the spruce (WS6) and hardwood (WS7) watersheds in the FEF. Asterisks denotes significant differences between spruce and hardwood pools at the  $\alpha=0.05$  level.

### Data Analysis

One-way analysis of variance (ANOVA) was performed to determine differences in C and N pool size within each compartment by watershed and in in situ net nitrification and net ammonification annually and within each season by watershed.

### Results

#### Inputs and Exports

Since 1973, combined wet and dry atmospheric deposition of  $\text{NO}_3\text{-N}$  is estimated to be 320 kg N/ha for each of the two watersheds. Total stream export of  $\text{NO}_3\text{-N}$  from the spruce watershed since 1973 is 45.93 kg N/ha, which is only 13 percent of the stream export of  $\text{NO}_3\text{-N}$  that occurred during the same time period in the hardwood watershed, which exported 341.07 kg  $\text{NO}_3\text{-N}$ /ha, exceeding the value of atmospheric deposition by approximately 21 kg N/ha. Annual DON export from the spruce watershed was also very low (mean = 0.477 kg DON/ha/yr) during the three years of measurement. In contrast, annual DON export (mean = 10.03 kg DON/ha/yr) from the hardwood watershed was nearly equal to export of  $\text{NO}_3\text{-N}$  (mean = 10.70 kg  $\text{NO}_3\text{-N}$ /ha/yr).

#### Potential Flux from N Mineralization

Total net N mineralization annual flux was approximately three times greater in the hardwood watershed than in the spruce watershed. Mean annual net N mineralization was approximately 182.50 and 64.0 kg N/ha/yr from the hardwood and spruce soils, respectively.

#### Soil and Forest Floor C and N Pools

Carbon and N pools within the mineral soil horizons were significantly lower in the spruce watershed relative to the hardwood watershed (Figure 1A). Within the A-horizon, spruce soil contained about 20 percent less C (kg/ha) than the hardwood soil (Figure 1A). Within the B-horizon, spruce soil contained approximately 30 percent less C (kg/ha) than the hardwood soil.

A-horizon soil in the spruce watershed contained nearly 35 percent less N than the hardwood soil (2.03 g N/kg in spruce versus 2.93 g N/kg in hardwood) (Figure 1B). Within the B-horizon pool, spruce soil contained nearly 38 percent less N content (kg/ha) than the hardwood soil (0.73 g N/kg in spruce soil versus 1.17 g N/kg in hardwood soil).

Forest floor C content (kg/ha) was significantly greater in the spruce watershed than the hardwood watershed (3,813 and 2,343 kg C/ha in the spruce and hardwood watersheds, respectively) (Figure 1A). Forest floor N (kg/ha) was significantly greater in the spruce watershed than in the hardwood watershed (132.25 kg N/ha versus 74.68 kg N/ha, respectively) (Figure 1B).

### Tree Biomass Pools

Both above- and below-ground biomass in trees, as estimated by allometric equations, were higher in the hardwood watershed (Figure 1C). Above-ground biomass estimates were approximately 30 percent less in the spruce watershed (116,800 kg/ha) relative to the hardwood watershed (166,000 kg/ha). Below-ground biomass estimates were approximately 45 percent less in the spruce watershed (21,000 kg/ha) relative to the hardwood watershed (38,000 kg/ha). This greater biomass in the hardwood watershed equated with larger pool sizes of C and N in the hardwood trees than the spruce (Figure 1A, B).

### Discussion

#### Contrasting Vegetation and C and N Pools

The goal of this study was to quantify selected ecosystem C and N pools in two watersheds that exhibit large differences in long-term stream export of  $\text{NO}_3\text{-N}$  measured since establishment of contrasting forest types in 1973. Results of this study indicate that we were unable to account for these differences in  $\text{NO}_3\text{-N}$  export via streamflow through estimation of the size of C and N pools within the forest floor, mineral soils, above-ground tree biomass, and below-ground tree root biomass in the two watersheds.

Total C and N pools were lower in the spruce watershed in nearly every compartment measured (Figure 1), as was total N mineralization. Total C pools were 28 percent less in the spruce and total N pools were 35 percent less in the spruce relative to the hardwood watershed. The B-horizon soil compartment exhibited the largest difference in both C and N stores (32 percent less C and 38 percent less N in the spruce watershed). These results were contrary to the hypothesis that soil and forest floor C and N stores would be higher in the spruce watershed, thereby accounting for 40 years of relatively high atmospheric N input and very low stream export of  $\text{NO}_3\text{-N}$  from the spruce watershed.

Total N pools in the mineral soil and in tree biomass of two additional watersheds (watersheds 4 and 10) within the FEF are shown in Figure 2. Watersheds 4 and 10 are often used as references because they have been left to natural recovery since being logged in 1905. Comparing the spruce watershed (WS6) to watersheds 4, 7, and 10, which are characterized by native hardwood forests, illustrates that the spruce watershed has considerably less N in the measured pools (Figure 2). It is also noteworthy that the native hardwood watershed of this study (WS7) has similar estimated N pool sizes in soil and biomass as reference watershed 10 (Figure 2).

#### What Accounts for Differences in C and N Pools?

Three possible mechanisms have been identified that could explain why, after 40 years of much lower  $\text{NO}_3\text{-N}$  export and high atmospheric deposition, the spruce watershed does not exhibit patterns of C and N accumulation comparable to the hardwood watershed.

1. The watersheds are intrinsically different, and the spruce watershed has always had much smaller storage of C and N than the surrounding watersheds;
2. The spruce watershed has been losing N via denitrification at a much greater rate than the hardwood watershed for the past 40 years; and (or)
3. The spruce watershed underwent a phase of organic matter degradation when the hardwood stand was replaced by the Norway spruce stand, causing a large amount of organic forms of N to be leached from the system (e.g., Guggenberger et al. 1994).

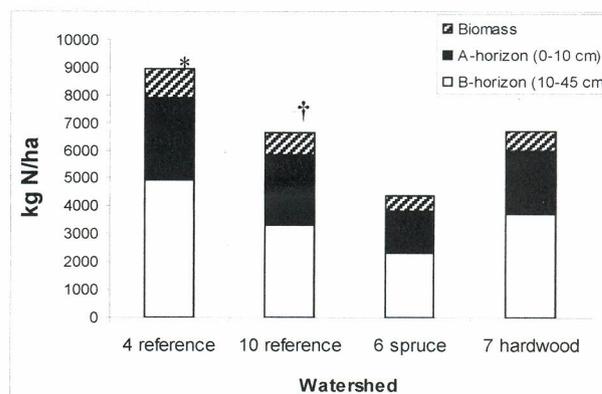


Figure 2. Nitrogen contained within A and B soil horizons and within total biomass (above- and below-ground) for four watersheds within the FEF.

\* from Adams et al. (2006); sampled in 2002

† from Christ et al. (2002); sampled in 1997

It is unlikely that the spruce watershed is intrinsically different from the surrounding hardwood watersheds within the FEF to the degree observed in the present study (Figure 2). The soils within all of these watersheds are of the same soil series and have similar historic land use and atmospheric inputs. Historic  $\text{NO}_3\text{-N}$  export and specific conductivity of streamwater indicate close similarity in ecosystem biogeochemical activity at the time of conversion to a Norway spruce stand. When analyzed by decade after conversion, it can be seen that in the first decade following treatment (1971–1980), patterns of stream  $\text{NO}_3\text{-N}$  values were very similar between the watersheds ( $R^2=0.96$ ). Furthermore, the divergence in specific conductivity did not occur until after the Norway spruce canopy closure occurred ( $R^2=0.20$  after 1981 and  $R^2=0.0005$  after 1991) (Kelly 2010).

Large losses of  $\text{NO}_3\text{-N}$  were not detected in the long-term stream chemistry data for the spruce watershed, suggesting that N might have been lost through fluxes in gaseous phase of  $\text{N}_2\text{O}$  or NO (Reddy and Patrick 1975) and (or) through stream export of DON (Campbell et al. 2000) (also not measured). It is unlikely that denitrification processes can explain the relatively small N pools in the spruce watershed because (1) large fluxes of denitrification usually result in accumulation of C in the organic horizons of soils, which was not observed in the current study, and (2) N losses via denitrification usually account for a small portion of total ecosystem N (Mohn et al. 2000). Additionally, soils in these watersheds are relatively well-drained upland soils with relatively low potential for significant denitrification.

It is more likely that soils within the spruce watershed underwent a phase of organic matter degradation or mass transport of sediment prior to spruce stand establishment, inducing a loss of C and N that was not detected in the long-term stream data that only measured losses of  $\text{NO}_3\text{-N}$  and that did not measure DON or particulate N. This concept of organic matter degradation or mass transport is strongly supported by a chronosequence study of soil C stocks beneath red spruce (*P. rubens*) forests in northeastern North America (Diochon et al. 2009). Soils within these forests exhibited increasingly smaller stocks of C from 1-, 15-, and 45-yr-old stands, reaching a minimum of approximately 76 Mg C/ha in the soil profile at 45 years. Soil C values in the 45-yr-old red spruce stand were very similar to the Norway spruce soils in the present study, which contain 74 Mg C/ha. Carbon loss (decrease in C concentration and content) from young stands in the Diochon et al. study (2009) was reported

to occur through enhanced mineralization of organic compounds (verified with stable C isotopic analysis), especially in the deeper soil horizons. Similar declines in soil C were also observed in spruce forests of similar age by other authors (e.g., Parker et al. 2001, Tremblay et al. 2002), indicating that this rate of C loss from spruce soils is a common phenomenon.

Forest clearing may result in decreases in soil C, but C stores generally recover to original levels after several decades, especially if the stand is allowed to regenerate (Harrison et al. 1995). Loss of soil C upon hardwood conversion to conifer can be attributed to both disturbance and changes in amount and composition of plant material returned to the soil via litter and root turnover (Lugo and Brown 1993). Additionally, the presence of ectomycorrhizal fungi introduced upon vegetation conversion have also been documented to induce a 30 percent soil C depletion within 20 years of establishment of an exotic *Radiata* pine (*Pinus radiata*) plantation (Chapela et al. 2001).

Spruce vegetation has high lignin content in litter materials and shallow rooting architecture. High lignin content results in larger proportions of soil organic N relative to inorganic forms because of slower decomposition and mineralization (Berg and Theander 1984). Shallow rooting architecture may result in leaching of soil C following decomposition of deep roots of the native hardwood that were present prior to conversion, with little subsequent vegetative uptake or stabilization deep in the spruce soil profile. Thus, the spruce features of slowly decomposable organic matter and shallow rooting may help explain the apparent large mass losses of soil C and N relative to the native hardwood in this watershed study.

## Conclusions

Results of this study suggest that a significant loss of C and N from ecosystem pools likely occurred following conversion from native hardwoods to a monoculture of Norway spruce in the FEF. Consequently, species selection should be taken into account when managing forests for future C sequestration, for provision of high-quality water, and for effects of high atmospheric inputs of N, especially when relatively short rotation times are implemented between harvests.

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