# Chapter 18
# Evolution of Soil, Ecosystem, and Critical Zone Research at the USDA FS Calhoun Experimental Forest

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> *The past is never dead. It's not even past.*
> (Faulkner, Requiem for a Nun, 1951)

**Abstract** The US Department of Agriculture (USDA) Forest Service Calhoun Experimental Forest was organized in 1947 on the southern Piedmont to engage in research that today is called restoration ecology, to improve soils, forests, and watersheds in a region that had been severely degraded by nearly 150 years farming. Today, this 2,050-ha research forest is managed by the Sumter National Forest and Southern Research Station. In the early 1960s, the Calhoun Experimental Forest was closed as a base of scientific operations making way for a new laboratory

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in Research Triangle Park, NC. Many papers were written during the Calhoun's 15 years of existence, papers that document how land-use history creates a complex of environmental forcings that are hard to unwind. One Calhoun field experiment remains active, however, and over nearly six decades has become a model for the study of soil and ecosystem change on timescales of decades. The experiment contributes greatly to our understanding of the effects of acid atmospheric deposition on soils, forests, and waters and of decadel changes in carbon and nutrient cycling in soils and forests. Perhaps the long-term experiment's major contribution is its clear demonstration that soils are highly dynamic systems on timescales of decades and that this dynamism involves both surface and deep subsoils. The ongoing experiment's success is attributed to relatively simple experimental design, ample plot replication, rigorous (but not too arduous) protocol for resampling and archiving, and to its ability to address changing scientific and management priorities that are important to society and the environment. In the last decade, the experiment has become a platform for research and education that explore basic and applied science. As this manuscript goes to press, the Calhoun Experimental Forest has been designated to become one of the National Science Foundation's national Critical Zone (CZ) Observatories, a development that will allow researchers to, return to the questions that originated the Calhoun Experimental Forest in the first place: how and why severely disturbed landscapes evolve through time.

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## 18.1 The Calhoun Experimental Forest Rooted in Southern Environmental History

Louis J. Metz (1958a) began his remarkable booklet that described research on the John C. Calhoun Experimental Forest, "The Calhoun Experimental Forest…was established in 1947 for work on Piedmont forest, soil, and water problems. Located in the Sumter National Forest, near Union, South Carolina, the forest was chosen because it represented poorest Piedmont conditions."

The "poorest Piedmont conditions" were an aftermath of farming mainly for cotton, tobacco, corn, and wheat that geographer Stanley Trimble (2008) estimated eroded 17 cm of soil between 1750 and 1950 from the Piedmont from Virginia to Alabama. The Fisk University sociologist Charles S. Johnson (Johnson et al. 1935) described the 1930s' Piedmont and the rest of the cotton-producing South as:

> a miserable panorama of unpainted shacks, rain-gullied fields, straggling fences, and rattle-trap Fords, dirt, poverty, disease, drudgery, and monotony that stretches for a thousand miles across the cotton belt.

The US Department of Agriculture (USDA) Forest Service ambitiously organized the Calhoun Experimental Forest with high-quality scientists including Metz, Marvin Hoover, Jim Douglass, Otis Copeland, and Carol Wells, all of whom were based in rural Union County, SC, to work "principally at soil improvement" thereby promoting forests and stabilizing watersheds. They explicitly stated that if they succeeded in their Calhoun efforts, they could succeed anywhere in the South where soils and landscapes had been so adversely transformed by agriculture.

Much is written about the history of the South, but mainly about the region's remarkable human history, its political and cultural strife, tragedy, even its mystique (Irish 1952; Roland 1982; Tindall 1964). Simkins (1947) even declared, "History, not geography, made the solid South." However, a history of the South can also be written about the strong human-historical interactions with the region's dynamically changing environment (i.e., the region's dynamic geography). According to Cowdrey (1996), this environmental history was only beginning to be explored, but since that time has experienced a flourish of activity (Sutter and Manganiello 2009). Consider that in the early eighteenth century, a colonial agriculture was extensively being initiated in the southern Coastal Plain and Piedmont, thus beginning the human–environment interactions that can motivate new discussions in "Southern Studies." Profitable cotton markets, an amenable climate, and the native fertility of soils spurred clearing and conversion of southern forests and the formation of an enormous agricultural economy. In South Carolina, as across the entire South,

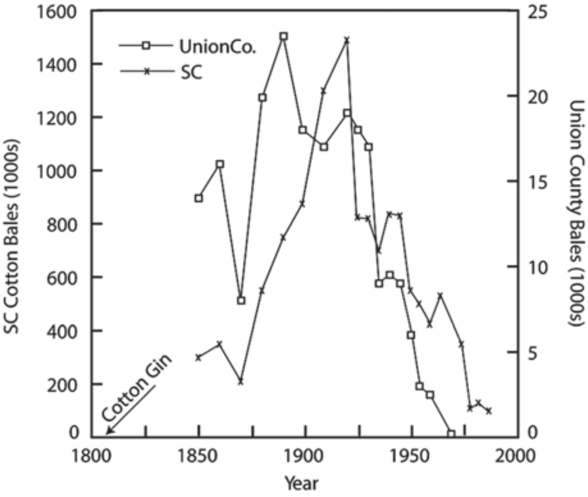


**Fig. 18.1** Nineteenth-century and twentieth-century patterns of cotton production in Union County where the Calhoun Experimental Forest is located and South Carolina. (US Department of Commerce Agricultural Census data as cited in Richter and Markewitz 2001). In recent years, cotton has returned to South Carolina, not in the Piedmont but on intensive forms on the upper Coastal Plain

cotton production grew rapidly through the nineteenth century, interrupted only by the Civil War (Gray 1933), finally peaking between 1910 and 1920 (Fig. 18.1).

Cotton's expansion until the early twentieth century was followed by a rapid collapse (Fig. 18.1) which we attribute to forces that derive from changing human–environment relations. After the Civil War, Piedmont plantations and farms were increasingly worked by tenant farmers and sharecroppers. The new economic system brought land degradation and extensive erosion and poverty to many of its farmers. Tenant farmers and sharecroppers cultivated fields to grow cotton in farming systems that required hand labor throughout hot and humid summers. By 1920, southern farmers found themselves fighting a losing battle against the devastating boll weevil in fields that were severely eroded (Gesen 2011). In retrospect, one is struck by how and why farmers held onto the land so long. Piedmont farmers abandoned the land bound for the industrial southern and northern cities or for more promising agricultural regions across the nation While the experience of all tenant farmers and sharecroppers was difficult that of black farming families is particularly moving (Scott 1919; Rosengarten 1974).

Much of this story today seems like ancient history. Viewed from interstate highways, it is easily seen that the Piedmont is no longer much cultivated and the regeneration of trees appears most impressive. Southern pines and southern oaks, kudzu, and Bermuda grass now blanket most of Charles Johnson's "unpainted shacks, rain-gullied fields, straggling fences," superficially obscuring agriculture's severe effects on the soil and land. To know the South, it is therefore necessary to travel into the rural landscape, hiking through old-field forests, learning to read the land (Leopold 1949; Wessel 1997) like an ecologist, forester, geomorphologist, archeologist, and soil scientist, and learning to talk with, and ask questions of, rural residents. Such a tour of the southern Piedmont will readily turn up rain-gullied fields under the blanket of green and quickly lead us to a conclusion that not only is the history of the South about people *and* the environment, but that the passage of time has hidden more than healed cultivation's severe impacts on the land. A southern history is all about the transformation of soils and ecosystems, and if we are content to view the secondary green blanket as a restoration, we have much more to learn from these deep changes in the land. To rephrase Simkins (1947), history and geography have made the dynamic South.

## 18.2 Ecological "Restoration" at the Calhoun Experimental Forest

In the 1930s, the Sumter National Forest was assembled from tax-delinquent and abandoned farmland as well as from land owned by both willing and unwilling sellers. Land was typically purchased for a few dollars an acre. New insights are found in a thesis by Curry (2010) about the cultural history of the severely eroded and deteriorated land that became the Sumter National Forest and about the New Deal's programs to improve the Sumter's land and the lives of Piedmont farmers. Many informative files about the federal land purchases that created the National Forest are stored in land-purchase files at the Sumter National Forest's Tyger River and Enoree District Forest Offices.

In 1947, the Calhoun Experimental Forest was created within the Sumter National Forest (Dunford 1947; Metz 1958a). The Calhoun's goals were ambitious: to stimulate recovery of soils and forests on the severely eroded southern Piedmont. The Calhoun laboratories and offices were headquartered in the area today occupied by the Fairforest Firing Range. Metz (1958a) remarked, "We want to find the cheapest, quickest, most effective ways of speeding tree growth, increasing plant nutrients, and improving soil structure so that the land stores water for plant use."

The scientists were impressed with, and even appalled by the ecological condition of the region, and were highly motivated to improve forests, soils, and watersheds (Fig. 18.2). Leno Della-Bianca meticulously photographed the Calhoun and Sumter with many hundreds of Kodachrome slides. Marvin Hoover (1950), who would become one of the nation's leading hydrologists, began one of his Calhoun papers, "Nowhere in the country have hydrological processes in the soil been altered by past land use to a greater extent than in the South Carolina Piedmont." The Calhoun scientists published widely of an array of topics, but most focused on the serious environmental effects that had arisen from land degradation of the Southern Piedmont.

Perhaps more than anything, the early research at the Calhoun Experimental Forest demonstrated that the Piedmont's land-use history had created a complex of ecological problems that would prove difficult to unwind (Staff 1951). Not only were soils often severely eroded and gullied but such conditions greatly increased surface and subsurface runoff, creating enormous problems with sedimentation and jeopardizing soil-water storage and accentuating plant-water stress and plant disease (Hoover 1950, 1952a, b, 1954; Metz 1958a). Papers were written to gain a better understanding of forest O horizons (Hoover and Lunt 1952; Metz 1954), which greatly increase soil stability even when present as a relatively light blanket of leaves and needles. Advanced soil-moisture measurements were tested and adapted to Calhoun conditions (Olson and Hoover 1957) including the neutron probe deployed to

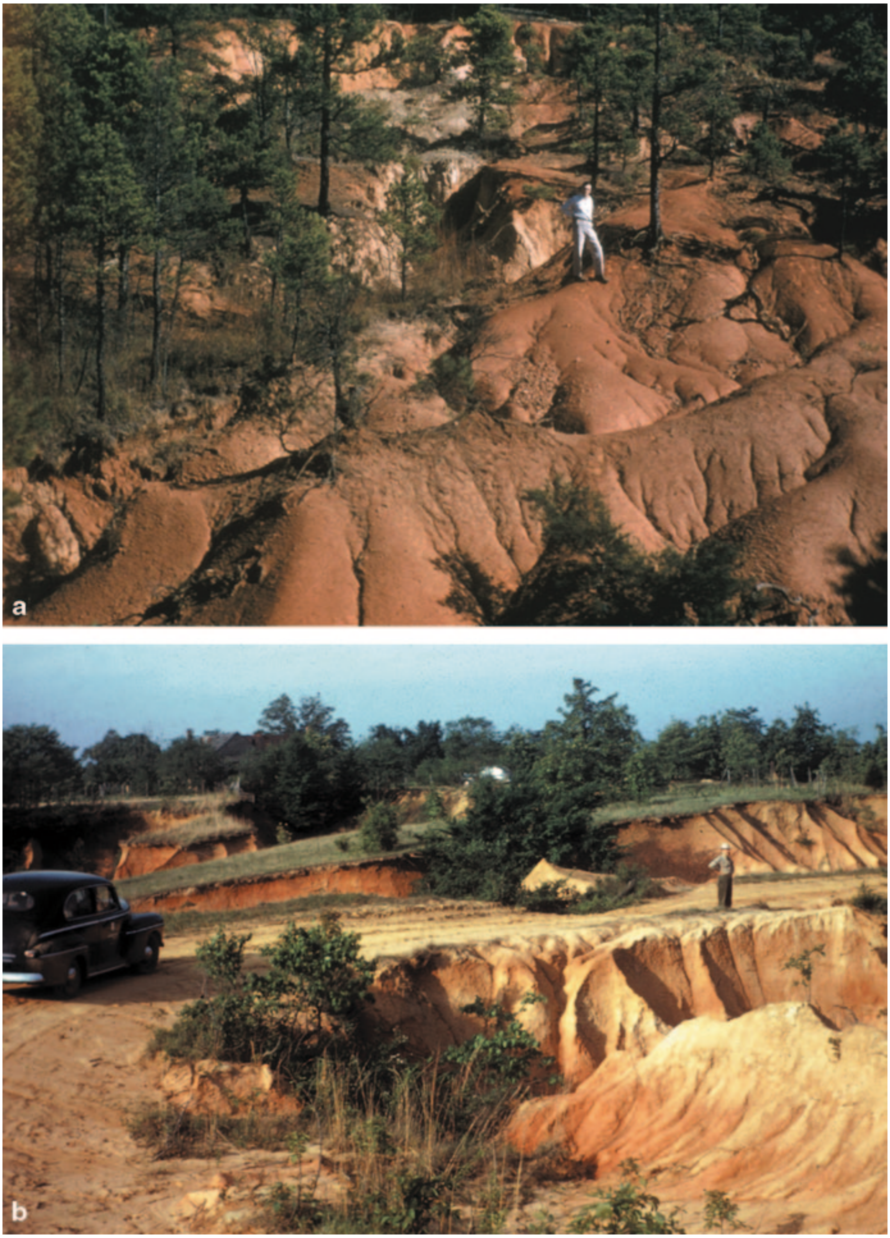


**Fig. 18.2** **a** and **b** Two scenes of the eroded land impacted by cotton on the Sumter National Forest and the Calhoun Experimental Forest. Metz (1958a) stated that the location of the Calhoun Experimental Forest was selected as it represented “poorest Piedmont conditions.” (USDA FS photographs from the 1950s)

5-meter depth (Hewlett and Metz 1960). Time series data demonstrated how contrasting vegetation types utilized soil moisture and altered soil temperature, and often these measurements were made to great soil depths (Douglass 1960, 1966; Greene 1953; Hoover 1950; Hoover et al. 1953; Metz and Douglass 1959; Patric et al. 1965), often in collaboration with Coweeta scientists.

These studies began a series of Calhoun studies that conceive of soil as potentially deep systems, much deeper than the superficial *solum* (Bacon et al. 2012; Markewitz et al. 1998; Richter and Markewitz 1995a, 2001; Richter et al. 2011; Richter and Yaalon 2012). Four small watersheds collected 10–15 years of precipitation and runoff data from contrasting land uses including exploitive farming and restored forest complete with gully control and terracing (Douglass 1972; Hewlett and Metz 1960). Precipitation's interception by tree canopies and litter layers was measured to ensure that all major forest water fluxes were quantified (Hoover 1953; Metz 1958b).

With the recognition that formerly cultivated Piedmont soils were associated with littleleaf disease and that the disease affected both shortleaf and loblolly pine (*Pinus echinata* and *Pinus taeda*), Calhoun scientists determined that severity of soil erosion was highly correlated with a disease complex associated with the pathogen *Phytophthora cinnamomi,* low nitrogen availability, and poor soil internal drainage (Copeland 1949a, b, 1954; Copeland and McAlpine 1955). Several studies examined root mortality of diseased trees (Copeland 1952). And by using rain shelters to impose drought stress on mature shortleaf pine trees, an alternative hypothesis was rejected that drought stress promoted littleleaf disease (Copeland 1955). Littleleaf hazard rating systems for the South were developed based on soil characteristics, one of which is still in use today (Campbell and Copeland 1954; Mistretta 1998). The studies of littleleaf spurred interest in shortleaf pine (Haney 1955, 1957), a species that in the twentieth and twenty-first centuries is having major trouble with its regeneration.

There was also great interest in how low soil fertility and high soil acidity might limit reforestation on eroded soils (Copeland and McAlpine 1955; Metz 1958a). Calcium and nitrogen were of greatest concern, and the beginnings of nutrient cycles were estimated. Fluxes of major nutrients were measured in contrasting forest stands including forest litterfall, tree foliage, wood, and soils (Metz 1952a, b; Metz and Wells 1965; Wells 1965; Wells and Metz 1963).

For reasons that today are not entirely clear, in the early 1960s, after about 15 years of work, the Piedmont Research Center and the Calhoun Experimental Forest were closed. According to Douglass (1972), research at the Calhoun Experimental Forest was terminated as part of a relocation of its scientists to Coweeta Hydrologic Laboratory and to a new, modern Forestry Sciences Laboratory in the Research Triangle Park, NC. Although research on the Calhoun Experimental Forest was no longer funded by the USDA Forest Service, the Calhoun continues to appear on national lists of Experimental Forests and Ranges and to maintain a director, currently USDA Forest Service scientist, Dr. Thomas Waldrop. Calhoun Experimental Forest records, files, data, and many hundreds of high-quality Kodachrome slides that document research during the 1940s and 1950s (e.g., Figs. 18.2 and 18.3) were moved for storage to the Coweeta Hydrologic Laboratory. Some files, mainly office

**Fig. 18.3** The pine spacing study designed and installed by Lou Metz. Planted in the winter of 1956–1957 on old cotton fields with four tree spacings and four experimental blocks (i.e., 16 permanent plots), the study is a model of research continuity. Thanks to the career-long work of Carol Wells, the field study grew into what is today Calhoun's Long-term Soil-Ecosystem Experiment. (USDA FS photo, Calhoun Experimental Forest)

communications and miscellaneous correspondence, remain behind in the Sumter's Tyger River and the Enoree District Forest Offices in Union and Whitmire, SC. Daniel deB. Richter (lead author of this chapter, currently at Duke University) inherited files (and the Calhoun sample archive) from the laboratory of Dr. Carol Wells who had served on Richter's PhD committee from 1977 to 1980.

## 18.3 The Calhoun Experimental Forest's Versatile Long-Term Field Experiment

After the closure of the Calhoun's Piedmont Research Center, only one of the original experiments remains active today. This experiment has endured entirely due to Carol Wells' career-long interest in forest soils, becoming today a >50-year field experiment that is synonymous in many circles with "the Calhoun Experimental Forest." The experiment was one of the last installed by Lou Metz and was a meticulously designed, large-scale, loblolly pine spacing study (Fig. 18.3). Today, known formally as the Calhoun Long-Term Soil-Ecosystem Experiment (LTSE), the experimental plots reside on broad, gently sloping interfluves that were previously variably eroded cotton fields. The pine seedlings were planted in 16 plots in a randomized complete block design with four blocks of different soil conditions and four seedling densities (at 6 × 6-, 8 × 8-, 10 × 10-, and 12 × 12-ft spacings). Soon after planting, the experiment caught the attention of a young soil scientist from the University of Wisconsin, Carol Wells, hired by Metz to add soil and analytical chemistry expertise to the Calhoun's staff. In 1962, Wells began a time series of periodic samples of the ecosystem, aboveground and belowground, using a rigorous resampling protocol that continues to this day. The soil-sampling protocols involve sampling plots about once every 5 years by compositing 20 within-plot samples (each 2-cm dia) from each of four soil depths within 0–60 cm. After air-drying, samples are passed through a 2-mm screen, and become part of an extensive sample archive, housed at Duke University's Nicholas School of the Environment.

What Metz and Wells set in motion was very special, as their field experiment, resampling, and archiving protocols have created one of the world's finest studies of soil and ecosystem biogeochemical change *over the life of a forest*. The study's success is attributable to its relatively simple experimental design, its resampling and archiving protocols that are rigorous but not overly arduous, its relatively deep resampling of the root zone, and its ability to address a series of scientific and management issues that are critically important to society and the environment.

The great pedologist Walter Kubiena (1970) once suggested that soils and finely made watches have much in common, in that to understand how a soil or a watch works, one must observe and study the system as a whole. Like Kubiëna, we credit Metz and Wells for being critical of a too reductionist approach to soil science, in which studies reduce the soil to its parts and take little advantage that can come from observing and experimenting with the whole soil and the plants it supports. To paraphrase Kubiëna's words, Metz and Wells created a field study that offers scientists the potential to study the relations of the soil's component parts and the functioning of the whole system.

In the beginning, the Calhoun's LTSE was known as "the Calhoun spacing study" because it was established to learn how tree density affects water relations and the growth of individual trees and stands of loblolly pine. Metz (1958a) indicated that the study was "to be used in the future for litter and soil-moisture studies." Wells was interested in what the study might explain about soil fertility, tree and stand nutrition, and how a growing forest altered soils physically and chemically.

From its inception, the Calhoun spacing study generated regional interest as indicated by historic files. Other spacing studies in North Carolina and around the South were directly modeled after the Calhoun study. A loblolly pine spacing study based directly on the Calhoun study was even planted in Maui, HI (DeBell et al. 1989). The Calhoun study was used by Wells in the IBP or the International Biological Program (Coleman 2010).

As the pine trees grew in the Calhoun spacing study, their periodically measured diameters and heights were converted to yield data that were used in PhD dissertations, regional stand-growth models, and forest industry databases. The data were used to quantify relationships among tree density, mortality, volumetric dimensions of tree and stand biomass, and ecosystem productivity (Balmer et al. 1975; Harms and Lloyd 1981; Buford 1983, 1991; DeBell et al. 1989; Hafley et al. 1982; Hafley and Buford 1985). Buford (1983, 1991) developed and evaluated several sophisticated growth models from the observed density-dependent trajectories of growth. DeBell et al. (1989) compared the trajectories of growth and mortality at the Calhoun with those of the identically planted loblolly spacing study in Maui, HI. This latter comparison allowed DeBell et al. (1989) to develop ideas about stockability, a novel concept that suggested new ways that stand density–tree size relationships are related to environment as well as genotype.

During the second half of the twentieth century, the South grew to become the largest industrial wood-producing region in the world. The harvested wood was mainly pine and much of it originated from old-field stands not dissimilar to the old-field forests of the Calhoun spacing experiment. A number of scientists were more than a little interested in and concerned about how old-field soils, so seriously altered by land-use history, would support the new intensive pine management. To increase understanding about the nutrition of these new forests, Wells devoted his research to the science of ecosystem nutrient cycling. Using the Calhoun's field experiment (i.e., the Calhoun spacing study) and a network of pine stands across the Piedmont, Wells was among the first to estimate pine forest nutrient uptake from soils; nutrient recycling in canopy litterfall, throughfall, and retranslocation; and overall soil-nutrient demands of intensive pine management (Wells and Jorgensen 1975, 1979).

By the end of Wells' career in the late 1980s, the Calhoun soil-ecosystem experiment, then 30 years since planting, was providing indications that soil nutrients were being substantially altered by pine forest development. In a paper evaluating effects of intensive harvesting on soil nutrient supply and sustained productivity, Wells and Jorgensen (1979) used the Calhoun field experiment (then nearly 20 years since planting) to illustrate several important points about soil fertility:

> In the South after a conversion of old fields or low-quality hardwood stands to pine, the mineral soil is the primary source of the nutrients retained in trees and accumulated in forest floor during the first 20 years of stand development when nutrient requirements are large. In a *Pinus taeda* plantation on a field converted from agriculture (sic, the long-term Calhoun field experiment), N content of the surface 60 cm of mineral soil decreased from 2392 kg/ha at age 5 to 2010 kg/ha at age 15 (Wells and Jorgensen 1975). Extractable P, K, Ca, and Mg also declined. Mineral soil changes appear to be small between the ages of 20 to 40 in *Pinus taeda* stands because during this period the forest floor provides nutrients at an increasing rate with stand maturity. It is possible, however, that the mineral soil has been depleted of readily available elements by the demands of the growing stand.

According to Stone (1979), Wells' research (Wells and Jorgensen 1979) was some of the most advanced work of its kind. In addition, at the moment of Wells' retirement in the late 1980s, the Calhoun field experiment was poised like few others to directly address two of the most vexing and highest-stakes environmental issues of our time: that of acid deposition effects on soils and forests and that of forest carbon sequestration and cycling. Wells was also well aware that the field experiment was able to quantify ecological processes that are basic to ecosystem science, for example, the rate at which biologically available nutrients are released by mineral weathering (Carol Wells' personal communication with Daniel Richter, late 1980s).

The remainder of this chapter is organized into four sections, two of which involve how the long-running Calhoun soil-ecosystem experiment has been used since the late 1980s to address the internationally significant environmental issues of: the effects of acid atmospheric deposition on soils, water, and forests (Sect. 18.1.4), and the rates and processes with which forests cycle and sequester carbon (Sect. 18.1.5). Subsequently, we describe the many ways the Calhoun experiment is exploring basic science questions about ecosystems and ecosystem development (Sect. 18.1.6). The chapter concludes with a brief evaluation about this evolutionary research trajectory that has been shaped both by information needs of society and by the gradually increasing duration of the Calhoun field experiment itself (Sect. 18.1.7).

## 18.4 What are the Effects of Acid Atmospheric Deposition on Soils and Forests?

Rain and snow across the eastern USA and throughout northern and central Europe had turned acidic as a result of post-World War II emissions of $SO_2$ from uncontrolled coal burning and $NO_x$ emissions from internal combustion engines. During the 1970s and 1980s, acidification of lakes, streams, soils, forests, and even architectural structures grew to become major concerns among scientists, public policy analysts, and the public. The environmental and financial stakes over acid deposition effects were high. While the processes and rates by which atmospheric acid deposition acidified soils and natural waters were widely studied (Binkley et al. 1989a; Johnson and Lindberg 1992; Likens et al. 2002), key issues remained unresolved. Uncertainties were exacerbated by poor understanding of a number of basic ecosystem processes, including soil mineral weathering reactions that ultimately buffer acid inputs to soils. While much was known about soil acidity via measurements of soil and water pH, aluminum solubility and reaction chemistry, short-term acidification experiments, and computer models, long-term direct observations of acidification in forest and wildland soils were notably absent. The situation would probably have been criticized by the whole-system advocate Kubiena (1970), as the acid rain issue revealed that soil and ecosystem sciences had been far too uniformly reductionist. *In other words, scientists knew a lot about how soil pH, acidity, and chemistry varies across space (at a moment in time), but we had little understanding and few direct observations of the rates at which individual soils were acidifying though time.*

The Calhoun field experiment, however, with its repeated soil samplings, archiving, and chemical analyses demonstrated significant acidification throughout the upper 60 cm of the rooting zone, a trend that was probably initiated soon after the last liming of cotton in 1955 (Fig. 18.4). Even by 1962, however, the soil's base saturation remained >70 % throughout the upper 60 cm of mineral soil. To grow cotton, the acidic Ultisol had been transformed into a "cultural Alfisol" by liming, an arable soil with relatively high exchangeable base saturation (Fig. 18.4). With the rapid growth of the forest, however, in the absence of continued liming and with acid deposition, the soil rapidly re-acidified. Binkley et al. (1989b) compared acidity in archived samples from 1962 and 1982, and estimated that decreasing pH was mainly due to reductions in exchangeable base cations, and that the soil's acid-neutralizing capacity was decreasing at about 1.3 kmol $ha^{-1}$ $y^{-1}$. The growing trees were trading protons for much-needed nutrient cations of Ca, Mg, and K. Subsequent studies of Calhoun's soil acidification combined observations of soil chemical change with nutrient-cycling information and concluded that mineral weathering release of calcium approached zero during the first three decades of forest development (Bacon 2014; Markewitz 1995; Richter et al. 1994). Markewitz et al. (1998) analyzed soil-solution chemistry down to 6-m depth and estimated that up to 40 % of the acidification in the upper 60 cm of soil was attributable to acid atmospheric deposition. Below 60 cm, however, sulfate adsorption effectively reduced cation leaching. Acid deposition was thus acidifying surficial layers of soil

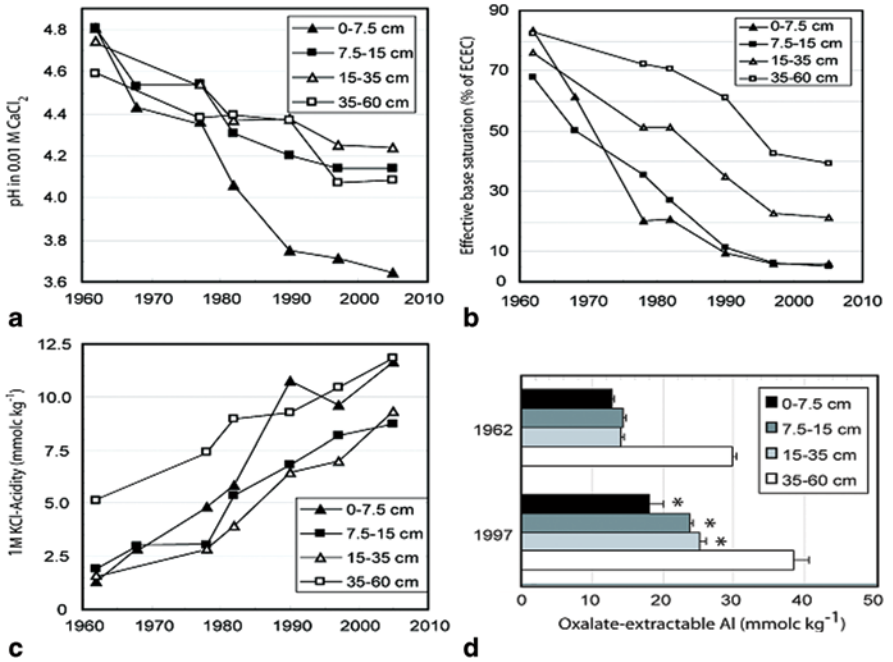


**Fig. 18.4** The development of the Calhoun pine forest has been accompanied by substantial soil acidification, here indexed by soil **a** pH in 0.01 M $CaCl_2$, **b** effective base saturation, **c** KCl-exchangeable acidity, and **d** oxalate-extractable Al

by translocating exchangeable base cations more deeply into the root zone and soil profile (from O, A, E, and upper B horizons into middle and lower B horizons). In this sulfate-adsorbing system, acid deposition did not leach base cations completely out of the ecosystem, but rather moved them lower in the soil profile (Markewitz et al. 1998). These observations of soil acidification were featured in national assessments of acid deposition and air pollution (Richter 1991; Richter and Markewitz 1995b) and results from Markewitz et al. (1998) were widely reported in the popular press.

Stepping back from the technical details of soil acidification, these environmental issues could only have been addressed with an exceptional long-term field study supported by a long-term sample archive. Worldwide, fewer than 40 long-term field experiments have sample archives that are as old as those assembled in the Calhoun experiment. Metz and Wells can be credited with creating a unique and especially valuable forest-soil experiment, given that nearly all of these 40 long-term experiments test changes in agricultural soils. The Calhoun's sample archive is today as valuable as the long-term field plots themselves, and the entire program of study will only increase in value in years to come. This latter point is amply demonstrated by the Calhoun's growing contributions to scientific understanding of forest carbon sequestration and cycling (Fimmen 2004; Fimmen et al. 2008a, b; Galik et al. 2009;

Gaudinski et al. 2001; Grandy et al. 2009; Harrison et al. 1995; Mobley 2011; Mobley and Richter 2010; Mobley et al. 2013; Richter 2007; Richter et al. 1999, 2001; Richter and Mobley 2009; Richter and Markewitz 1996; Richter et al. 1995, 1999, 2006b, 2007a, b; Smith et al. 1997; Strickland 2009; Strickland et al. 2010).

## 18.5 Forest Carbon Sequestration and Cycling: Where has all the Carbon Gone?

National and international demand for quantitative information about soil and whole ecosystem gains and losses of carbon are drawing upon research sites such as that at the Calhoun for carbon cycling information (e.g., Galik et al. 2009; Richter et al. 1999). The Calhoun study is particularly well situated to address both soil and ecosystem carbon losses and sequestration: (1) The long-term Calhoun field experiment is part of a highly eroded landscape, and a major and contentious question concerns whether soil erosion is an atmospheric $CO_2$ source or sink (Billings et al. 2010; Van Oost et al. 2007). (2) The long-term field study quantitatively estimates carbon changes in the whole ecosystem aboveground *and* belowground over nearly five decades (Billings and Richter 2006; Mobley 2011; Mobley et al. 2013; Richter and Markewitz 1996; Richter et al. 1999). The Calhoun experiment's repeated soil-carbon sample archive and inventory to a soil depth of 60 cm makes exploring soil-carbon dynamics especially fruitful, as only about 10 % of the > 300 of the world's soil-carbon change studies have sampled soil deeper than 30 cm (Post and Kwon 2000; Richter and Mobley 2009; West and Post 2002).

Although cultivation might conventionally be considered to affect only losses of soil carbon, erosion recently has been proposed to be an important carbon sink due to transport and burial of eroded soil particles that contain soil organic carbon. A modeling exercise using data from across the Calhoun Experimental Forest was developed to provide a range of potential carbon effects associated with soil erosion (Billings et al. 2010). Modeling the influence of erosion associated with 150 years of agriculture on the strength of net soil-carbon sources or sinks suggests that erosion has been a substantial driver of carbon dynamics. Depending on the fate of eroded carbon—whether it was oxidized or retained as soil organic matter—the modeling suggests that up to ~ 9 kg of soil carbon $m^{-2}$ was accrued, or up to ~ 3 kg carbon $m^{-2}$ was released as $CO_2$, as a result of erosional forcings.

In 1995, the Calhoun's long-term field experiment and long-term time series of carbon data were selected to be the forest data used by several dozen carbon modelers at the International Soil Organic Matter Network (SOMNET) workshop. The Calhoun carbon data complemented data sets from the famous Broadbalk Wheat and the Park Grass experiments that represented cultivated and grassland systems, respectively. Outcomes of this carbon modeling were summarized in Smith et al. (1997), which, among other conclusions, emphasized the need for more concerted efforts at modeling soil-carbon change over decades' timescales and the need for many more long-term soil experiments such as the Broadbalk, Park Grass, and the Calhoun.

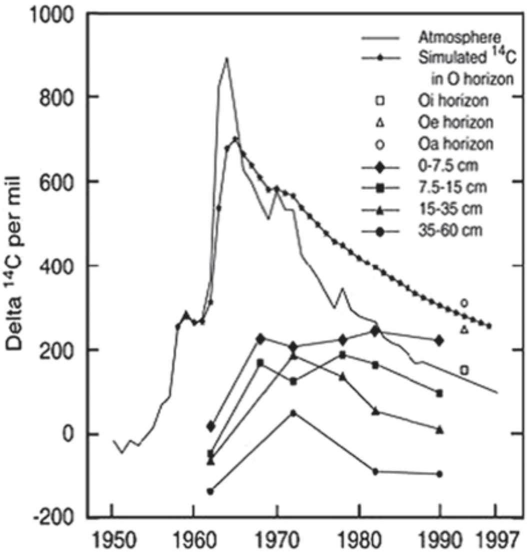
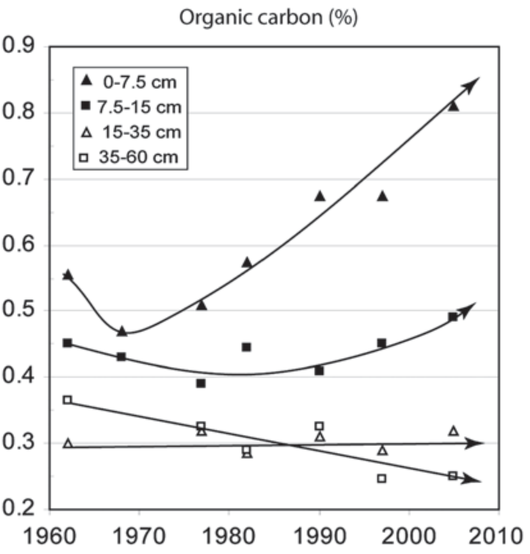


**Fig. 18.5** Time trends of $^{14}C$ in atmospheric $CO_2$ (1950–1997), three layers of 1992 forest floor (Oi, Oe, and Oa), and mineral soil (in 1962, 1968, 1972, 1977, 1982, and 1990) at the Calhoun Experimental Forest. Model-simulated changes in $^{14}C$ in O horizons (1957–1996) are estimated from a decomposition model of Wells and Jorgensen (1979). Estimates of litterfall inputs over the four decades were set to coincide with the pattern of $^{14}C$ in atmospheric $CO_2$

In the soils of the Calhoun's long-term field experiment, long-practiced cultivation prior to reforestation had greatly depleted organic carbon from the sandy A horizons. Under the secondary forest, enormous amounts of forest organic carbon have been added to the soil, and the historic effects of cultivation are slowly receding from the soil's memory (Targulian and Goryachkin 2004). Yet, the drastic increases in soil-carbon inputs have not resulted in much soil sequestration due to active decomposition and plant and microbial demands for nutrients. Ongoing research focuses on these processes, which is reflected in both the quantity and composition of the soil's changing organic matter.

Overall, the aggrading forest in the Calhoun experiment has been a strong sink for atmospheric carbon from planting to the late 1990s. For example, the forest as a whole has sequestered over 16 kg C $m^{-2}$ in its first four decades, a rate in excess of 400 g C $m^{-2}$ $y^{-1}$ (Galik et al. 2009; Harrison et al. 1995; Richter et al. 1999). Nearly all of this carbon accumulation is in tree biomass, aboveground and belowground, and secondarily in the soil, i.e., the forest floor and mineral soil. Remarkably, surface mineral soils have sequestered minimal carbon over five decades of forest development, and the experiment demonstrates how rapidly the decomposer system in the mineral soil oxidizes organic carbon inputs. This rapid rate of decomposition is also clear in the cycling of $^{14}C$ (radiocarbon) through the forest and soil (Fig. 18.5). Forest carbon inputs to the soil profile are labeled with $^{14}C$ because the pine forest was planted in the winter of 1956–1957 and has grown entirely within the era of aboveground thermonuclear bomb testing. By 1964, atmospheric $CO_2$ had nearly doubled its content of $^{14}C$ (Fig. 18.5) and while forest photosynthates were within several years distributed throughout the upper 60 cm of soil, the radiocarbon rapidly passed through mineral soils deeper than 15 cm (Fig. 18.5).

**Fig. 18.6** Mineral-soil carbon in permanent plots at the Calhoun Experimental Forest. The randomized complete block repeated analysis indicates significant increases over time in the 0–7.5-cm layer and decreases in the 35–60-cm layer



Thus, in spite of the substantial carbon sink of the whole aggrading forest during the period of active forest growth, there has been little carbon sequestration in the mineral soil. This result has varied somewhat with soil depth, however. In the four layers of mineral soil sampled, the most surficial 7.5 cm has significantly increased in its carbon concentration and content as an A horizon has redeveloped under the forest after long-practiced cultivation of cotton (Fig. 18.6). The mean content of carbon sequestered in the surficial 0–7.5-cm layer is about 2.9 Mg $ha^{-1}$ from 1962 to 2005, a statistically significant increase. In contrast, the deepest depth sampled, 35–60 cm, significantly lost about 4.2 Mg C $ha^{-1}$ during the same period counterbalancing the modest gains observed in surficial layers (Fig. 18.6). Our hypothesis for this loss of soil carbon at that depth is that organic matter's decomposition was promoted by forest growth due to the forest's greatly increased transpiration and the forest's demand for nutrients. Especially from the deepest depth sampled, 35–60 cm, water uptake by trees is much larger than that by cotton and this has hypothetically promoted oxidative conditions required for significant mineralization to proceed. Ongoing research is exploring this hypothesis and that of forest-priming effects on soil organic carbon decomposition (Mobley 2011).

## 18.6 The Calhoun Long-Term Field Experiment and Basic Soil and Ecosystem Science

Over the years, Calhoun investigators have evaluated how decades of forest growth have altered soil chemistry and used the soil-change data to study difficult-to-measure ecosystem processes involving chemical elements not only of carbon (see

Section 18.5), but of nitrogen, phosphorus, potassium, calcium, magnesium, and trace elements boron, copper, iron, manganese, and zinc. Such processes include not only acidification and organic carbon sequestration but also nitrogen fixation, atmospheric nitrogen deposition, turnover of organic and mineral fractions of soil phosphorus, dynamics of Fe and Al oxy-hydroxides, and mineral weathering reactions involving calcium, magnesium, potassium, and trace elements. Promising preliminary studies have been conducted on the mobility of atmospheric lead derived from leaded gasoline and on the legacies of arsenic historically applied to cotton as pesticides to combat the boll weevil. We have also begun studies of the effects of land-use history on soil biology, soil ecology, and fungal biodiversity. And not only have human-affected changes in Calhoun soils and ecosystems been studied but also the natural pedogenic system has been a focus of research as well. Recently, we proposed a new hypothesis for crustal weathering involving redox reactions initiated in rhizospheres (Fimmen et al. 2008b; Richter et al. 2007b). In 2010, soils were sampled and inventoried for cosmogenic beryllium (specifically, the radionuclide $^{10}$Be) to estimate soil residence time on the Calhoun's biogeomorphically most stable interfluves, which we hypothesize to be much older than generally appreciated (Bacon 2010; Bacon et al. 2012). This is an active period of research at the Calhoun Experimental Forest.

### 18.6.1 Soil and Ecosystem Nitrogen

Soil nitrogen in the Calhoun's long-term experiment has been a subject of intense study. Four decades of forest growth has resulted in the transfer of about 30 % of the total nitrogen in the upper 60 cm of mineral soil into new forest biomass and forest floor, via soil organic matter mineralization and subsequent tree uptake of bioavailable nitrogen. The forest grew itself into a state of acute nitrogen deficiency, with low LAI, (< 2.5 m2m-2) and foliar N Concentrations in upper crowns of 1.06%. This progressive nitrogen limitation (Johnson 2006) is attributed to the rapid rate of tree uptake of nitrogen combined with the extremely low rates of nitrogen mineralization in the pine forest floor during the first four decades of forest development. The repeated samplings of soil indicated that the source of soil N came initially from the most surficial layers of mineral soil but that over the life of the forest, the 35–60-cm layer of soil was the source of a very large fraction of the N accumulated in biomass and forest floor (Billings and Richter 2006; Richter et al. 2000). Forest development also imparted pronounced depth dependence in $^{15}$N in soil organic matter over several decades, due to the transfer of > 800 kg N ha$^{-1}$ into aggrading plant biomass and forest floor. The deepest layer sampled, 35–60-cm soils, experienced the greatest change in $^{15}$N, reaching a maximum of 9.1 ‰, during the 7.6 ‰ shift over four decades (Billings and Richter 2006). A modest whole-ecosystem accretion of nitrogen (in plants, forest floor, plus soil) suggests that the most likely source of the additional nitrogen in the ecosystem is from incorporation of atmospheric nitrogen deposition rather than $N_2$ fixation (Richter et al. 2000).

### *18.6.2 Soil and Ecosystem Potassium, Calcium, and Magnesium*

Four decades of forest growth in the old-field soils of the Calhoun field experiment have significantly depleted soil-exchangeable cations. Mineral weathering release rates of the three principle nutrient cations, calcium, magnesium, and potassium were evaluated from estimates of mineral-soil depletions, nutrient accumulations in biomass and forest floor, atmospheric inputs, and soil leaching removals. The rates of weathering resupply differed greatly among the three cations. For calcium, accumulations in tree biomass and forest floor plus that lost to leaching were comparable to observed depletions of soil-exchangeable calcium. Thus, for calcium, mineral weathering and deep-root uptake did not buffer soil's exchangeable pools even on timescales of decades. For potassium, however, the patterns could hardly have contrasted more. Removals of soil potassium by tree uptake plus leaching losses exceeded observed depletions of soil-exchangeable potassium by nearly 20 times. Bioavailable potassium was readily replenished by non-exchangeable mineral sources, patterns also observed in laboratory and greenhouse experiments and attributable to relatively large bioavailable potassium-containing minerals in the Calhoun soils (Markewitz and Richter 2000). The behavior of magnesium shared attributes of the contrasting patterns of calcium and potassium. While forest growth significantly depleted soil-exchangeable magnesium, depletions were not to the full extent of magnesium contained in biomass and forest floor and that lost to leaching (Richter et al. 1994; Richter and Markewitz 2001). Additional studies need to identify the minerals involved in supplying bioavailable fractions of potassium and magnesium and to make progress on soil water movement and leaching (Gnau 1992).

### *18.6.3 Soil and Ecosystem Phosphorus*

Forest growth also drew heavily upon fractions of mineral-soil phosphorus to supply the $>80$ kg P $ha^{-1}$ contained in biomass and forest floor in three decades. While agricultural fertilization had built up phosphorus in organic compounds and that associated with calcium, iron, and aluminum phosphates, surprisingly, the most labile forms of bioavailable phosphorus, that indexed by exchange resins, $NaHCO_3$, and Mehlich-III extractants, remained relatively high throughout this period of forest development (Richter et al. 2006a). Decreases in soil phosphorus were statistically significant and most substantial in slowly cycling organic and inorganic phosphorus associated with iron and aluminum oxides and especially from calcium compounds, and it was these latter fractions that accounted for nearly all of the phosphorus contained in biomass and O horizons. These dynamics in soil phosphorus are attributed to the strong phosphorus sink strength of the aggrading forest (at 2.9 kg $ha^{-1}$ $year^{-1}$ over 28 years), the legacies of fertilization, and the ability of relatively slowly cycling phosphorus to supply substantial amounts of bioavailable phosphorus over decades' timescales. Forest development had clearly restructured the chemistry of soil phosphorus in only a few decades (Richter et al. 2006a).

### *18.6.4 Soil and Ecosystem Trace Elements*

The range of responses among the ecosystem's trace elements provides more evidence that soil systems are highly dynamic over timescales of decades (Li 2009; Li et al. 2008). Soil-extractable boron and manganese were significantly depleted by four decades of forest growth with depletions comparable to accumulations in biomass and forest floor. Thus, uptake of boron and manganese by trees greatly outpaced resupplies from atmospheric deposition, mineral weathering, and deep-root uptake. The changes in boron and manganese contrasted with those of soil-extractable zinc and copper which changed relatively little during forest growth, indicating that zinc and copper resupplies (viatmospheric deposition, mineral weathering, and deep-root uptake) kept pace with accumulations by the aggrading forest (Li et al. 2008). Lastly, forest iron cycling was qualitatively different from that of all other macronutrients and micronutrients. Forest floor accumulations of iron dwarfed iron inputs in litterfall and canopy throughfall. Moreover, soil oxalate-extractable iron, taken to represent iron in short-range-order forms of oxides, *increased* about tenfold more than tree-biomass accumulations. We hypothesize that the forest's large soil inputs of organic matter over four decades combined with the ecosystem's profound acidification have altered the surface chemistry of the soil's relatively large crystalline pools of iron oxy-hydroxides, in effect increasing more reactive forms of short-range-order components (Li et al. 2008). These changes in iron oxide surfaces may have altered the bioavailability and retention of other nutrients, contaminants, and organic matter, components which intimately interact with oxides.

### *18.6.5 How do Land-Use Histories Alter Soil Ecology, Organic Matter Chemistry, and Soil Heterogeneity?*

The Calhoun's LTSE provides special insight into soil biogeochemical changes that accompany ecosystem development and land-use history. To augment this ecosystem study and explore processes not well captured in the soil archive-based study, we have investigated how soil ecology, soil heterogeneity, and organic matter chemistry were altered by past land uses and their developmental trajectories. A network of ecosystems (on biogeomorphically stable interfluves and similar soil series to those found in the Calhoun's LTSE) was established with the main difference among sites being land-use history. The different histories include remnant hardwood stands never cultivated or fertilized serving as reference sites and three other ecosystems being historically cultivated for cotton and then continuing to be cultivated for corn and wheat, converted to grasslands for hay and pastures, and converted to secondary pine forests which at the time of sampling were about 50 years in age. Three replicates of each of the four ecosystems were located across the Calhoun Experimental Forest, the Sumter National Forest, and local private farmlands.

To examine how soil macrofauna were influenced by land-use histories (Callaham et al. 2006), soils of the four ecosystems were collected quarterly. Hardwood stands that were never cultivated or fertilized supported by far the most taxonomically diverse communities, followed by pine stands, pastures, and cultivated fields in order of decreasing diversity. For earthworms, scarab and carabid beetles, diplopods, chilopods, gastropods, and Diptera, there were long-term effects of soil disturbance and plant composition, with less diverse invertebrate communities typically having a few, often nonnative, disturbance-tolerant taxa in the most disturbed sites (Callaham et al. 2006).

To determine how microbial diversity and activity were land-use dependent, Strickland et al. (2010) determined that land use and soil-extractable phosphorus (an index of past fertilization) were both strongly associated with the mineralization of $^{13}$C-labeled glucose applied in the field across seasons. Measures of microbial community size, activity, and composition all appeared to be relatively poor predictors of mineralization. In a related study, Strickland et al. (2009) used contrasting litters and demonstrated that the concept of "litter quality" is not simply determined by the chemical characteristics of the plant detritus but is largely determined by the history of the microbial communities responsible for the initial stages of decomposition.

To evaluate how land uses had affected fungal communities, Jackson et al. (2005) not only quantified high species diversity of fungi in O and A horizon soils of hardwoods, cultivated fields, grasslands, and in old-field pines but also observed deep taxonomic shifts in the makeup of these communities that were associated with land-use change (Jackson 2010). At the species level, all land uses were distinct, while phylogenetic analysis at higher taxonomic levels revealed shifts from a broad range of ruderal, disturbance-tolerant, lower fungi in cultivated and grassland soils to the dominance of several lineages of ectomycorrhizal fungi associated with the forest's return on the landscape. This pattern was also evident in molecular surveys of soil microeukaryotes, as well as assays of fungal propagules. Jackson's (2010) work highlights the very powerful effects of land-use change on soil microbial diversity.

To begin to examine how land use has altered the chemistry of soil organic matter, soil samples were collected from the four ecosystems and key attributes of the chemical structure of organic matter determined (Grandy et al. 2009). Structure of organic matter was evaluated using pyrolysis–gas chromatography/mass spectroscopy. The dominant chemical components of soil organic matter included common pyrolysis products of lignin (e.g., 4-vinylguaiacol and 4-acetylguaiacol), polysaccharides (e.g., levoglucosenone and furfural), nitrogen-bearing compounds (e.g., pyridine and pyrrole), as well as a variety of lipids and compounds of unknown origin. In these analyses, there were no detectable effects of land-use history on soil organic matter chemistry expressed as either individual moieties or chemical groups. Across all soils, the nitrogen content of organic matter was strongly correlated with soil biological processes including enzyme activities and fungal/bacterial ratios. Soil texture strongly predicted both the abundance of lignin derivatives and nitrogen-containing compounds. The study showed the potential for strong relationships between soil biological processes and soil organic matter chemistry and for the overriding influence of edaphic soil properties such as soil texture on these relationships.

Lastly, to examine effects of land-use history on soil spatial heterogeneity of chemical elements and soil properties, Li et al. (2010) sampled surficial soils (0–7.5-cm mineral soils) using a spatially explicit design within three 0.09-ha plots in three replicates of the never-cultivated hardwoods, cultivated agricultural fields, and old-field pine forests about 50 years in age. Results indicated that land-use history altered soil properties' central tendencies and their spatial heterogeneities; within-plot variations were generally much higher in hardwood and pine forest soils than in cultivated soils; for soil carbon and major and trace elements, trend surface analysis, correlograms, and interpolation maps indicated pronounced spatial patterns were evident in surface soils under hardwood and pine forests and much less so in cultivated soils. Relative to soils that have never been cultivated, spatial heterogeneity is greatly reduced in many soil properties by plowing, fertilization, and other practices associated with agricultural crop production, but pine forest growth on previously cultivated soils reestablishes at least some of the heterogeneity of soil properties within a few decades. Overall, within-plot variances were high for most properties especially of the forested soils and emphasize that researchers should pay careful attention to soil-sampling designs and sample sizes, given the variability of soil properties they are studying. Li et al. (2010) demonstrate clearly that optimal sample sizes are a function of land-use history.

### *18.6.6 The Discovery of a New Biologically Driven Mineral Weathering Reaction?*

Detailed investigations of biologically driven acidification and weathering have for several decades been a theme of research at the Calhoun (Richter and Markewitz 1995a, b, 2001; Richter et al. 1994; Markewitz and Richter 1998). Research has recently focused on rhizosphere effects on pedogenesis in general (Richter et al. 2007b) and on rhizogenic iron–carbon redox cycling (Fimmen et al. 2008b) as an underexplored ecosystem process with many implications (Fig. 18.7).

Since the early days of research at the Calhoun Experimental Forest, internal soil drainage and aeration were understood to be key characteristics of upland Piedmont soils (Copeland and McAlpine 1955; Hoover 1950). In many upland soils with inhibited drainage, precipitation events periodically inhibit oxygen diffusivity, especially in subsoil B horizons, which allows the oxidation of organic reductants to mobilize manganese and iron via reductive dissolution (Fimmen et al. 2008b; Richter et al. 2007b). Rhizospheres are microsites in subsoils with concentrations of organic reductants and where reduction is most pronounced. Without oxygen, manganese and iron are reduced and mobilized from near-root microsites only to oxidatively precipitate in surrounding, more oxidizing soil environments (Fig. 18.7). Although upland Calhoun soil profiles in most conditions are aerobic, these periodic suboxic and anoxic events are most pronounced in rhizosphere microsites that create redoximorphic features that are strongly depth dependent (Fig. 18.7). Because oxidation and reduction reactions of redox-active metals are accompanied by significant

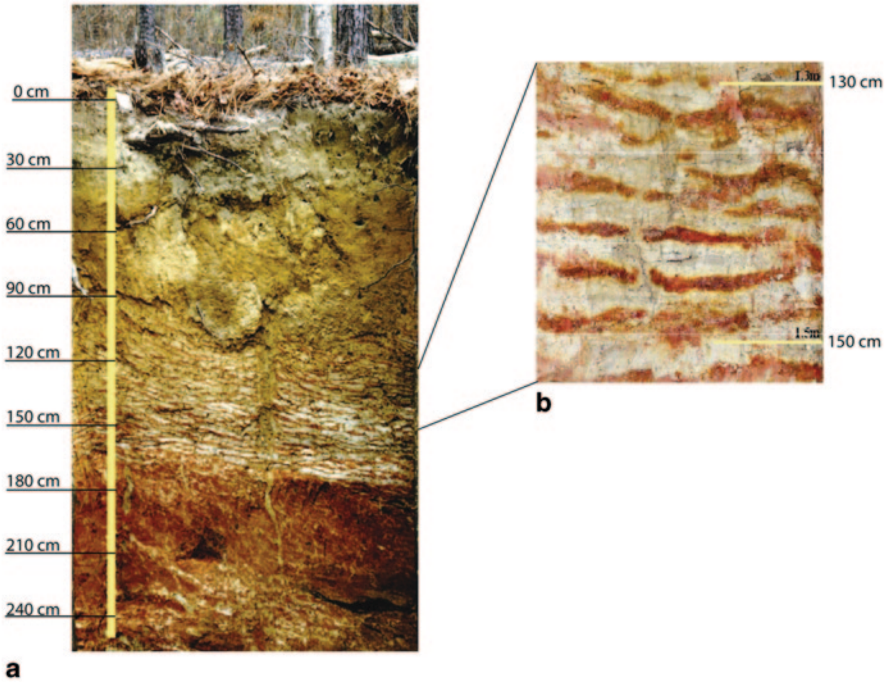


**Fig. 18.7** Calhoun soil profile illustrating major soil horizons, 0–240-cm depth. The inset photo from 130 to 150 cm illustrates prominent redoximorphic microsites of the lower B horizons

transfers of electrons and protons, we hypothesize that these iron–carbon redox reactions are part of a potent weathering process, complementing the more well-studied acid-promoted and ligand-promoted reactions as biogeochemical processes that drive crustal weathering (Fimmen et al. 2008b; Richter et al. 2007b). Moreover, we hypothesize that rhizogenic iron–carbon redox cycling is significant due to the deep and extensive rooting and mottling of many upland subsoils across a wide range of plant communities, lithologies, and soil-moisture and temperature regimes.

### *18.6.7 Just How Old are Piedmont Soils and Land Surfaces?*

On the granite–gneiss bedrock of the southern Piedmont, soil development on biogeomorphically stable surfaces is not dissimilar to some of the advanced weathering-stage soils in the humid lowland tropics. Soil systems of the Calhoun Experimental Forest are extremely acidic, all weatherable primary minerals have been exhausted for many meters, and soil profiles have accumulated to fantastic depths, i.e., to several tens of meters, all over unweathered bedrock (Bacon 2010; Bacon et al. 2012; Richter and Markewitz 1995a, 2001). Mass-balance calculations using total elemental contents referenced to insoluble elements such as zirconium or titanium indicate that nearly all calcium-bearing and sodium-bearing minerals are depleted for 5 m to greater than 10 m in depth (Oh and Richter 2005; Rasmussen et al. 2011).

To estimate residence times of such soils and interfluves, geomorphologists inventory meteoric $^{10}$Be in soil profiles. The minimum age of a land surface can be estimated from the quotient of a soil's $^{10}$Be inventory and the estimated rate of atmospheric deposition of $^{10}$Be, accounting for radioactive decay and erosional losses. In the past, the approach assumes immobility of $^{10}$Be, i.e., that atmospheric deposition is accumulated in the soil profile with no solution leaching. Beryllium solubility, however, is strongly controlled by pH, and in chemical systems with pH less than 5, beryllium dehydroxylates and reacts as a divalent cation, thereby becoming subject to cation-exchange reactions like those affecting the mobile cations calcium and magnesium. Mass-balance estimates of total beryllium ($^{9}$Be) in this Calhoun soil profile indicate that at least 60 % of the beryllium in unweathered rock has been lost by leaching. By coupling this mass balance of total beryllium with the meteoric $^{10}$Be inventory, we have redefined pedogenic time on the Piedmont and estimate that soils on Piedmont interfluves have resided at Earth's surface for much if not all of the Quaternary. (Bacon 2010; Bacon et al. 2012).

## 18.7 Conclusions: The Future of the Calhoun LTSE and Critical Zone Observatory

In May of 2007, 8 of the 16 sampling plots of the Calhoun's LTSE were clearcut harvested. A local logger was contracted to clear all trees from the plots planted in the winter of 1956–1957 and in surrounding buffer zones and to do so in an operational manner. In the winter of 2008–2009, the cutover plots were replanted with pine seedlings by Duke University students, and seedling survival as of the summer of 2011 is more than 95 %. A comprehensive sampling of fresh logging slash was initiated on the eight cutover plots, and this organic material has been resampled in 2010, 3 years after logging.

Looking back, the long-term Calhoun experiment has quantified pine forest growth effects on a bare old-field soil; looking forward, the Calhoun experiment will quantify pine forest growth effects on a cutover forest soil. The dynamics of the variable amounts of logging slash among the eight cutover plots provide great experimental interest to the renewed long-term study. The long-term experiment will be testing differences in soil and ecosystem biogeochemistry between a second-rotation pine plantation with that of forests planted in 1956–1957 that are transitioning to hardwoods.

We know remarkably little about how soils change over decades and centuries, not only because soils are so spatially variable, hard to observe, and highly complex but also because so few long-term field experiments have been set out to directly observe changes in soils over time. In the last century, while long-term measurements of weather, floods, water quality, human health, wildlife, earthquakes, and air pollution have all become indispensable for guiding decision-making in natural resource and environmental management, long-term observations of soils have lagged far behind (Richter et al. 2007a). Humanity is rapidly changing the Earth's soil on local to global scales (Richter 2007; Richter et al. 2011), and long-term soil experiments such as those which Metz and Wells set out on the Calhoun Experimental Forest are becoming increasingly valuable (Richter et al. 2007a; Richter and Yaalon 2012).

The continuity of the long-term Calhoun experiment has allowed researchers to learn much about the functioning of soils and whole ecosystems, and about the importance of environmental history to the environmental present and future. The more we have studied the Calhoun ecosystems, the more we appreciate the importance of historical impacts that still affect many components and processes of contemporary Calhoun soils and ecosystems. There is still much to learn at the Calhoun's LTSE, just as there was when the Calhoun Experimental Forest was first established. One difference is that in 2010, the region's soils, so long cultivated for cotton, have now been greatly altered by old-field forest regeneration over more than half a century of forest development. Both historic cultivation and reforestation have now transformed Calhoun soils like many others across the South, and nearly all soils of the region are now thoroughly influenced by human culture.

After Wells' retirement in the late 1980s, the field experiment has been continued by Daniel Richter in a Duke University–USDA FS collaboration with key USDA Forest Service support from Mac Callaham, Tom Waldrop, Mary Morrison, and Beth LeMaster. Many others have participated along the way. Since the 1980s, researchers have competed successfully for financial support from a wide range of research organizations, sustaining the Calhoun's long-term research entirely from short-term competitive research grants. The USDA's competitive grants programs supported Calhoun research on acid deposition effects in the late 1980s and early 1990s. After passage of the 1990 Clean Air Act diminished the research priority of acid deposition, forest carbon cycling became a national research priority, and from the mid-1990s to the present, Calhoun research has been supported to document both the forest's accumulation rate of carbon and the biogeochemical details of the forest carbon cycle. The carbon research has been funded by several competitive research programs of the National Science Foundation and the USDA as well.

After 2001 and the publication of *Understanding Soil Change,* the Calhoun field experiment became a platform that investigated a range of basic biology, ecosystem, and biogeochemistry questions. This research has been supported by NSF's programs in the Biology and Geosciences Directorates, the Andrew W. Mellon Foundation, the Trent Foundation, the Forest History Society, and Duke University. This support has encouraged the evolution of the Calhoun field experiment toward one that couples soil and ecosystem processes, quantifies biogeochemical changes in ecosystems aboveground *and* belowground on timescales of decades, documents soil biological community responses to ecosystem development, and examines the importance of environmental history in forests and soils.

Calhoun researchers are convinced that LTSEs are critical to understanding and managing ecosystem sustainability. We have therefore established a Web site-driven inventory of the world's LTSEs to initiate a global network of LTSE experiments and scientists. The LTSE inventory now numbers about 250 studies on all continents, and the project encourages scientists to write cross-LTSE review papers and initiate new cross-LTSE research (Richter and Yaalon 2012).

Calhoun researchers also welcome the news received in June 2013 that the research site will become one of the nation's nine Critical Zone (CZ) Observatories.

The concept of the CZ is related to the ecologist's "ecosystem" (Pickett and Cadenasso 2002), and Calhoun researchers view the CZ as an "expanded ecosystem," ranging as it does from the atmosphere and uppermost plant canopy boundary layers down through the root zone and soil to the deepest penetration of groundwater (Amundson et al. 2007; Brantley et al. 2006; Lin 2010). While the lower bounds of the ecosystem are often marked by the depth of rooting, the subsurface CZ extends throughout the full biogeochemical zone of Earth's crustal weathering. The CZ is an "expanded ecosystem" due also to its scientific breadth that marshals participants from biology, ecology, geology, pedology, hydrology, biogeochemistry, climatology, geomorphology, sedimentology, geochemistry, geophysics, engineering, materials research and even social science, environmental history, and perhaps someday environmental humanities. The US National Research Council (NRC 2001) described the integrated study of Earth's CZ as one of the most compelling research areas in the Earth sciences in the twenty-first century, and Calhoun researchers anticipate addressing questions about how natural and human forcings affect CZ dynamics and evolution, specifically to improve understanding and management of the Earth's CZ in the face of land-use change and land degradation, and how human-forced CZs alter human well-being.

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