Satisfying a Forest's Four-Decade Nitrogen Demand: The Case for Long-term Soil-Ecosystem Experiments

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Frederick Clements (1916):

"Long-term ecological field studies require concerted action such as is unknown at present, but there can be little question that continuous investigations of this nature will soon be organized by great botanical institutions."

The Problem with Understanding Soil and Ecosystem Change:

Soils are open systems that change rapidly in some properties and more gradually in others. Yet quantitative understanding of soil change is remarkably limited, due mainly to the notable absence of long-term studies that investigate soil and ecosystem change over time scales of decades. *Soil science and management can benefit greatly from a network of efficiently operated studies designed to observe soil change over the time scales of decades.*

The Calhoun Experimental Forest:

Effects of forest development on soil and water chemistry are studied at the Calhoun Experimental Forest in the central Carolina Piedmont, a four-decade study with 16 permanent plots, seven soil resamplings, and a comprehensive soil archive. An Ultisol supports the ecosystem, that had previously been managed for cotton, corn, and wheat for about 150 years. In 1957, old cotton fields were planted with seedlings of loblolly pine (*Pinus taeda*), and biogeochemical changes in the old-field forest have been closely observed over the subsequent four decades.

Specific Objectives of the Forest-Nitrogen Project:

At the Calhoun Experimental Forest, the N cycle was examined over the first four decades of pine forest development following over a century of agriculture. Objectives were to evaluate over the time scale of four decades:

(1) soil depletion and resupply,

(2) changes in N bioavailability in forest floor and mineral soil, and ecosystem N accretion.

Site Description of the Calhoun Ecosystem:

Climate: warm temperate regime with annual mean temperature 16°C and precipitation 1170 mm

Soil: Clayey, kaolinitic, thermic Typic Kanhapludult of the Appling series derived from granitic gneiss

Landform: broad interfluve < 3% slope

Land use history: cleared of primary forest in the early 19th century primarily for cotton, corn, wheat.

Four Decades of Pine Growth Substantially Altered Soil N:

When forests establish themselves on old agricultural fields or cutover lands, significant changes can occur to the soil's N capital (Figure 1). Young trees take up large amounts of N, retain a large fraction of N uptake to the forest floor, and eventually the forest floor resupplies mineralizable N for plants and organic and inorganic N to mineral soils (Switzer and Nelson 1972, Wells and Jorgensen 1975). Significant changes in redistribution of N have been quantified in the long-term Calhoun Experimental Forest (Figures 1 to 3).

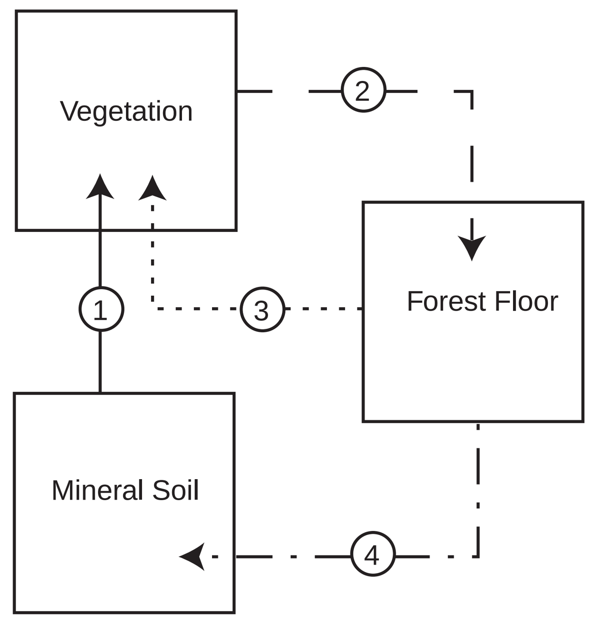

Figure 1. Conceptual diagram of the long-term N cycle in a loblolly pine ecosystem. Changes in N over 35 to 40 years are indicated in the ecosystem's three main components as estimated in eight permanent plots at the Calhoun Experimental Forest, South Carolina.

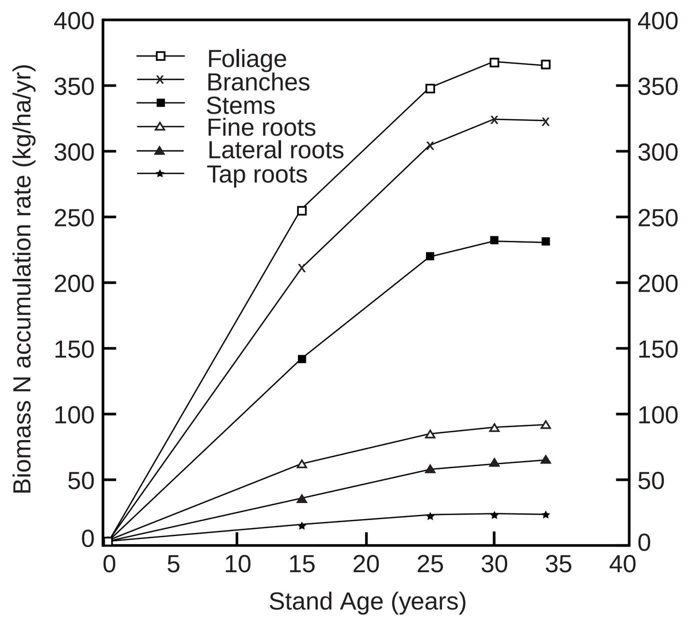

Figure 2. Accumulation of N in tree biomass of the Calhoun Experimental Forest (1957 to 1991). Accumulation rate was most rapid in the first 25 years of forest development.

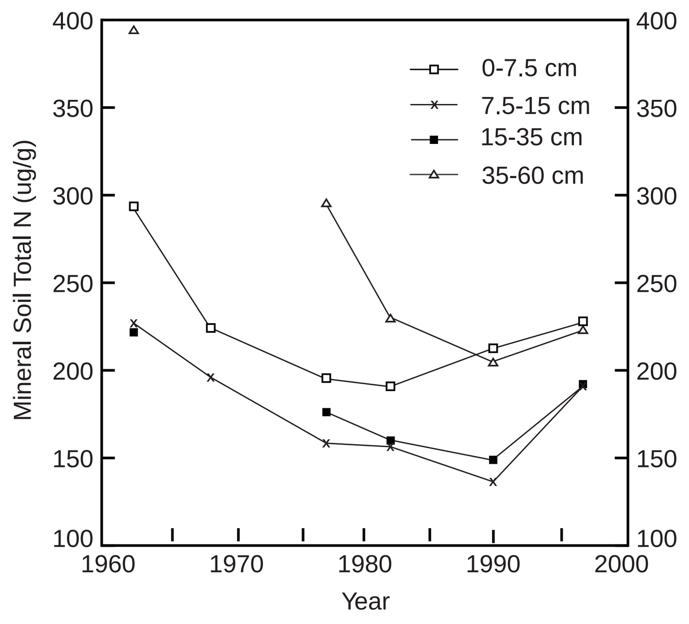

Figure 3. Decreases in total N of mineral soil during forest development. Depletions of N were most rapid during the initial 25 years of forest growth.

The Ecosystem's Development of N Deficiency:

The development of N deficiency is expressed by changes occurring in trees, forest floor, mineral soils, and the trees themselves (Figure 1).

The pine forest floor after 40 years contains 742 kg ha^{-1} (s.e. 25.4), and represents a substantial sink for N. A model of Jorgensen et al. (1980) simulated N accumulation and release rates in the pine forest floor (Figure 4). The same model has successfully simulated ^{14}C contents of the forest floor (Richter et al. 1999). The simulation suggests that the release rate of N in the forest floor has gradually increased over the four decades to about 12.1 kg ha^{-1} at age 40 (Figure 5).

The mineral soil (0 to 0.6 m) in 1997 contains about 70% of the total N contained in the first soil sampling in 1962 (Table 1, Figure 3), decreasing from 2687 to 1863 kg ha^{-1}, respectively. Both mineralizable N (Figure 6) and C/N ratio (Figure 7) in mineral soil indicated decreases in bioavailability of mineral-soil N, especially during the first 25 years of forest development. After age 25, as tree biomass no longer accumulates N at a rapid rate (Figure 2), and mineral soils appear to be increasing in both N content and in N bioavailability. This recent recovery of mineral-soil N is expressed by the temporal pattern of total N (Figure 3), aerobically mineralizable N (Figure 6), and C/N ratios (Figure 7).

Table 1. Changes in total N of mineral soils of the eight permanent plots between 1962 and 1997 (0 to 0.6-m soil depth).

Plot	N in 1962	N in 1997	Change
	----------kg ha^{-1}----------		
1-8	1942.9	1357.1	-585.8
2-8	3099.0	1966.3	-1132.7
3-8	2338.9	1615.0	-723.9
4-8	2572.9	2202.9	-370.0
1-10	3013.9	1737.8	-1276.1
2-10	2933.7	2288.1	-645.6
3-10	2590.0	1902.1	-687.9
4-10	3001.5	1836.5	-1165.0
Mean	2686.6	1863.2	-823.4
CV%	15.0	16.3	-39.5

The pine trees after forty years exhibit several symptoms of N deficiency. In the 1990s, first-flush pine foliage averages only 1.06% N, and very low leaf area index of pine crowns (H.L. Allen, personal communication, NCSU, Raleigh). At age 40, annual tree uptake of N is about 44.1 kg ha^{-1}, with retranslocation from senescing foliage, mineralization of forest floor, and atmospheric deposition each contributing 54, 27, and 18 % of the total uptake.

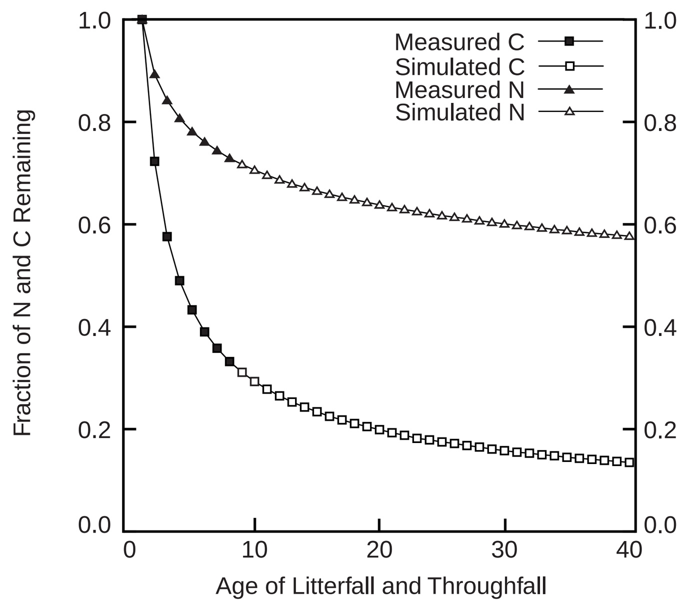

Figure 4. N and C remaining in forest floor after being added in a given year's litterfall plus throughfall (Jorgensen et al. 1980). Generally, all nutrients such as Ca, Mg, K, and P follow the rapid turnover pattern of C. Only N appears to be strongly retained in the pine forest floor.

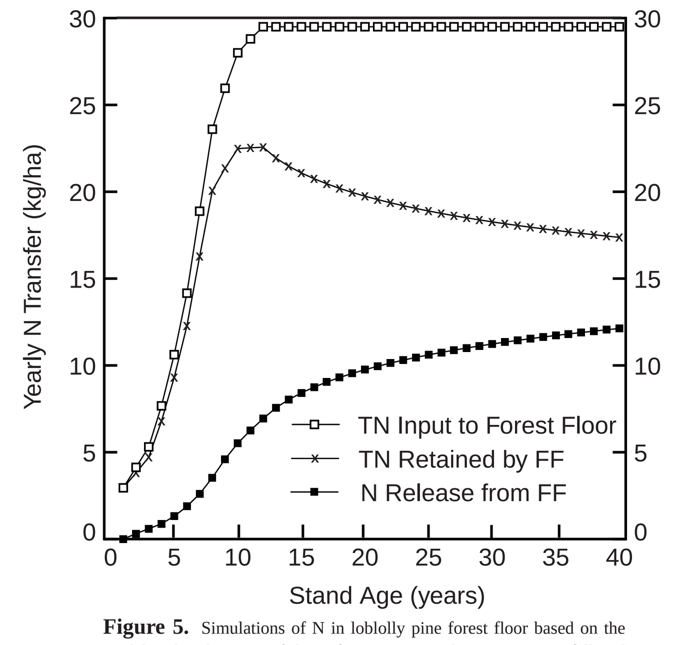

Figure 5. Simulations of N in loblolly pine forest floor based on the model and eight years of data of Jorgensen et al. (1980). Litterfall and throughfall estimates of N at the Calhoun Experimental Forest were from Urrego (1992) and Markewitz et al. (1998). The simulation emphasizes that the forest floor has been a strong sink for N over the four decades.

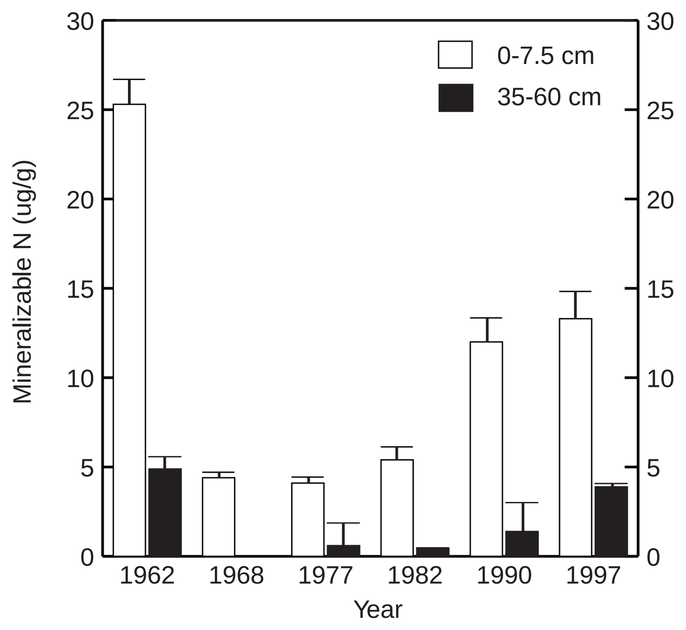

Figure 6. Patterns of mineralizable N as estimated by 30-day aerobic incubations of mineral soils conducted in 1999. Potential storage effects on incubations introduce uncertainties with these data, yet the patterns of mineralizable N strongly suggest sharp decreases in bioavailability of N during the first 25 years of forest development (1957 to 1982), and modest increases in recent years (1990 to 1997).

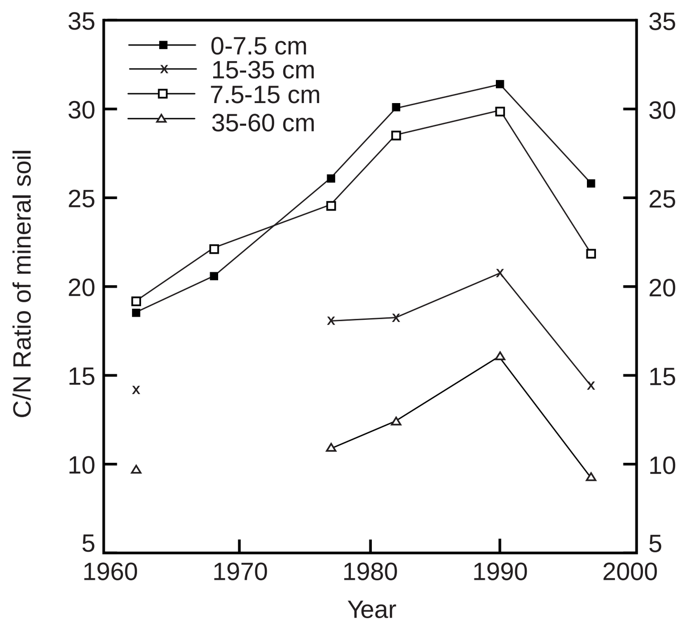

Figure 7. Changes in mineral-soil C/N ratios during forest development. Large shifts in the quality of soil organic matter are suggested by these patterns, as the old-field forest has matured over a four-decade period.

What is the rate of the ecosystem's accretion of N?

Soil losses of N by leaching and denitrification are assumed to be minimal, and results suggest that N_2 fixation has added little N to the old-field pine forest. Table 2 indicates how N in the whole ecosystem increased over 35 years from 2767 to 2971 kg ha^{-1} (s.e. 142.3 and 120.1, respectively), an accretion of 205 kg ha^{-1} (s.e. 120.9) that is significant at a probability of 0.06. The yearly accretion rate of 5.9 kg ha^{-1} y^{-1} is similar in magnitude to that measured in atmospheric deposition (Markewitz et al. 1998) at the site (4.2 kg ha^{-1} y^{-1} as wet-only deposition).

Table 2. Changes between 1962 and 1997 in N of eight permanent plots of the Calhoun ecosystem in mineral soil, forest floor, plus trees (1962 to 1997).

Plot	1962 Eco-System*	-------------Mid-1990s-----------			Ecosystem N Accretion
		Biomass	O horizon	Eco-System*	
	------------kg ha^{-1}------------				
1-8	2022.9	378.6	665.0	2400.7	377.8
2-8	3179.0	300.3	840.3	3106.9	-72.1
3-8	2418.9	359.3	711.1	2685.4	266.5
4-8	2652.9	408.6	687.7	3299.2	646.3
1-10	3093.9	343.3	673.3	2754.4	-339.6
2-10	3013.7	384.3	743.2	3415.6	401.9
3-10	2670.0	395.0	847.9	3145.1	475.1
4-10	3081.5	356.4	770.0	2962.9	-118.6
Mean	2766.6	365.7	742.3	2971.3	204.7**
CV%	14.5	9.3	9.7	11.4	167.0

* sum of N in mineral soil, forest floor, and trees. In 1962, tree seedlings and forest floor were not measured but estimated to contain 80 kg ha^{-1} after five years of growth based on other studies of old-field loblolly pine forests (Switzer and Nelson 1972).

** significantly different from 0 at a probability of 0.06 using a paired t-test.

Project Conclusions:

1. Mineral soil was substantially depleted of total N (by 823 kg ha^{-1}), a depletion that was especially rapid during the first 25 years of forest development.

2. The depletion of mineral-soil N was in response to a massive transfer of N from the mineral soil to forest floor (742 kg ha^{-1}) and tree biomass (366 kg ha^{-1}). Forest floor served as a strong N sink, and release rates of N at age 40 were simulated to be 12.1 kg ha^{-1} y^{-1}.

3. Accretion of N in the ecosystem was modest (5.9 kg ha^{-1} y^{-1}) and was comparable to inputs from atmospheric N deposition. Since losses of N from the pine ecosystem are taken to be insignificant, N_2 fixation appears to contribute only minor amounts of N to the pine-dominated ecosystem.

Future of the Calhoun Experimental Forest:

Two projects are planned for the Calhoun experiment.

1. Experimental treatments are being proposed to enrich the data produced from the 16 permanent plots. These experiments will investigate the efficiency of nutrient cycling, fertilization, nutrient-use, and ecosystem-nutrient retention.

2. The long-term Calhoun forest is serving as a model for a growing network of statistically rigorous, long-term soil-ecosystem experiments that will contain comprehensive soil archives. The network currently contains two other southeastern forests (Sand Hills, NC and Upper Coastal Plain, AL) and two tropical sites (Costa Rica and Indonesia).

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Acknowledgements

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