Understanding Ecosystem Change at the Calhoun Experimental Forest's Long-Term Soil Experiment

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Environmental history in the Southern USA

Human history has had significant and far reaching impacts on the Earth's soil. Even still, notably few studies anywhere estimate rates and processes of soil's degradation, restoration, and sustainability through historic time. We study such phenomena in the USA's South where much is written about economics, human inequity, strife, and tragedy, and far too little about history's impact on the environment. In the South as elsewhere, one of the most significant environmental impacts of human history is on the soil, which across enormous areas has been thoroughly transformed by human activity: chemically, biologically, and physically.

In 1947, the USDA Forest Service with incredible foresight established the Calhoun Experimental Forest to document and promote the Southern soil's recovery from up to 150 years of extensive cultivation mainly for cotton (Metz 1958).

To better understand why the Forest Service chose the Calhoun Experimental Forest and to better tell the story of the Calhoun's contribution to science and management, we first very briefly review landscape history in the South.

In the early 1800s, new cotton markets spurred the clearing and conversion of the great Southern forest to an agricultural economy based largely on cotton. Interrupted by only the Civil War, cotton's production boomed throughout the 19th century (Gray 1933), peaking by many measures in the 1920s (Fig. 1). But shortly after 1920, as rapidly as cotton had grown, it collapsed.

Many factors spelled cotton's rapid demise, chief among these being depredation by the exotic boll weevil, expanding cotton production in other regions, emigration of farmers to cities, but also the accumulating toll paid by Southern soil (a factor referred to as "soil exhaustion" at the time). A historian (Johnson et al. 1935) described the 1930s Southern landscape as, "a miserable panorama of unpainted shacks, rain-gullied fields, straggling fences, and rattle-trap Fords ... that stretches for a thousand miles across the cotton belt." Although the passage of subsequent decades has hidden cotton's impacts on the soil under a cover of pines, kudzu, honeysuckle, and Bermuda grass, the South's soils have been almost permanently altered by this land-use past.

Original perspectives at the Calhoun Experimental Forest

It was during depression-era in the 1930s that the USDA Forest Service created the Sumter National Forest which would later include the Calhoun Experimental Forest. The Sumter forest was assembled from highly eroded lands, and according to Dr. Lou Metz (1958), the Experimental Forest's first director, "the Calhoun Forest was chosen because it represented poorest Piedmont conditions." Across whole watersheds, soils formerly cultivated for cotton were eroding and gullying, and were chemically altered, physically degraded, and lacking in vegetative cover (Fig. 2).

Metz and his staff of first-rate scientists initiated soil studies in earnest (e.g., Hoover 1950, 1952, Hoover and Lunt 1952, Metz 1952, Hoover et al. 1953, Metz 1954, Copeland and McAlpine 1955). They conceived their work to be “aimed principally at soil improvement.” Metz would go on to say, “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.” If soils and watersheds could be restored and stabilized at the Calhoun, they could likely be restored anywhere in the South.

The Calhoun’s Versatile Long-Term Soil Experiment

One of the Metz’ experiments would become one of the finest long-term ecological studies in the world (Fig. 3). The study, now known as the Calhoun Long-Term Soil Experiment (LTSE), was initiated by Metz in 1957, was guided and expanded by Dr. Carol G. Wells (USFS) from the 1960s to the 1980s (Wells and Jorgensen 1975), before becoming managed by a Duke University-USFS collaboration in the late 1980s (Richter and Markewitz 2001).

The nearly 50-year-old experiment demonstrates remarkable continuity, collaboration, and productivity of research. The experiment’s long-running success is due to its ability to address a changing series of scientific issues important to society and the environment. The experiment’s versatility has allowed researchers to attract financial support from a wide range of research organizations, but also to develop a quantitative understanding for why environmental history is directly relevant to contemporary environmental issues.

This versatility can be illustrated by five issues that the long-term Calhoun study has addressed since it was initiated nearly five decades ago.

1. Soil and Watershed Restoration: At the beginning, the Metz experiment was straightforward: to plant pine seedlings at four densities or spacings (at 6 x 6, 8 x 8, 10 x 10, and 12 x 12 ft) and thereby to learn details of how pine forests grew on previously cultivated farmland (Fig. 3). The experiment supported the overall mission of the Calhoun Forest and that of an on-going national effort initiated during the 1930s: to improve soil and watershed management across the Southern landscape (Metz 1958).

Results from the study were reported in Forest Service publications and historic Calhoun correspondence demonstrates a regional interest in the spacing study. On the other hand, research priorities were changing in the 1960s and 1970s, other loblolly spacing trials were planted, and the local Calhoun research station was closed and moved mainly to the Research Triangle Park, North Carolina. The Calhoun spacing trial would have disappeared if it were not for the Dr. Carol Wells' continuing interest in the experiment as a study of nutrient cycling and productivity (Wells and Jorgensen 1979).

2. Industrial Wood Production: During the latter half of the 20th century, the USA South grew to become the largest industrial wood-producing region in the world. The harvested wood came mainly from old-field pine stands not unlike the Calhoun plantings of Metz. As the Calhoun pine stands grew they provided growth and yield data that were used in Ph.D. dissertations, regional stand-growth models, industry data bases, and various plant productivity investigations, all aimed at relationships of tree spacing, mortality, linear and volumetric dimensions of tree and stand dynamics, biomass, and ecosystem productivity (DeBell et al. 1989, Buford 1991). The work paralleled research throughout the region, being aimed at gaining technical understanding of ecosystem processes that control fiber productivity. How remarkably ironic that the South was the world's major producer of cotton fiber in the 19th century, and also of industrial wood fiber in the 20th, basically on the same soil resource.

Although results of the Calhoun forest continue to have implications for watershed improvement and industrial wood production, the experiment's purview has expanded greatly to address contemporary environmental issues such as acid rain, carbon sequestration, and ecosystem sustainability.

3. Air Pollution's Effects on Soil Acidification: Thanks to Dr. Carol G. Wells, the Calhoun field study is supported by a soil-sample archive that makes it one of the world's few research installations at which soil chemical change can be directly observed for many decades. During the 1980s, when scientific and public interest in acid deposition was great, the ecological impacts of acid rain were more than a little controversial. In part, this uncertainty was due to the notable absence of long-term ecological research studies and thus an absence of direct evidence of soil acidification. Computer simulations of soil chemistry proved to be no substitute for direct observation (Binkley et al. 1989, Richter et al. 1994), and thus the Calhoun's direct evidence for significant acidification (Fig. 4) was featured in national assessments of acid rain and air pollution (Richter 1991, Richter and Markewitz 1995).

Not only have Calhoun soils acidified significantly since the 1960s, decreasing more than a full pH unit in surficial layers of soil (Fig. 4), the experiment was used to estimate that up to 40% of the directly observed increases in soil acidification was attributable to air pollution's acidity in precipitation (Markewitz et al. 1998). The Calhoun continues to be one of the very few long-term experiments that can make such estimates.

4. Forest Carbon Sequestration: The long-term Calhoun study demonstrates not only how and why forest growth acidifies soil, the experiment has quantified how the forest sequesters organic carbon in the decades of its development (Harrison et al. 1995, Richter et al. 1999).

Rising national and international demands for data on carbon gain and loss from ecosystems have made research sites such as the Calhoun invaluable for providing carbon cycling information for scientists, policy analysts, and the general public. The Calhoun study is particularly special as its carbon estimates are of the whole forest ecosystem over four decades, i.e., direct observations of 40-year changes in carbon sequestration in plant biomass, forest floor, *and* mineral soil.

Cultivation depleted organic matter of Calhoun soils when the soil supported cotton, although these cultivation effects are slowly slipping from the soil's memory, as the forest adds enormous amounts of organic carbon to the soil each year and expands its woody root systems throughout the upper meters of soil. The Calhoun forest as a whole has proven to be a very strong sink for atmospheric CO_2, sequestering over 16 kg m^{-2} in its four-decade lifetime, a rate in excess of 400 g m^{-2} y^{-1} (Richter et al. 1999).

On the other hand, Calhoun results document the remarkably rapid rate at which the mineral soil turns over most organic carbon inputs. Under Calhoun conditions, i.e.,pines growing in the warm temperate zone on upland soils with coarse-textured surface layers, favor rapid decomposition (turnover) of forest carbon inputs. Rapid turnover is readily evident in the record of "bomb carbon" in the Calhoun forest and soil (Fig. 5). Because the Calhoun forest was planted and has grown entirely within and immediately after the era of aboveground thermonuclear bomb testing (the 1950s and '60s), the nearly doubled concentration of radio-carbon (14 gram per mole carbon) in atmospheric CO_2 labeled all Calhoun forest carbon with the bomb-carbon signature. Figure 5 illustrates how rapidly and deeply bomb carbon entered and passed through the soil system, and emphasizes how rapidly forest-carbon has been lost from the mineral soil as well. These data demonstrate that will take many more decades for the forest to recover the organic carbon lost due to cultivation.

5. Basic Soil and Ecosystem Functioning: In addition to providing an invaluable record of soil acidification and carbon sequestration, the Calhoun experiment informs us about the basic science of how soil functions, e.g., how soil provides an organic basis to soil fertility, how soil supports a continuity of plant growth, how soil immobilizes atmospheric pollutants, and how soil interacts with the greater environment of drainage water and the atmosphere.

Despite 10,000 years of soil use for agriculture and engineering objectives, we know remarkably little about how soil functions, mainly because as one scientist in *Science* magazine stated in July 2004, "soil is the most complex biomaterial on the planet." A variety of analytical techniques from microbiology, molecular biology, organic chemistry, stable isotope geochemistry, and soil ecology are all being trained on the Calhoun soil and ecosystem to learn more about the fundamentals of how humans change the high-order interactions of biology, chemistry, and physics that create and sustain soils. The spacing study installed by Metz and expanded by Wells has grown to be one of the most exciting long-term experiments on soils in the world.

What more can be learned?

Long-term measurements of weather, floods, water quality, human health, wildlife, earthquakes, and air pollution, are all indispensable for environmental science and for guiding decision-making in natural resource management. In contrast, there are few long-term soil experiments with which scientists and the general public can use to observe soil change as it is transformed by humans nearly everywhere on Earth. Humanity is changing fundamental relationships between the Earth's soils and the atmosphere, water systems, and biota, yet observations of soil change are notably deficient.

Although it has taken nearly 50 years, the continuity of the Calhoun LTSE now provides very special research platform to learn much about the basic functioning of soils, the ecosystem dynamics that soils support, and the significance of environmental history to the environmental future. There is obviously much to learn at a research site like the Calhoun Experimental Forest, where soils continue to be influenced by legacies of land-use past, just as they were when Metz and his colleagues established the Forest in 1947. The difference that six more decades makes is that in 2005, Southern soils long-cultivated for cotton have now been fundamentally altered by the growth of secondary forests that have both benefited but also demanded much from their rooting zones. Both historic cotton and contemporary forest ecosystems have transformed the chemistry, biology, and physics of soils such that Calhoun soils like those across the South are now a system deeply influenced by human culture.

Investigators at the Calhoun consider long-term soil experiments (LTSEs) to be an indispensable approach to understanding soil sustainability; and they have initiated a website-driven inventory of the world's LTSEs which they hope will eventually lead to a networking of such experiments. The project seeks to stimulate cross-site studies among LTSEs such as that at the Calhoun, Rothamsted, and others, studies aimed at understanding soil functioning and sustainability. The project's website is: <http://ltse.env.duke.edu>.

Legacies of cotton and more recent forests have both depleted and enriched soil fertility, depending on chemical element and biogeochemical process. The soil system is not dissimilar to an observation made about human events by William Faulkner in his 1951 *Requiem for a Nun*, "The past is never dead. It's not even past."

Selected Calhoun Experimental Forest and Related Citations

Billings, S.A., D.D. Richter. Changes in stable isotopic signatures of soil nitrogen and carbon during forty years of forest development. *Oecologia* (submitted July 2005)

Binkley, D., D. Valentine, C. Wells, and U. Valentine. 1989. An empirical analysis of the factors contributing to 20-yr decrease in soil pH in an old-field plantation of loblolly pine. *Biogeochemistry* 8:39-54.

Buford, M.A. 1991. Performance of four yield models for predicting stand dynamics of a 30-year-old loblolly pine (*Pinus taeda* L.) spacing study. *Forest Ecology and Management* 46: 23-38.

Callaham, M.A., D.D. Richter, D.C. Coleman, and M. Hofmockel. Long-term land-use effects on soil invertebrate communities in Southern Appalachian Piedmont soils. *European Journal of Soil Science*. (in press).

Copeland, O.L. and R.G. McAlpine. 1955. Interrelationships of littleleaf, site index, soil, and ground cover in Piedmont shortleaf pine stands. Ecology 36: 635-641.

DeBell, D.S., W.R. Harms, and C.G. Whitesell. 1989. Stockability: a major factor in productivity differences between *Pinus taeda* plantations in Hawaii and the southeastern United States. *Forest Science* 35:708-719.

Fierer, Noah, Jason A. Jackson, Rytas Vilgalys, and Robert B. Jackson. The assessment of soil microbial community structure using taxon-specific quantitative PCR assays. *Applied Environmental Microbiology.* (in press).

Fimmen, R.L. 2004. Organic geochemistry of the South Carolina Piedmont: Decomposition, Mineral Associations, and Ferrolysis. Ph.D. Dissertation, Duke University, Durham, NC, USA.

Fimmen, R., D.D. Richter, D. Vasudevan, M.A. Williams, and L.T. West. Rhizogenic iron and carbon redox cycles that drive mineral weathering. *Science* (submitted 2006).

Gray, L.C. 1933. *History of Agriculture in the Southern United States to 1860.* The Carnegie Institution of Washington, Washington, D.C.

Harrison, K., W. Post, and D.D. Richter. 1995. Recovery of soil carbon by reforestation of old-field soils. *Global Biogeochemical Cycles* 9:449-454.

Hoover, M.D. 1950. Hydrologic characteristics of South Carolina Piedmont forest soils. Soil Science Society of America Proc. 14: 353-358.

Hoover, M.D. 1952. Water and timber management. Journal of Soil and Water Conservation 7: 75-78.

Hoover, M.D. and H.A. Lunt. 1952. A key for the classification of forest humus types. Soil Science Society of America Proc. 16: 368-370.

Hoover, M.D., D.F. Olson, and G.E. Greene. 1953. Soil moisture under a young loblolly pine plantation. Soil Science Society of America Proc. 17: 147-150.

Jackson, J., R. Vilgalys, and D.D. Richter. 2005. Using ITS clone libraries to assess soil fungal diversity in the South Carolina Piedmont. Soil Ecology Society. 10th Biennial Conference. Argonne, IL.

Johnson, C. S., E. R. Embree, and W.W. Alexander. 1935. *The Collapse of Cotton Tenancy*. University of North Carolina Press, Chapel Hill, USA.

Li, J.W. and D.D. Richter. 2005. Long-term changes in soil Mn, Zn, and Cu as affected by four decades of forest growth. Soil Science Society of America Abstracts to Annual Meeting, Salt Lake City.

Markewitz, D. 1995. Soil acidification, soil potassium availability, and biogeochemistry of aluminum and silicon in a 34-year-old loblolly pine (*Pinus taeda* L.) ecosystem in the Calhoun Experimental Forest, South Carolina. Ph.D. Dissertation, Duke University, Durham, NC, USA.

Markewitz, D. and D.D. Richter. 1998. The bio- in Al and Si geochemistry. *Biogeochemistry*. 43:1-17.

Markewitz, D. and D.D. Richter. 2000. Long-term soil potassium availability from a Kanhapludult to an aggrading loblolly pine ecosystem. *Forest Ecology and Management* 130: 109-129.

Markewitz, D., D.D. Richter, H.L. Allen, J. B. Urrego. 1998. Three decades of observed soil acidification at the Calhoun Experimental Forest: Has acid rain made a difference? *Soil Science Society of America Journal* 62: 1428-1439

Metz, L.J. 1958. The Calhoun Experimental Forest. Southeastern Forest Experiment Station, Asheville, NC., 24 p.

Metz, L.J. 1952. Weight and nitrogen and calcium content of the annual litter fall of forests in the South Carolina Piedmont. Soil Science Society of America Proc. 16: 38-41.

Metz, L.J. 1954. Forest floor in the Piedmont region of South Carolina. Soil Science Society of America Proc. 18: 335-338.

Richter, D.D. 1991. Effects of acidic deposition on soils. pp. 16/73-16/78. In P.M. Irving (ed.) Volume III, Terrestrial, Material, and Visibility Effects of Acidic Deposition, State of Science and Technology, U.S. National Acid Precipitation Assessment Program, Washington, D.C.

Richter, D. D. and D. Markewitz. 1995. How deep is soil? *BioScience* 45: 600-609.

Richter, D.D. and D. Markewitz. 1995. Atmospheric deposition and soil resources of the southern pine forest. pp. 315-336. IN S. Medlarz and R. Mickler (ed.) Air Pollutants and Southern Pine Forests. Ecological Studies Series. Springer-Verlag, New York.

Richter, D.D. and D. Markewitz. 2001. *Understanding Soil Change.* Cambridge University Press, UK.

Richter, D.D., D. Markewitz, C.G. Wells, H.L. Allen, R. April, P. Heine, and B. Urrego. 1994. Soil chemical change during three decades in an old-field loblolly pine (*Pinus taeda* L.) ecosystem. *Ecology* 75:1463-73.

Richter, D.D., D. Markewitz, J. Raikes, and H.L. Allen. Soil phosphorus dynamics in a rapidly aggrading pine forest. *Oecologia* (submitted 2005).

Richter, D.D., D. Markewitz, P.R. Heine, V. Jin, J. Raikes, K. Tian, and C.G. Wells. 2000. Legacies of agriculture and forest regrowth in the nitrogen of old-field soils. *Forest Ecology and Management* 138:233-248.

Richter, D.D., D. Markewitz, S.A. Trumbore, and C.G. Wells. 1999. Rapid accumulation and turnover of soil carbon in a re-establishing forest. *Nature* 400:56-58.

Wells, C.G. and J.R. Jorgensen. 1975. Nutrient cycling in loblolly pine plantations. pp. 137-158. In B. Bernier and C.H. Winget (ed.). *Forest Soils and Forest Land Management*, Fourth North American forest soils conference. Laval Univ. Press, Quebec, Canada.

Wells, C.G. and J.R. Jorgensen. 1979. Effect of intensive harvesting on nutrient supply and sustained productivity. pp. 212-230. In A. Leaf (ed.). *Impact of Intensive Harvesting on Forest Nutrient Cycling*. State University of New York at Syracuse, USA.

Rise and fall of Old South cotton

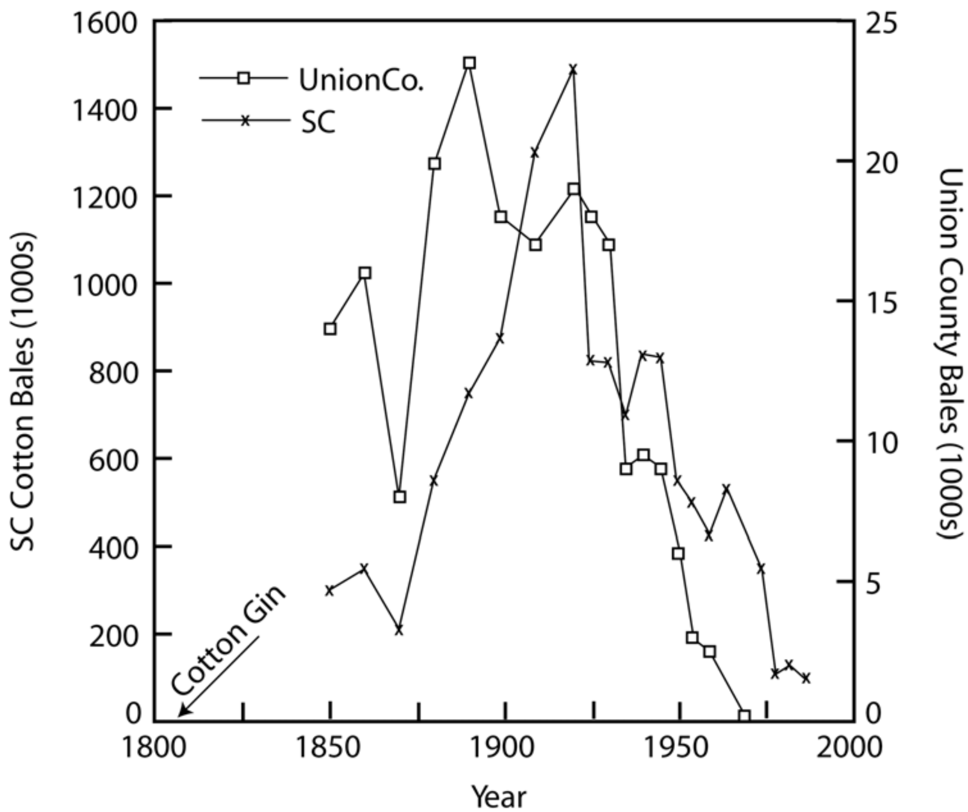

Fig. 1. 19th and 20th c. pattern of cotton production in South Carolina and in Union County, the county where the Calhoun Experimental Forest is located. (US Dept. Commerce Agricultural Census data, cited in Richter and Markewitz 2001).

Gullies in South Carolina Piedmont

Fig. 2. An example of cotton's erosional impact on Southern Piedmont soil, not uncommon throughout the old cotton belt (USFS photo, 1950s, Calhoun Experimental Forest).

Calhoun LTSE, newly planted in 1958

Fig. 3. The pine-spacing trial designed by Dr. Metz that grew into the Calhoun's Long-Term Soil Experiment (LTSE). Planted in the winter of 1956-57 on old cotton fields with four tree spacings and four experimental blocks (ie, 16 permanent plots), the study is a model of research continuity (USFS photo, Calhoun Experimental Forest).

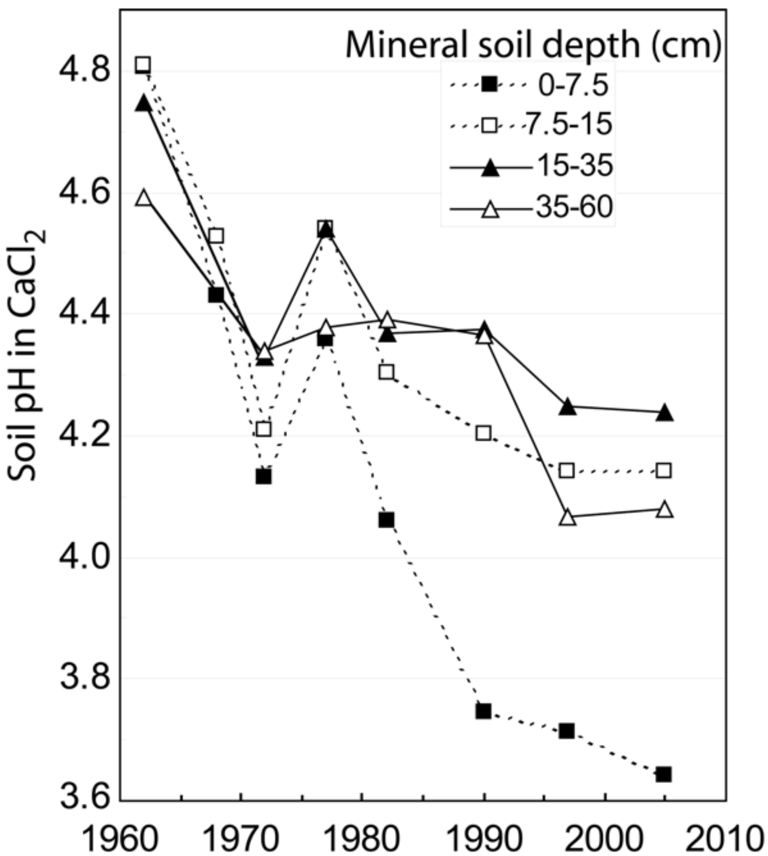

Figure 4. The growth of the Calhoun pine forest has been accompanied by substantial soil acidification, here indexed by soil pH in 0.01 M $CaCl_2$). The pH has decreased in surficial soils by nearly 1.2 pH-units, the 7.5 to 60-cm layers by about 0.5 pH-units.

Rapid turnover of mineral soil ^{14}C

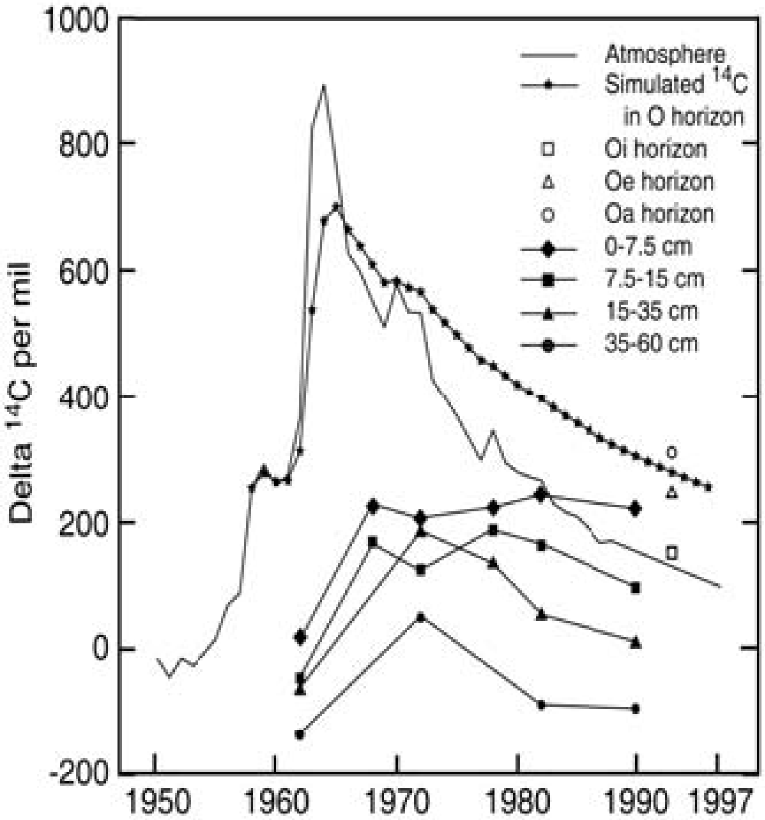

Fig. 5. Time trends of ^{14}C (bomb carbon) in atmospheric CO_2 (1950-1997); three layers of 1992 forest floor (Oi, Oe, & Oa); and mineral soil (in 1962, 1968, 1972, 1977, 1982, and 1990) at the Calhoun Experimental Forest. Simulated changes in ^{14}C in O horizons (1957-1996) are estimated from a decomposition model & estimates of litterfall inputs over the four decades. Forest carbon of the regrowing Calhoun forest coincides with the aboveground thermo-nuclear bomb explosions that nearly doubled ^{14}C in CO_2 by 1963, the year the USA and USSR signed the Nuclear Test Ban Treaty.