SOIL SCIENCE AND SURVEY AT HARVARD FOREST

by

A. Allen

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Abstract

Personnel at Harvard University and its research forest have made important contributions to soil science over the last 150 yr. From the early days of agricultural geology through the period of intensive forest-site management (in southern New England) to the modern focus on historic land-use effects and global change, Harvard scientists and collaborators have made soil-based studies a priority. Although the focus of this article is on the Harvard Forest soil survey and update, the context for that discussion is the long history of Harvard's involvement with soil science.

Harvard Forest (in Petersham, Massachusetts) is a Harvard University research institution. It is the oldest experimental forest in the USA and has been continuously owned and managed by Harvard University since 1907. During the 1993 field season, I was involved with the soil survey and sampling of permanent plots which were established in 1937. As field work progressed, I became aware of inconsistencies in our large scale (1 in. = 200 ft) soil survey maps which had been in use since 1941. At the end of the field season, an effort to update these original maps was initiated. While gathering background information for the update project, I was led to consider some important historical contributions by Harvard University personnel to soil science and forest soil survey.

Harvard Forest Description

By and large, the modern Harvard Forest's 3000 acres support stands of second growth mixed hardwoods [maple (*Acer* spp.), birch (*Betula* spp.), beech (*Fagus* spp.), cherry (*Prunus* spp.), ash (*Fraxinus* spp.), oak (*Quercus* spp.)], with some stands of old-field white pine (*Pinus strobus*) and plantations of red pine (*Pinus resinosa* Ait.) and spruce (*Picea spp.*), all growing in the transition zone between northern and central hardwoods. The landscape was extensively cleared for cultivation and pasturage with 70 to 80% deforestation at the height of agricultural clearing in 1860. The only parcels left uncleared were generally stony and/or wet and are currently dominated by eastern hemlock (*Tsuga canadensis*) and red maple (*A. rubrum* L.). Following abandonment, the old fields were either allowed to self-seed from the edges with white pine or were planted with non-native pine and spruce. The even-aged pine stands suffered extensive damage in the 1938 hurricane and, except for sheltered remnant stands, were replaced by native hardwoods already present in the understory. The modern forest is growing on soils formed from schistose and gneissic glacial drift of mixed mineralogy. Sandy loam tills (coarse-loamy, mixed, mesic or frigid Typic Dystrochrepts or Haplorthods) with or without hardpans predominate on most upland landscape features (drumlins and roche moutonnees), while sandy outwash

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[1] Soil Scientist, Harvard Forest, Harvard University, P.O. Box 68, Petersham, MA 01366.

is found in lower slope terraces and deltas. Muck and peat over till or outwash occurs in closed depressions on low-lying landscape positions.

Pre-Soil Survey History (1848–1939)

A logical place to begin a history of Harvard's involvement in soil science is with the tenure of Louis Agassiz, the father of modern glacial theory. Agassiz came to Harvard in 1848, after initiating the scientific study of "ice-ages" in Europe. He was the first person to establish the extent of continental glaciation in America and, as professor at the Lawrence Scientific School of Harvard University, lectured extensively on geologic stratigraphy, geohistory and glaciation (Teller, 1947).

Although there is no indication that Agassiz ever wrote or lectured on the subject of soils, one of his more well-known students who did was Nathaniel Southgate Shaler (Tandarich et al., 1988). Harvard Forest's headquarters building is named after him and, according to his autobiography, he was "the only person who ever took the degree of geology under Agassiz." He was appointed professor of geology at Harvard in 1869 when he was 28 yr old. Concurrent with his work at Harvard he spent 16 yr with the U.S. Geological Survey, served as commissioner for the Topographical Survey of Massachusetts, and was a member of the Massachusetts Highway Commission, and the Massachusetts State Board of Agriculture. He directed the Atlantic Coast Division of the National Survey, and advised on mines and quarries nationally and internationally. Under Shaler's direction, the first topographic map of Massachusetts was completed. Shaler published nearly 200 technical titles (in addition to numerous popular magazine articles) on subjects including paleontology, glaciation, mountain building, shorelines, earthquakes, the elevation of the continents, swamps and peat deposits, soils, phosphate beds, petroleum, coal, building stones, changes in climates, caverns, and lunar geology (Wolff, 1906). Among his contributions to the study of forestry and soils is an article entitled "Forests of North America" published in the May 1887 edition of *Scribner's Magazine* in which he described the forests of the continent in terms of major biomes. In this article he described soil as "the least replaceable of any of those features on which the life of the earth depends. It is the harvest of the ages; and once lost, it cannot be supplied save by eons of time." He goes on to say, "The most serious misfortune connected with the reckless destruction of our forests arises from the loss of the soil from large areas of land, by which regions naturally fertile have been converted into deserts of irremediable sterility." He wrote 126 pages on "The Origin and Nature of Soils" for the 12th Annual Report of the Director of the U.S. Geological Survey in 1892 and delivered a lecture entitled "Soils of Massachusetts" at the annual meeting of the Massachusetts State Board of Agriculture in 1890.

A number of Shaler's contemporaries, at Harvard's research forest, helped to initiate the earliest attempts "to cross-fertilize soil science and the art of forestry" (Simmons and Lyford, 1941). The changing emphasis of Harvard Forest soil research has paralleled the shift in overall forest research emphasis from single species forest management to forest community and landscape ecology.

Early soil research focused on the influence of marketable forest species on soil and vice versa. R.T. Fisher, first director of the Harvard Forest (1907–1934) published an article entitled "Soil Changes and Silviculture on the Harvard Forest" (Fisher, 1928). Fisher, in collaboration with H. Hesselman (Director of the Swedish Institute of Experimental Forestry) describes improvements in soil properties as old-field white pine stands on "heavy" glacial till soils are converted to mixed hardwoods. This and subsequent articles by Harvard researchers and students (Griffith et al., 1930; Johnston, 1932; Gast, 1937), relating site suitability and productivity to soil properties during forest succession, helped to explain why pure stands of white pine were not always the best suited to upland sites. The "first generation" of Harvard Forest researchers also included Spurr (1939), who related juniper species to soil reaction and Scholz (1937) who studied the effect of soil texture on growth of red (*Q. coccinea* Muenchhi) and chestnut oaks (*Q. prinus* L.).

The Soil Survey (1939–1941)

P.R. Gast was the Harvard scientist primarily responsible for the original Harvard Forest soil survey. To my knowledge this was the first intensive forest soil survey completed in this country and was undertaken following a January 1939 request from P.R. Gast to C.E. Kellogg (Soil Survey Division Chief, U. S. Department of Agriculture) that stressed the "study of soils for their forest capabilities and maximum forest production." This written request was followed by a conference on "Soils and Forest," held at the Harvard Forest in June 1939. Representatives of the U. S. Department of Agriculture, forestry and soil science instructors from universities throughout the Northeast, experiment station personnel, and other research foresters observed forest soils and discussed the potential for and requirements of soil surveys on forested lands. Several weeks after the conference a letter was drafted from Harvard Forest Director Dr. W. Shepard to Dr. E. C. Auchter, Chief of the Bureau of Plant Industry, Chemistry and Soils (later the Soil Conservation Service). That letter detailed the survey requirements and noted how well-situated research forests were to utilize the results of detailed soil studies to improve forest management practice. Shepard emphasized that "just as agronomists and horticulturists are able to relate management of crops to soil types, the forester should be able to relate the management of forest crops of the region to soil types." In July 1939, authorization was granted to the chief of the Bureau of Plant Industry for Charles S. Simmons (Soil Survey Party Leader in Durham, New Hampshire) to implement soil surveys at Harvard Forest, Gale River Experimental Forest (U. S. Forest Service, Littleton, New Hampshire), and Fox Forest (New Hampshire Forestry and Recreation Department, Hillsboro, New Hampshire). Survey work at Harvard Forest was begun in the fall of that year and the resulting large scale (1:2400) soil maps have been in use since they were completed in 1941. Prior to the completion of the Harvard Forest survey by Simmons, the only extant soil survey resources for the area were in a small-scale (1:62 500) soil map of Worcester County (Latimer et al., 1927).

Post-Soil Survey Research (1941–1994)

Harvard Forest research after the soil survey was oriented towards the development of soil and topographic-based site concepts used to classify land for "best-use" forest species management. Many researchers were interested in relating the newly mapped soil types to tree species growth and distribution. Hoisington and Carr (1949, unpublished data) investigated the use of the red oak site index as a guide to the identification of soils and found that there was no correlation to the soil type as mapped. A number of studies looked at regrouping the existing soil units to more closely represent the ranges in stand types that they supported. In general, these studies divided some well-drained series according to upper (drier) and lower (moister) topographic position and combined the divided parts with other series having similar drainage classification and occurring on similar positions (Lutz and Cline, 1947; Spurr, 1956). Stout (1952) acknowledged the relationship of stand-types to extremes of mapped soil drainage [i.e., white pine on excessively drained outwash vs. red maple, white ash (*Fraxinus americana* L.) and yellow birch (*B. alleghaniensis* Britton) on very poorly drained, mucky mineral soils). At the same time, he recognized that on well-drained soils, species distribution is related to variation in such characteristics as depth to restricting layers and surface microtopography, both of which control rooting zone available moisture. A similar study that focused more closely on relating surficial geology and subsequent soil development to forest stands was carried out by Lyford et al. (1963). Both Stout and Lyford produced transect diagrams and maps at a "near-ultimate" scale (1 in. = 66 ft) which demonstrated variability within the soil types mapped by Simmons.

Many of Forest Director (1946–1967) Hugh Raup's writings and lectures on forestry, botany, and land use acknowledged the importance of integrating soil and vegetation studies (Raup, 1940, 1954, 1957). His address at the 1954 meeting of the New England Section of the Society of American Forests was entitled "Soil: A Basic Resource in Wood Production." This address underscored both the forester's need for site evaluation information and the soil scientist's desire to use forest patterns to better understand soils and their distribution. The pre- and postsoil survey history of forest site concept development at Harvard Forest was summarized by Goodlett in 1960.

Walter Lyford joined the Harvard Forest staff in 1960 after serving as the northeast region soil correlator for the Soil Conservation Service (SCS). His work encompassed Harvard Forest's shift in emphasis as forest management decreased and ecology increased in importance on its research agenda. He was a classically trained pedologist with broad ranging research interests in forest–soil site relationships (Lyford et al., 1963), soil formation (Lyford, 1963, 1973), soil morphology (Lyford, 1964a), soil geography (Lyford, 1974b), root-soil interactions (Lyford, 1966, 1980), and soil water (Lyford, 1964b; Lyford and Patric, 1980).

As forest research has become more ecologically oriented, studies relating soil properties to plant communities, watersheds, disturbance processes, and nutrient cycling on the local, regional and global scale have been initiated. The general role of soil nutrients in forested ecosystems has been investigated by a number of forest researchers (Patric and Smith, 1975; Pritchett, 1979; Stone, 1975), with recent emphasis on C and N dynamics (Aber et al., 1993a; Aber, 1992; Boone, 1994; Bowden et al., 1991; Nadelhoffer et al., 1984). Climate change (Aber et al., 1993b) and disturbance (Aber et al., 1983; Bowden et al., 1993a) effects on soil chemical and physical properties also have interested Harvard Forest soil scientists. The soil and forest floor organic matter component has been investigated, in recent years as a potential source and/or sink of greenhouse gases and nutrients (Aber et al., 1990a, 1990b; Boone, 1994; Bowden et al., 1993b; McClaugherty et al., 1984; Melillo et al., 1989).

These types of field-based soil process studies require a sound, soil morphological context to enable: (i) correlation of chemical and physical properties, (ii) determination of landscape relationships and (iii) comparison and contrast with other sites. Consequently, verification of Harvard Forest's original (1941) soil maps, using modern standards, was determined to be a priority in 1992.

Soil Survey Update (1994)

By 1992 Simmons' maps had become outdated for two reasons: (i) the system of U. S. Soil Taxonomy (upon which modern soil classification is based) was only beginning to develop in the early part of this century, and was not implemented until 1975 (Buol et al., 1989). In 1941, soil series were divided into soil types according to surface texture, allowing for a smaller number of series than are presently established (Hole and Campbell, 1985). The present system allows for finer distinctions in texture, drainage, and horizonation which are reflected in the redefinition of the series concept. (ii) Some of the original (1941) soil series, as named, have been discontinued while others underwent changes in definition as new series were added to capture more of the variability of soils on the landscape, especially in upland (less intensively cultivated) areas. For example, in 1941 there were 59 established series for Massachusetts whereas in 1994 there were 184. The classification and naming of soils has changed greatly since the 1940s and these changes have affected the relationships between historic and modern series concepts. The difficulties encountered relating historic to modern soil nomenclature combined with the need to provide an accurate soil morphological context for modern research provided the impetus for the update project.

Before deciding how to proceed with the update, Simmons' mapping protocol and all subsequent Harvard Forest soil information was reviewed. Modern data included soil studies, surveys and descriptions for the Harvard Forest collected by Lyford (1974), Stout (1952), Lyford et al. (1963), and B. Taylor (1988, unpublished data). These data helped to verify the original survey and interpretations made by Simmons. Current soil series descriptions from the U.S. National Cooperative Soil Survey (Soil Survey Staff, 1994) were compiled, including classification keys and designations from Soil Survey Staff (1992), advance SCS Worcester County soil survey map sheets for Harvard Forest tracts, and catena-based legends for Worcester and Franklin Counties from Conservation District and Soil Survey Staff (B. Booth and A. Averill, personal communication). This information showed good agreement between modern soil surveys, landscape and drainage patterns, and Simmons' mapped units. Use of the original soil unit delineations and descriptions was a concern because early surveyors tended to focus on soil properties in the rooting zone of field crops and would often fail to recognize or would misinterpret features at greater depths (e.g., C horizon texture and consistence and the occurrence of bedrock near the surface that didn't actually outcrop). These shortcomings seem to have been largely avoided at Harvard Forest due to the fact that foresters were involved in establishing the soil survey protocol and the product was intended to have forestry applications. In recent investigations on the Prospect Hill tract, at 19 of 20 sites where drainage class and the presence of a hardpan was determined in 1993, there was agreement with 1944 designations (R.D. Boone, unpublished data).

Simmons did not describe surface stoniness or slope for any of his soil types. Surface stoniness is a good indicator of the geologic and land-use history of a soil body. It should be noted that the stoniness described in Simmons' soil types is subsurface. In modern classification, subsurface stoniness is implicit in the series concept and stoniness modifiers, added to the phase of series name, describe surface conditions only. Slope gives an indication of the geomorphology of a landscape feature (on which soils subsequently developed) and influences drainage, rate of soil formation, and erosion. The merits of mapping slope and stoniness were discussed at the Soils and Forest Conference in 1939 and the consensus at the time was that these properties, although important in cultivated areas, did not relate directly to forest growth. In the light of this 1939 rationale and due to the high degree of detail already present on this map, it was decided not to add slope and stoniness phases in the update.

It is important to note that the excessive, somewhat poor, and very poor drainage classes were not recognized in 1939. For example, the Whitman soil (coarse-loamy, mixed, nonacid, mesic Typic Humaquepts) was called poorly drained in 1941 but classifies as very poorly drained in the modern system. This leaves two drainage classes in the wetland-upland transition zone (poorly and somewhat poorly drained) unaccounted for in the 1944 mapping. Based on modern field work and knowledge of the local landscape, it is thought that Simmons included excessively drained soils in well-drained map units, poorly and very poorly drained soils in poorly drained units, and somewhat poorly drained soils in moderately well drained map units.

Shaler Hall is located on the 1000-ft elevation contour which serves as the current boundary between mesic and frigid soil temperature regimes (Soil Survey Staff, 1975a). Due to the fact that one of the three mapped tracts is above 1000 ft (frigid zone) a decision had to be made regarding the assignment of mesic vs. frigid zone soil series. For two reasons, it seemed preferable to map all three Harvard Forest tracts using primarily series recognized as occurring in the mesic temperature zone. First, although the current county survey mapped soils above the 1000-ft contour (including Prospect Hill Tract) as frigid zone types, it was much less intensive than survey work done by Harvard Forest staff. Analysis of the database established during the most recent soil survey of the ~1200-acre Prospect Hill tract, completed in 1993 by R.D. Boone et al. (personal communication), showed that only 23% of the 567 pits described across the tract had genetic E, Bs, or Bh horizons, which are characteristic of frigid Spodosols in our region. Second, Simmons' original survey was done using series currently recognized as mesic, and frigid-type soil characteristics (i.e., spodic E, Bs and Bh horizons) were noted, and mapped when infrequently encountered. In addition, there are plant nutrition-related biochemical differences between the frigid (Spodosol dominated) soil series and the mesic (primarily Inceptisol) series. Considering these factors, there may be a need for more frigid Inceptisol series (few exist) to account for transition zones between mesic and frigid temperature regimes. This need is especially great in central New England, where soil disturbance and transitional hardwood vegetation retards cheluviation and subsequent development of spodic characteristics.

After careful consideration of the strengths and weaknesses of the Simmons soil maps a decision was made to reclassify and update these maps in 1994. Following the resource review and verification of existing soil unit boundaries, all Simmons' soil types were classified using Soil Survey Staff, (1992) to the family level (selected examples, Table 1). Simmons' soil types were then correlated to modern series (selected examples, Table 2) and new maps were produced. These maps retain the original soil unit boundaries and large scale while utilizing modern classification systems for nomenclature and drainage. Although there is great

Table 1. Selected 1941 soil types classified by 1992 Soil Taxonomy.

1941 soil type	Taxonomic name
Acton stony loam	Coarse-loamy, mixed, mesic Typic Dystrochrepts
Acton stony silt loam	Coarse-loamy, mixed, mesic Aquic Dystrochrepts
Berwick fine sandy loam	Sandy, mixed, mesic Typic Dystrochrepts
Berwick loamy sand	Mixed, mesic Typic Udipsamments
Brookfield stony loam	Coarse, loamy, mixed mesic Typic Dystrochrepts
Brookfield stony loam, shallow	Loamy, mixed, mesic Lithic Dystrochrepts
Buxton silt loam	Loamy, mixed, mesic Lithic Dystrochrepts
Charlton stony fine sandy loam	Coarse-loamy, mixed, mesic typic Dystrochrepts
Charlton stony fine sandy loam, shallow	Coarse-loamy, mixed, mesic Typic Dystrochrepts
Essex stony loam	Coarse-loamy, mixed, mesic Typic Dystrochrepts
Gloucester stony fine sandy loam	Coarse-loamy, mixed, mesic Typic Dystrochrepts
Gloucester stony fine sandy loam, shallow	Loamy, mixed, mesic Lithic Dystrochrepts
Gloucester stony loam	Coarse-loamy over sandy or sandy-skeletal, mixed, mesic Typic Dystrochrepts
Gorham stony fine sandy loam	Sandy-skeletal, mixed, mesic Typic Dystrochrepts
Hinckley loamy sand	Sandy-skeletal, mixed, mesic Typic Udorthents
Hinckley stony fine sandy loam	Coarse-loamy over sandy or sandy-skeletal, mixed, mesic Typic Dystrochrepts
Peru stony loam	Coarse-loamy, mixed, frigid Aquic Haplorthods
Sudbury f.s.l., ground-water podzol phase	Sandy-skeletal, mixed, frigid Typic Haplorthods
Sudbury fine sandy loam	Sandy, mixed, mesic Aquic Dystrochrepts

Table 2. Selected historic-modern series correlations.

1941 soil type	1994 soil series
Acton stony loam	Scituate loam
Acton stony silt loam	Rainbow silt loam
Berwick fine sandy loam	Merrimac fine sandy loam
Berwick loamy sand	Windsor loamy sand
Brookfield stony loam	Brookfield loam
Brookfield stony loam, shallow	Brimfield loam
Buxton silt loam	Scio silt loam
Charlton stony fine sandy loam	Charlton fine sandy loam
Charlton stony fine sandy loam, shallow	Chstfield fine sandy loam
Essex stony loam	Paxton loam
Gloucester stony fine sandy loam	Montauk fine sandy loam
Gloucester stony fine sandy loam, shallow	Hollis fine sandy loam
Gloucester stony loam	Canton loam
Gorham stony fine sandy loam	Gloucester fine sandy loam
Hinckley loamy sand	Hinckley loamy sand
Hinckley stony fine sandy loam	Agawam fine sandy loam
Peru stony loam	Peru loam (spodic)
Sudbury f.s.l., ground-water podzol phase	Sheepscot fine sandy loam (spodic)
Sudbury fine sandy loam	Sudbury fine sandy loam

detail and accuracy in these maps a number of studies have shown that between the extremes of mapped soil properties, trees respond to even smaller-scale variations in soil properties and microtopography (Hoisington and Carr, 1949; Goodlett, 1960; Lyford et al.,1963). The updated maps will allow for accurate naming and description of Harvard Forest soils when using the original map scale and delineations.

Conclusions

The disciplines of soil science and forest soil survey have benefited greatly from the contributions of Harvard University scientists, forest managers, and their collaborators. The Harvard forest soil research legacy extends over 150 yr and is being continued today at the research forest (currently designed as a Long Term Ecological Research Site by the National Science Foundation). The soil survey update at Harvard Forest is only one small part of ongoing research into soil legacies of historic land-use and soil-related aspects of climate change, pollution deposition, forest health, and nutrient cycling.

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References

Aber, J.D. 1992. Nitrogen cycling and nitrogen saturation in temperate forest ecosystems. Trends Ecol. Evol. 7:220–223.

Aber, J.D., C. Driscoll, C.A. Feder, R. Lathrop, G. Lovett, J.M. Melillo, P.A. Steudler and J. Vogelmann. 1993b. A strategy for the regional analysis of the effects of physical and chemical climate change on biogeochemical cycles in northeastern (U. S.) forests. Ecol. Model. 67:37–47.

Aber, J.D., A. Magill, R.D. Boone, J.M. Melillo, P.A. Steudler, and R.D. Bowden. 1993a. Plant and soil responses to chronic nitrogen additions at the Harvard Forest, Massachusetts. Ecol. Appl. 3:156–166.

Aber, J.D., J.M. Melillo, C.A. McClaugherty, and K.N. Eshleman. 1983. Potential sinks for mineralized nitrogen following disturbance in forest ecosystems. Environ. Biogeochem. Ecol. Bull. (Stockholm) 35:179–192.

Aber, J.D., C.A. Wessman, D.L. Peterson, J.M. Melillo, and J. Fownes. 1990a. Remote sensing of litter and soil organic matter decomposition in forest ecosystems. p. 87–103. *In* R.J. Hobbs and H.A. Mooney (ed.) Remote sensing of biosphere functioning. Springer-Verlag New York, Inc.

Aber, J.D., J.M. Melillo, and C.A. McClaugherty. 1990b. Predicting long-term patterns of mass loss, nitrogen dynamics and soil organic matter formation from initial fine litter chemistry in temperate forest ecosystems. Can. J. Bot. 68:2201–2208.

Boone, R.D. 1992. Influence of sampling date and substrate on nitrogen mineralization: Comparison of laboratory-incubation and buried-bag methods for two Massachusetts forest soils. Can. J. For. Res. 22:12.

Boone, R.D. 1994. Light-fraction soil organic matter: origin and contribution to net nitrogen mineralization. Soil Biol. Biochem. 26:11.

Bowden, R.D., J.M. Melillo, P.A. Steudler, and J.D. Aber. 1991. Effects of nitrogen additions on annual nitrous oxide fluxes from temperate forest soils in the northeastern United States. J. Geophys. Res. 96:D5.

Bowden, R.D., K.J. Nadelhoffer, R.D. Boone, J.M. Melillo, and J.B. Garrison. 1993a. Contributions of aboveground litter, belowground litter and root respiration to total soil respiration in a temperate mixed hardwood forest. Can. J. For. Res. 23:1402–1407.

Bowden, R.D., M.S. Castro, J.M. Melillo, P.A. Steudler, and J.D. Aber. 1993b. Fluxes of greenhouse gases between soils and the atmosphere in a temperate forest following a simulated hurricane blowdown. Biogeochemistry 21:61–71.

Buol, S.W., F.D. Hole, and R.I. McCracken. 1989. Soil genesis and classification. Iowa State Univ. Press, Ames.

Fisher, R.T. 1928. Soil changes and silviculture on the Harvard Forest. Ecology 9:1.

Gast, P.R. 1937. Contrasts between the soil profiles developed under pines and hardwoods. J. For. 35:1.

Goodlett, J.C. 1960. The development of site concepts at the Harvard Forest and their impact upon management policy. Harvard For. Bull. 28. Harvard For., Petersham, MA.

Griffith, B.G., E.W. Hartwell, and T.E. Shaw. 1930. The evolution of soils as affected by the old field White pine-mixed hardwood succession in Central New England. Harvard Forest Bulletin. 15. Harvard For., Petersham, MA.

Hole, F.D., and J. Campbell. 1985. Soil landscape analysis. Rowman and Allanheld Publ., Totowa, NJ.

Johnston, J.W. 1932. The fauna of soil as affected by the old field white pine-mixed hardwood succession. M.F. thesis. Harvard Univ., Cambridge, MA.

Latimer, W.J., R.F.R. Martin, and M.O. Lanphear. 1927. Soil survey of Worcester County, Massachusetts. USDA Rep. Field Operations of Bur. Soils. USDA, Washington, DC.

Lutz, R.J., and A.C. Cline. 1947. Results of the first thirty years of experimentation in silviculture in the Harvard Forest. 1908-1938. Part I. The conversion of stands of old field origin by various methods of cutting and subsequent cultural treatments. Harvard For. Bull. 27. Harvard For., Petersham, MA.

Lyford, W.H. 1963. Importance of ants to Brown Podzolic soil genesis in New England. Harvard For. Pap. 7. Harvard For., Petersham, MA.

Lyford, W.H. 1964a. Coarse fragments in the Gloucester soils of the Harvard Forest. Harvard For. Pap. 9. Harvard For., Petersham, MA.

Lyford, W.H. 1964b. Water table fluctuations in periodically wet soils of central New England. Harvard For. Pap. 8 Harvard For., Petersham, MA.

Lyford, W.H. 1966. Fungal hyphae and the morphology of B horizons of New England soils. Harvard For. Pap. 17. Harvard For., Petersham, MA.

Lyford, W.H. 1973. Forest soil microtopography. p. 47–58. *In* D.L. Dindahl (ed.) Proc. 1st Soil Microcommunities Conf. U.S. Atomic Energy Commission. U. S. Atomic Energy Commission. CONF-711076. Distrib. Cat. UC-48. Washington, DC.

Lyford, W.H. 1974. Narrow soils and intricate soil patterns in Southern New England. Geoderma 11:195–208.

Lyford, W.H. 1980. Development of the root system of northern red oak (*Quercus Rubra* L.). Harvard For. Pap. no. 21. Harvard For., Petersham, MA.

Lyford, W.H., J. Goodlett, and W. Coates. 1963. Landforms, soils with fragipans and forest on a slope in the Harvard Forest. Harvard For. Bull. 30. Harvard For., Petersham, MA.

Lyford, W.H., and J.H. Patric. 1980. Soil-water relations at the headwaters of a forest stream in central New England. Harvard For. Pap. 22.

McClaugherty, C.A., J.D. Aber, and J.M. Melillo. 1984. Decompostion dynamics of fine roots in forests ecosystems. Oikos 42.

Melillo, J.M., J.D. Aber, A.E. Linkins, A. Ricca, B. Fry, and K.J. Nadelhoffer. 1989. Carbon and nitrogen dynamics along the decay continuum: Plant litter to soil organic matter. p. 53–62. *In* M. Clarholm and L Bergstrom (ed.) Ecology of arable land. Kluwer Acad. Publ.

Nadelhoffer, K.J., J.D. Aber, and J.M. Melillo. 1984. Seasonal patterns of ammonium and nitrate uptake in nine temperate forest ecosystems. Plant Soil 80:321–335.

Patric, J.H., and D.W. Smith. 1975. Forest management and nutrient cycling in eastern hardwoods. USDA-FS Res. Pap. NE-324. Upper Darby, PA.

Pritchett, W.L. 1979. Properties and management of forest soils. John Wiley & Sons, New York.

Raup, H.M. 1940. Old field forests of southeastern New England. J. Arnold Arbor. 21:266–273.

Raup, H.M. 1954. Soil: A basic resource in wood production. Society of American Foresters 15:2.

Raup, H.M. 1957. Vegetation adjustment to the instability of the site. p. 36–48. *In* Proc. 6th Technol. Meet. Int. Union Conserv. Nat. and Nat. Resources. Edinburgh 1956.

Scholz, H.F. 1931. Physical properties of the cove soils on the Black Rock Forest. Black Rock Forest Bull. no. 2. Cornwall Press Inc., Cornwall, NY.

Scholz, H.F. 1937. The effect of soil texture upon the growth of red and chestnut oaks. Black Rock For. Pap. no. 11. Cornell Press Inc., Cornwall, NY.

Soil Survey Staff. 1992. Keys to soil taxonomy. SMSS Technical Monograph No. 19. Blacksburg, VA: Pocahontas Press, Inc.

Soil Survey Staff. 1994. Official series descriptions. USDA-SCS, Washington, DC.

Spurr, S.H. 1939. The influence of two Juniperus species on soil reaction. Soil Sci. 50:4.

Spurr, S.H. 1956. Forest associations in the Harvard Forest. Ecol. Monogr. 26:245–262.

Stone, E.L. 1975. Effects of species on nutrient cycles and soil change. Philos. Trans. R. Soc. London, B 27:149–162.

Stout, B. 1952. Species distribution and soils in the Harvard Forest. Harvard For. Bull. no. 24. Harvard For., Petersham, MA.

Tandarich, J.P., R.G. Darmody, and L.R. Fuller. 1988. The development of pedological thought: some people involved. Phys. Geogr. 9:162–174.

Teller, J.D. 1947. Louis Agassiz, scientist and teacher. Ohio State Univ. Press, Columbus, OH.

Wolff, J.E. 1906. Memoir of Nathaniel Southgate Shaler. Bull. Geol. Soc. Am. 18:592–608.