Available online at www.sciencedirect.com

SCIENCE DIRECT®

Forest Ecology and Management 220 (2005) 1–16

Forest Ecology and Management

www.elsevier.com/locate/foreco

Forest soils education and research: Trends, needs, and wild ideas

R.F. Fisher[a,*], T.R. Fox[b], R.B. Harrison[c], T. Terry[d]

[a] *Temple-Inland Forest Products Corp., Forest Research & Productivity, P.O. Drawer N,*
303 S. Temple Drive, Diboll, TX 75941, USA
[b] *Virginia Polytechnic Institute and State University, VA, USA*
[c] *University of Washington, WA, USA*
[d] *Weyerhaeuser Company, WA, USA*

Abstract

Requirements of an excellent forestry education have changed. Students are now required to complete more quantitative, social science and humanities courses. There are cogent reasons for this, but it has resulted in a marked decrease in the emphasis being placed on the land. Only 15% of the North American forestry schools require geology or geomorphology, while 15% have it as a recommended elective. Thus, as many as two-thirds of forestry graduates may be geologically illiterate! Ninety percent of US forestry schools require a soils course, but only 50% require forest soils. All Canadian forestry schools require both soils and forest soils. While this erosion of emphasis placed on the soil resource has taken place in education, the use of soils information in natural resource management has dramatically increased. Many organizations are increasing the intensity of forest management and moving toward the domesticated forest, which requires more knowledge of forest soils. All natural resource professionals need a firm understanding of the land and the processes that shape it. Nineteenth century forest soils research was basic and in the 20th century it was largely empirical. The 21st century requires a balanced mix of basic and applied research with more integration with other natural resource disciplines. Many principles remain to be elucidated, but in some areas descriptive research is still necessary. The establishment of long-term regional data sets that can be used in testing hypotheses to be translated into management guidelines should be a priority. Planning tools must be developed so that the best knowledge can be applied to management. In both research and planning, science rather than politics must set the agenda. We need to teach students the full range of soil management possibilities including active management as well as conservation and preservation. We must 'bust' our conceptual blocks in both education and research. We do not need more education; we need better education. Forest soils research needs to utilize emerging remote sensing technology both to improve our research efforts and to aid in land management planning. Remote sensing, GIS, and GPS technology can revolutionize silvicultural research, but we may need to alter our research paradigm to take advantage of it. We are too often prisoners of our past. We, those of us in education, government agencies, industry, and NGOs, must learn to work together or we will not meet the challenges of the new century.

Keywords: Forestry education; Forest management; Silvicultural treatments

---

* Corresponding author. Tel.: +1 936 829 1475; fax: +1 936 829 1476.
E-mail address: dickfisher@templeinland.com (R.F. Fisher).

0378-1127/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2005.08.001

1. The role of forest soils in contemporary forest management

In his keynote address at the Fourth North American Forest Soils Conference, Earl Stone proposed that there was a continuum of forest management activity from protection of wildland forests to intensive management of what he called the domesticated forest (Stone, 1975). Intensive forest management in North America was still in its infancy when Earl stated "I myself am convinced that the domesticated forest and its various intergrades will contribute greatly to future wood supplies". Earl clearly elucidated that the need for information on forest soils would increase as forest management intensity increased. More than 30 years later, we now see that Dr. Stone's predictions have come to pass. Many organizations throughout North America and the world have created versions of the domesticated forests and recognize that detailed knowledge of forest soils is the cornerstone of modern intensive forest management.

Organizations practicing intensive forestry use soils information at nearly all points of forestland management. Site-specific management is the paradigm that defines the domesticated forest where biological, economic, environmental, and social considerations are integrated together to determine the appropriate level of management intensity in each individual stand. The level of management inputs varies on each site, and consequently in the domesticated forest stands managed to maximize timber production are frequently adjacent to stands that are managed for non-timber objectives, such as aesthetics, wildlife habitat, or water quality protection. Soil information is thus crucial in determining the silvicultural system and level of management intensity that is appropriate. Because site quality is not fixed in the domesticated forest, soil–site relationships must be more clearly understood so that both the current and potential productivity under alternative management regimes can be predicted. Foresters need to understand the potential effects of silvicultural practices on ecosystem resource allocation. They also need knowledge of the impacts of these cultural practices on soil physical, chemical, and biological properties across soil and climatic gradients. Offsite impacts of intensive management in the domesticated forest must also be minimized. Soil information is a key factor used to determine the extent of streamside management zones needed to protect water quality, and to define areas needing special management considerations.

Table 1
Industrial timberland ownership in the United States and the presence of soil mapping programs

Company (million acres)	US timberland	Soil mapping
International Paper	12.5	Yes
Plum Creek	8.1	Yes
Weyerhaeuser	8.1	Yes
MeadWestvaco	3.5	Yes
Boise	2.3	Yes
Rayonier	2.2	Yes
Temple-Inland	2.2	Yes
Potlacth	1.5	Yes

The importance of forest soils is highlighted by the fact that each of the largest industrial forest landowners in the United States has mapped, is actively mapping their soils, or makes use of National Resource Conservation Service soils maps (Table 1). These organizations recognize the value of soils as an essential tool to improve management, and are willing to pay to acquire information on them for the land that they manage. Companies, particularly those who manage domesticated forests, rely heavily on forest soils information when making management decisions. Forest soils information is usually integrated with geologic, climate, micro-site environment, landform, and topography and can be made available to foresters through a geographic information system. Specific examples of how these data are used to aid management are numerous.

Information on soil trafficability and susceptibility to detrimental soil disturbance from ground-based harvesting equipment is used to determine "wet" and "dry" weather logging sites and aid in harvest scheduling. In harvest planning and road layout, soils data can be used to match harvest equipment and methods to the stand, soils, and topography. Soils data, such as texture and drainage are used in risk-rating soils as to their susceptibility to compaction, rutting, and puddling. These same factors are used in road location decisions. Soils, geology, and landform are all a part of "Watershed Analysis" processes for locating sensitive areas for slope stability and minimizing sediments in streams. Many organizations require that all harvest managers and operators go through soils and best management practices (BMP) training. Some organizations have soil disturbance standards for ground-based harvesting which indicates what levels should not be exceeded and what types of disturbance should be ameliorated. Often, the balance between cost of amelioration and avoidance is balanced for the best decision (Heninger et al., 2001).

There is a great deal of agronomy involved in the management of domesticated forests. Soil information is used to determine tillage and other site preparation needs. The widespread use of bedding on poorly drained soils in the South is perhaps the best example of how mechanical site preparation treatments have been matched to specific soil types. Mechanical site preparation guidelines for well-drained upland sites that describe the best treatment options for soil tillage, slash disposal, and vegetation management have been developed on a regional basis and are continuously being refined. These guidelines are largely based on soils information. Chemical site preparation has replaced mechanical site preparation on many sites in the South. Herbicides are widely used to control competing vegetation which generally results in significant increases in growth of the desired crop trees (Miller et al., 2003). Consequently, the fate of herbicides in the environment is of growing importance (Neary and Michael, 1996; Ice and Binkley, 2003). Foresters are frequently questioned about the safety and fate of the chemicals they use, and are often assaulted by members of the public with strong biases and large amounts of misinformation. Foresters must understand the role of the soils in determining the efficacy and fate of chemicals introduced into the environment (Michael and Neary, 1993). For example, picloram was banned from many forestry uses because of its mobility in the environment and its tendency to contaminate groundwater and streams when it was applied. Glyphosate, on the other hand, is tied up quickly in the soil and generally does not reach surface or ground waters unless it is added directly to them. Hexazinone, which is primarily a soil active herbicide, is influenced by soil clay and organic matter content. Effective use of hexazinone requires that rates be adjusted upward to account for the increased amount of organic matter and clay in the soil. However, because hexazinone is soluble in water, applying these same rates in sandy soils can lead to leaching of the herbicide from the soil (Ahrens, 1994).

There has been increasing use of nutrient amendments to enhance forest productivity particularly in the southern US where the annual fertilization rate exceeds 647,500 ha per year (Allen et al., 1998; Allen, 2000). Foresters need to understand the interactions between soil and plants that are crucial in water and nutrient uptake. They also need to understand the fate of applied fertilizers in the ecosystem and their potential impact on water quality (Ice and Binkley, 2003). Understanding these processes will help us enhance forest productivity and maintain high water quality. Phosphorus fertilization of stands at-time-of-planting and N fertilization of established stands is frequently guided by soils information. In the South, the growth response to P fertilization at planting varies dramatically by soil type, primarily determined by geologic formation, soil texture, and drainage class (Jokela, 2004). In the Northwest, Edmonds and Hsiang (1987) showed that the response of Douglas-fir could be partially predicted by the C:N ratio of the forest floor. Carter et al. (1998) also found coastal Douglas-fir basal area response to fertilization to be related to site index and mineral soil mineralizable-N. In all cases average relative response declined with increasing site index. Soil properties and landform characteristics are key determinants of site index. There remains a lot more potential for developing the capability of predicting the impacts of forest fertilization based on soil properties; however, the variability of soil continues to be a challenge.

Species deployment decisions in many parts of the South are driven by soil properties. In the Lower Coastal Plain of Georgia and Florida, the decision as to whether to plant loblolly pine, slash pine, longleaf pine or sand pine is often made based on the soil properties of a site. A decision key (Fig. 1) on which species to plant has been developed for this region (Fox, 2004) utilizing the CRIFF soil groups previously developed by Fisher and Garbett (1980). Allocation of genetic stock is another decision that is strongly influenced by soil, climate, and landform. Half-sib families are currently allocated to the site where they can maximize net present value based on productivity potential and wood quality. Although there is little genotype by environment interaction among families of loblolly pine, better families tend to grow much faster than poorer families on higher quality sites (McKeand et al., 1997). Differences among families

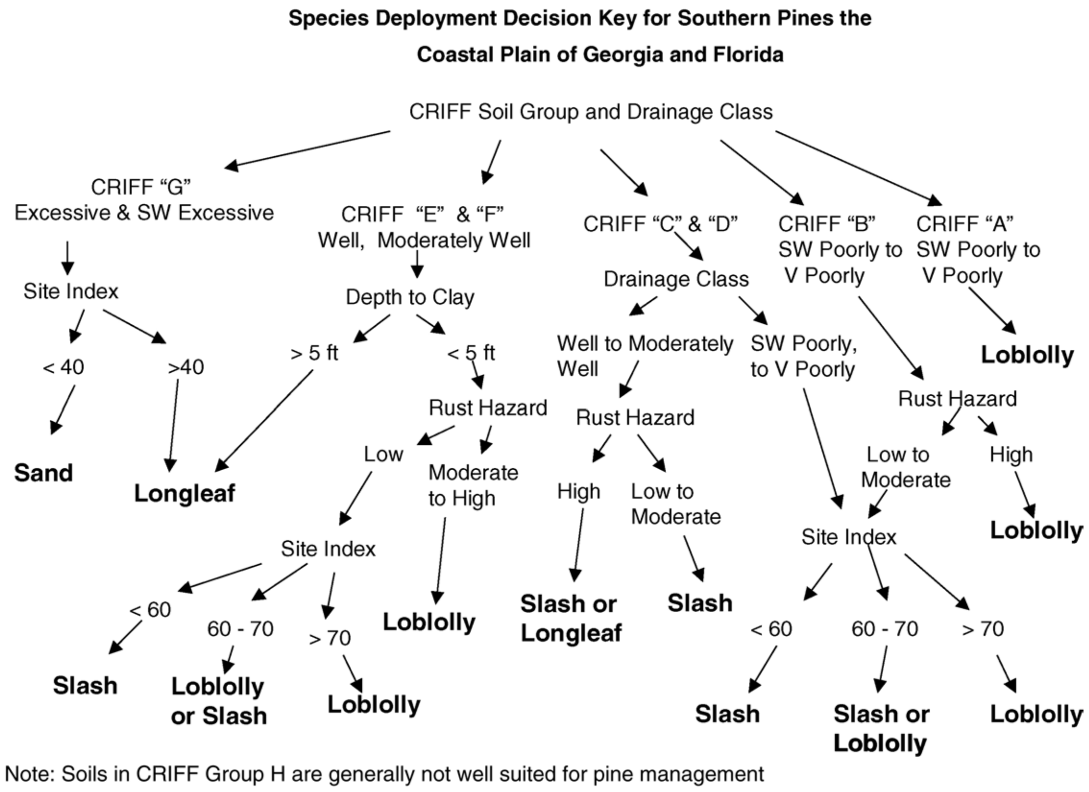

Fig. 1. Species deployment decision key for Southern Pines (Fox, 2004).

are less pronounced on poor quality sites (Fig. 2). Foresters can use this information to optimize deployment of the limited quantities of the very best genotypes available. The need for site-specific allocation of genotypes will be greater in the future as foresters begin to deploy elite full-sib families and clonal blocks.

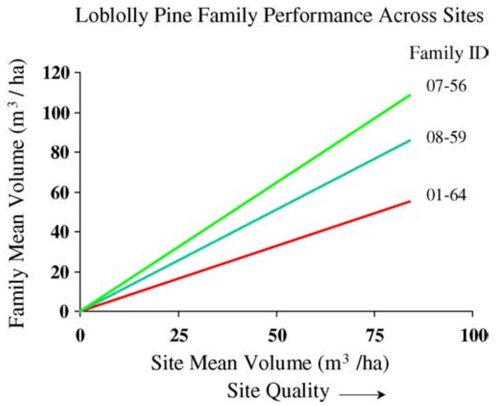

Fig. 2. Impact of site quality on growth of selected loblolly pine families (McKeand et al., 1997).

We know that climate and soils affect wood-quality, and this knowledge is now starting to be exploited. Late growing season moisture availability increases latewood production and thus specific gravity, but it can also increase the propensity for second-flushing which can increase ramicorn branching or stem sinuosity in some species.

In the southern United States, growth rates in intensively managed loblolly pine stands in the domesticated forest can approach those of exotic species in the southern hemisphere (Borders and Bailey, 2001). Achieving these spectacular growth rates is dependent on intensive manipulation of soil resources through weed control, fertilization, and in some cases irrigation. Integrated, site-specific management regimes are being implemented where improved genotypes are matched to specific soil types and silvicultural treatments including site preparation, weed control, and fertilization are integrated to maintain optimal water and nutrient availability throughout the rotation. The thoughtful integration of detailed soils, landform, and stand information to apply silvicultural treatments and track crop performance at the micro-site as well as the stand level is termed ‘‘precision forestry’’ and it is beginning to be more of a reality everyday in industrial forestry.

Domesticated forests in the southern hemisphere owe much of their extraordinary yield attainment to excellent soil management and the application of precision forestry. For instance, the high yields of Eucalypts species in Brazil is completely dependent on the application of fertilizer nutrients, and general recommendations are based on soil measures, such as CEC, extractable P, organic matter content, and soil moisture holding capacity (Gonçalves and Benedetti, 2000). The application of fertilizer B to enhance wood quality in Brazil is now based on soils and geology. In dryer parts of interior Brazil, such as the Cerrado region, the inclusion of terracing to turn periodic episodic rainfall into soil moisture, and the use of subsoiling to depths as great as 90 cm has created productive forests where forestry was earlier practiced on an extensive scale. Forest enterprises in Brazilian states like Bahia and Espirito Santo are creating entire economies based on forest production in some of the historically poorest regions of the world. The long-term implications of these production forests in terms of soil properties and potential degradation have not even been considered as hundreds of millions of dollars are invested in afforestation operations and infrastructure to manage, harvest, and utilize the forests. The variety and scope of forestry problems related to soils worldwide will continue to create a demand for educated forest soil scientists at all levels.

2. Forest soils education and the modern forestry curriculum: trend and needs

The components of an excellent education in forestry have changed over the years. The need to train ‘‘dirt foresters’’ for timber management careers that start in the field, although still an important component of a forestry degree, has gradually been replaced by the need to train ‘‘ forest managers’’ with more communication, financial, personnel, and advanced computer skills. Consequently, in addition to the traditional forestry courses in dendrology, measurements, silviculture, management and policy, students now must take a greater number of non-traditional classes to meet these new requirements Many universities, including land grant institutions, now require that all students take a core curriculum of general classes more typically associated with a liberal arts degree than a traditional degree in forestry. Room must also be made within the forestry curriculum for students to receive training in the new tools and techniques that are revolutionizing our profession, such as geographic information systems and biotechnology. Because of the increasing importance of non-timber issues that foresters now must deal with, such as T&E species management and carbon sequestration, the teaching of forest ecology has generally expanded, sometimes into several courses, or with material integrated into existing junior or senior level courses. Additionally, social psychology of resource use and natural resource policy now typically occupy two, and sometimes more courses in a general forestry degree. At first, much of this coursework was added by expanding the requirements for the B.S. degree in forestry, and the typical forestry degree required at least one summer quarter of coursework compared to a general university degree. However, with increased costs at universities and lowered funding, the time necessary to obtain a degree has become a serious issue with forestry schools, and most have responded by reducing the total credits required. Although these changes in the curriculum have created a more well-rounded forestry graduate, they have resulted in a decrease in the emphasis placed on another important part of forestry—the land upon which the forests grow.

In the mid-1970s, Bill Pritchett was contemplating writing a forest soils textbook. He surveyed the US forestry schools to determine the audience for such a book. He asked whether or not geology and soils were required courses. He also asked whether a soils course, if required, had a forest soils emphasis, and whether a required or elective forest soils course was offered. In 2002 we repeated his survey and added the Canadian schools to the list of ‘‘accredited’ forestry schools polled.

We found a significant decline in the number of schools requiring geology during that period. Only

15% of North American forestry schools require a course in geology or geomorphology, while another 15% include such a course as a recommended elective. This means that less than a third of forestry graduates are likely to have grounding in the basic geologic sciences. This seems unconscionable for professionals who will spend their careers working with the land, and with a primary emphasis on conserving its natural resources. Geological principles are critical for understanding landscapes, landforms, and soil properties, which are formed, weathered, and shaped by geological processes. Most forest management agencies and many companies in the forest industry employ geologists, but should not the foresters who work with these specialists be conversant with geology and geomorphology? Understanding geologic principles is important to be able to "read" and manage at all scales ranging from the forest stand to the landscape level. The classic work of Hans Jenny (Jenny, 1941), who spent much of his career working in forest soils, describes the factors of soil formation and clearly demonstrates the links between geology, geomorphology, and soils. Two of these factors identified by Jenny, topography and parent material, are as much within the realm of geologists as they are soil scientists. The factors of soil formation elucidated by Jenny determine soil properties that are critically important to foresters, such as site quality, operability, and long-term sustainability.

At the present time in the US, 90% of forestry schools require a course in soil science, but only 50% require a forest soils course, while 5% have forest soils as a recommended elective. In Canada, all forestry schools require both a course in soil science and a course in forest soils. Of the US schools that just require a course in soil science, only 30% have a segment of that course that is specifically designed to emphasize forest soils. The number of North American forestry schools with a forest soils professor has declined by about half over the past 25 years to less than 40%.

This means that forestry students, if they are exposed to soils at all, generally are only required to take one introductory course. These courses are typically very large, with 100 students or more, and sometimes do not include labs or field trips. In most cases in the US, the required course in soil science is taught primarily to agriculture students by professors in agronomy and soils. In these general soils classes, forestry students are intermixed with students majoring in soils, crops, turf, and horticulture. Consequently, general soils courses taught at land grant schools seldom have a forest management flavor, and normally do not emphasize the properties and processes that differentiate forest soils from agricultural soils, such as the importance of the forest floor, large perennial root systems, and closed nutrient cycles. These problems are exacerbated because faculty at land-grant schools are sometimes assigned to teach the general soils courses on a rotational basis, and thus find it difficult to tailor the class to meet the needs of a specific subset of students by providing examples related to forestry. The result is that forestry students are "turned off" and fail to gain an appreciation for the importance of soils in their own discipline.

Unfortunately, because of the limited education in soils that forestry students typically receive, most foresters upon graduation are unable to effectively use information on soils as a tool to improve forest management. Even among mid-career foresters, a lack of understanding of basic forest soil processes indicates that they have little ability to understand soils as a dynamic and manageable forest resource. The authors are constantly surprised by the number of foresters they encounter who do not even take soil properties into consideration when they make silvicultural prescriptions to the stands they manage.

Consequently, most industrial and governmental forestry organizations find it necessary to organize internal short courses on soils for their employees so that they can effectively use information on soils as a tool to improve forest management decisions. In the South, the Forest Nutrition Cooperative at North Carolina State University and Virginia Tech developed a weeklong course on forest productivity for employees of its industrial cooperators. This course emphasizes the important role that soils play in the silvicultural decision process for southern pines. The course has been taught for over 10 years to more than 1000 foresters from industry, state agencies, and consulting firms. Many industrial foresters, after they complete the soils short course, ask "why did not they tell us this in college?" Another example exists in the Pacific Northwest where the University of Washington and Oregon State University host a

Natural Resources Institute, called the Silvicultural Institute until 1996, with the specific goal of giving practicing forestland managers additional educational opportunities. There are 10 modules of 2 weeks each. Attendee evaluations have consistently ranked the 2 days of intensive forest soils training among the ‘‘most useful’’ segments.

Forestry students not only need to know where soil came from and how and why it changes over time, but they also need to know how management activities affect soil properties and processes, and how they can manage soil to meet their resource objectives. There is a need for forestry students to have a course that addresses geology and geomorphology/landscape processes/and hydrology, as well as fundamental soil science. If students are only going to get one or at most two land process courses, a lot has to be packed into them in order to expose students to the many facets of land/soils and watershed management and soil–plant relationships. Many of today’s forest and land management issues are not related to growing trees, but instead pertain to:

- water quality/water yields/run-off rates;
- stream/fisheries protection;
- sediment management;
- slope stability in road construction and harvesting operations;
- protection of wetlands, seeps, and other unique habitats and landscape features;
- effective road maintenance and road and harvest engineering.

Increased knowledge of forest soils as a fundamental component of the forest ecosystem is needed by all natural resource managers. This includes those professionals dealing with recreation, wildlife, fisheries, threatened and endangered species, urban forests, as well as timber production. For example, the distribution and abundance of many plant and wildlife species is related to soil properties. Issues surrounding soil erosion, slope stability, and compaction are critically important to recreation specialists developing campgrounds and trails for hiking and horseback riding. The recent boom in mountain biking and ATV use, and the concomitant increase in erosion and trail degradation, emphasized the need for soils information to individuals charged with managing these activities. Fisheries students need to understand how processes in the soil affect the fate and transport of nutrients, chemical pollutants, and sediment and thus impact water quality and fish habitat. Unfortunately, just as the existing agronomic general soils courses may be too narrowly focused, traditional forest soils courses that emphasize those aspects of forest soils related to timber production, may be too narrowly focused. Non-forestry students with a need for information on forest soils may be ‘‘turned off’’ by a parochial forest soils class that focuses on the role of forest soils in timber production.

The basic challenge is how to get these skills into students with a 4-year program of study. With the addition of requirements, forestry programs of 1970s and 1980s often required more than 4 years of study, but that trend toward expanding requirements has reversed. These points argue not for a collection of existing courses that further strain and restrict the curriculum, but rather for carefully designed courses that cover a broad range of land process/soil–plant interaction topics without becoming cursory. This combination of breadth and depth of treatment is possible, but it requires inventiveness, diligence, and a strong commitment from faculty.

Most forestry schools are presently struggling with how to integrate a wide range of informational needs into single courses or sequences of courses to reduce the tendency to proliferate courses (Fisher, 1996). Often these integrated courses come at the senior level (capstone courses), and involve producing a working plan for the management of a forest, with the goal of integrating multiple considerations into that management. Students typically work in teams. These kinds of courses clearly are useful, but it is increasingly recognized that such integrated courses might also be taught earlier. If such courses are offered at the junior level, there is the opportunity to build on what students learned earlier, these ‘‘columnar courses’’ could tie things together and support the capstone course. In all cases, consideration of soils should play a central role in such courses.

The existing shortcomings in forest soils education are troubling for the future of all types of forestry. Lack of a solid grounding in forest soils, no pun intended, is a handicap to urban foresters, agency foresters, wildlife and fisheries biologists, recreation specialists, consulting foresters, and industrial foresters alike. However, the increasingly agronomic nature of urban and industrial forestry poses special problems. The irony is that as forestry has moved toward the domesticated forest, with the concomitant need for more information on forest soils to make the system work, most forestry schools have reduced the exposure most students receive to forest soils.

By now many of you are saying to yourselves that these folks do not understand that degree programs can only contain so many courses. Undergraduate forestry programs are already being asked to reduce their credit hour requirements. We urge you to consider that the number of courses is not as important as the course content and the quality of instruction (Fisher, 1996). The real challenge in education is creating an environment wherein you can stretch the student's ability to learn and then to fill that environment with highly relevant material.

We may have to challenge the paradigm that a student earning a 4-year forestry degree will have any degree of specialization. The need for a broader based undergraduate education coupled with the reduction in credit hours required for graduation mandated by university administration, may make it impossible to obtain adequate training in specializations, such as forest soils. Although, new and better teaching methods coupled with better prepared and more highly selected students, and a rigorous approach to professional education may be the solution (Fisher, 1996).

The concerns we raise are not unique to forest soils. Almost every other sub-discipline in forestry is lamenting over these same issues. Colleagues in forest harvesting, economics, biometrics, pathology, entomology, physiology and probably every other discipline complain that students are unable to take enough courses to understand or even fully appreciate the importance of their specific discipline. It may be time to rethink the forestry education system in the United States and admit that a 4-year curriculum is inadequate for some if not most of our students. The breadth and depth of knowledge required to understand and effectively manage such a complex system as a forest cannot be crammed into a 4-year program. In many parts of the world, forestry has in fact been a 5-year program of study for a long time. We recognize that education is a life-long process and we cannot teach students everything they need to know in college. However, we have to produce students with the necessary background they need to become lifelong learners. Our observations suggest that we are failing in this task for many students with regard to soils and geology.

One solution to this may be to revive the use of the M.F. degree in forestry schools as a means whereby students can gain a degree of specialization in a selected sub-discipline. Traditionally M.F. degrees were reserved for individuals with a baccalaureate in some other discipline or mid-career foresters returning to school after they had gained work experience. Students enrolling in a M.F. program were often sent back to school by their employer to take a slate of courses focused on a specific area and thereby gain competence in this area. However, in recent years, students pursuing this type of M.F. degree program have decreased because few organizations are willing to send employees back to school. This is possibly because many organizations now hire individuals with M.S. degrees who have less need for this type of training. However, many students would be better served by a M.F. degree program rather than a research orientated M.S. degree. Recognizing that the M.F. is a non-research degree, it may be attractive to many students who wish to pursue a career as managers but recognize that they require additional training.

Therefore, we should explore the opportunity to revitalize the M.F. degree, or some similar academic structure, to solve some of the deficiencies in the current 4-year undergraduate forestry program. The M.F. degree taken during the fifth year would allow students to take additional coursework to obtain specialized training that would make them more competent foresters and thus, in turn, more competitive in the job market. This approach has been utilized by other disciplines, most notably by business schools through their nearly ubiquitous MBA programs. Students from a variety of background are able to complete an MBA and obtain advanced training needed for a successful career in business. In a similar manner, Virginia Tech has recently instituted a M.F. curriculum in Watershed Management so that students from a variety of disciplines can specialize in this important area. Discussion among the forest soils faculty at Virginia

Tech has led to the development of a curriculum in forest soils suitable for a M.F. degree. The level of interest among students in such a program remains to be seen.

Another alternative to be considered is the so-called 3-2 program offered by a number of colleges and universities in collaboration with Duke University. In a 3-2 program, students spend 3 years pursuing a bachelors degree in a liberal arts and science program, usually at one college or university, and then spend 2 years in a masters program at another university; although, all 5 years could be spent at one school. After completing their masters program, the student is granted a B.S. by their first school and a M.F. by the second. Such a system does not conflict with the programs now in place at many state universities that drastically penalize students with an excessive number of credit hours in their bachelors program, and it likely produces better and more broadly trained graduates.

So far we have addressed undergraduate education in forest soils, but graduate education has also faltered in several ways over the past 25 years. Those who receive masters and doctorates in forest soils are undoubtedly better trained as research scientists than those who graduated 20 or even 10 years ago, but they often lack the breadth and practicality to be effective outside of the academic milieu. Stressing individual achievement instead of teamwork in higher education is perhaps even more of a problem in graduate than in undergraduate education. It is very common for research at modern forestry schools to be the result of individual faculty initiatives focused on narrow problems of scientific interest. Graduate students rarely get the opportunity to work on problems that require multidisciplinary approaches.

The tendency of faculty within forestry institutions to rate research that has obvious and immediate application to industrial forestry lower than more theoretical or ecological research is particularly detrimental to creating graduates that can work on problems related to forest productivity. There is a major demand within agencies that manage forests and other natural resources and within forest industry for individuals that have both great skill in modern science and the breadth and ability to address practical problems in a timely fashion. Operational questions arise daily in any group involved in natural resource management, and the need to address uncertainty and assess responses is particularly important. These are "planning" decisions rather than "scientific" questions, and people who know science but also respect planning are vital in natural resource organizations.

Planning requires one to understand the implications and risks of various options based on the information at hand and then to choose the best alternative, whereas science requires one to attempt to disprove all hypotheses. This dichotomy often bothers scientists working within management organizations. However, such people are vital both to offer alternatives that management may not include in the available set and to use their knowledge and existing information to evaluate the set of alternatives. The skill to bring science and risk assessment to management in this way is sorely lacking in most graduate students.

The very nature of the research conducted by many graduate students in forest soils may contribute to the problems with using forest soils information as a management tool. Many graduate student research projects in recent years have focused on laboratory analysis of soil physical, chemical, microbiological, and mineralogical properties. The soil is reduced to a sample in the lab rather than a natural three-dimensional body on the landscape. This type of research is driven by the nature of research funding currently available. To obtain research grants, projects must deal with cutting edge problems. Descriptive studies of soils and how they occur on the landscape and how their properties may affect management decisions are difficult to fund. In this situation, graduate students with a concentration in forest soils, may have little field forest soils experience and may have difficulty using forest soils information as a tool to solve problems faced by forest managers.

Although there are many ways to better incorporate forest soils into a graduate curriculum, in fact it may be more effective to focus at the other end of the education system, youth education. Rather than trying to convince juniors and seniors in college that forest soils are important and that they need to extend their college career by another year, perhaps we need to work to instill in our youth an interest in the fascinating world that exists below the ground. At this end of the spectrum, forest soils education needs to be extended into youth education in the K-12 curriculum.

Considerable effort has already been made to incorporate environmental education into the K-12 science curriculum (Martin et al., 2004). Project Learning Tree (PLT) was developed to provide unbiased educational materials on environmental topics to elementary and secondary school teachers. Individual PLT modules have been developed on topics, such as forest ecology and biodiversity. Developing a PLT module on the role of forest and soil ecology in forest ecosystems would be a worthwhile effort that could spark the interest of students at an early age. There are also opportunities to incorporate topics in forest soils into other natural resource education programs aimed at youth. Many students participate in environmental education as an extracurricular activity, including such nationwide programs as Envirothon, Forestry Judging, and Wildlife Habitat Evaluation Program (WHEP) (Kirwin, 2005). Students are exposed to many issues related to soils in these programs and there are great opportunities to build upon that base and increase interest in and appreciation for forest soils. There are other opportunities to demonstrate to our youth the importance of soils to them. The current effort by the Soil Science Society of America to fund a soils exhibit at the Smithsonian Institute in Washington is an excellent example of this. Perhaps some of the concepts developed for the exhibit at the Smithsonian can be packaged in a way that allows them to be incorporated into the displays at local museums of natural history so that student throughout the country can benefit.

As in all things, we are too often prisoners of our past. We have difficulty envisioning an education substantially different from our own. We read and study the literature and ways of thinking about problems that are often unsuitable for solving them. We have conceptual blocks. Faced with a problem we are hard pressed to come up with more than one approach to solving it. From an early age, we copied the problem solving skills of our elders. If we ventured into novel ways of approaching a problem we were often told that it would never work and that we were ‘‘strange’’. This is not unique to forest soils folks or even to humans. James Adams has written a delightful little book, *Conceptual Blockbusting*, which can serve as a guide to better ideas (Adams, 2001). We would all profit from studying it.

3. Research trends and needs in forest soils

In the 19th century, forest soils research was actually basic research, and important concepts regarding soil organic matter and cation exchange were developed through forest soils research. In the 20th century, forest soils research took a decidedly applied path. This was dominated in North America by soil-site studies and the quest for simple ways to predict site productivity from soil properties. Empirical studies of the effects of fertilization and tillage on survival and growth were also important. Late in the century, studies of the impact of forest management practices on the productive capacity of the soil dominated. Also near the end of the century we saw the shift of some researchers toward more basic studies, but a preponderance of empirical studies continues.

There is no doubt that we are critically short of basic knowledge of both soil and plant processes, and sound research in these areas is vitally needed. But as that knowledge is developed we need applied research that will enable managers to use the new knowledge to improve yield and maintain environmental quality. As in other forestry situations, the long life span of trees and the length of common forestry rotations present unique research challenges. Today’s need for integration of information is a major challenge in forest soils. We must be able to take basic and applied research and develop tools that can be used to make better decisions.

Modern computer technology will surely be the way we solve the problems with integration of information. PCs and GIS technologies are available to every forester, but the necessary data and skill to use these resources are not always available. These technologies must be developed into user-friendly tools so that they leave the domain of GIS and computer specialists located in a central office and reach the domain of the forester—the pickup truck parked on an isolated woods road. A fundamental obstacle that must be overcome for this to occur is posed by the ‘‘frequency of use’’ paradox. A typical scenario for implementing new technology is that a forester attends a training class and ‘‘learns’’ how to use the tool. Unfortunately, when he or she returns to the job, it is days, weeks, or months before they have the need or opportunity to use the tool again. Because the technology is not intuitive, they then have great difficulty using the tool. If they only need to use the tool periodically, the need for a user-friendly, intuitive interface is much greater. Just as Sisyphus in Greek mythology is forever pushing the stone to the top of the hill, foresters are forever struggling to gain proficiency with their technology. In most cases, they are never able to get past the steep portion of the learning curve and become proficient before they are forced to turn their attention to another issue. When they return, they find that they are back at the start of the learning curve, just as Sisyphus's stone has rolled back to the bottom of the hill. This is probably the reason why GIS technology is not fully utilized to its potential as a day-to-day tool by many field foresters.

An important research need, particularly when we are finally able to fully integrate GIS technology into our day-to-day activities, is to develop regional databases that include results from studies that test key hypotheses across soil and climate zones from which soil management guidelines can be developed. We must provide the regional databases and tools to help the forester make informed decisions. Bracketing the ranges of properties so that the land manager can fit their observations within the model would provide a valuable predictive tool. The studies must be well designed to show the implications of a set of treatments and cause and effect research must be conducted to understand why the treatments did or did not respond as expected, and the two approaches must be tied together. This is not unlike the cooperative work that has been done in the past; the main difference is delving into the mechanisms of response and testing hypotheses rather than just developing a surface area of response. Examples of studies that include large regional databases include:

- The USFS Long Term Soil Productivity Studies that were established under the leadership of Bob Powers (Powers and Fiddler, 1997).
- A regional database of soil disturbance studies compiled by Weyerhaeuser in collaboration with the USFS, University of Washing, NCASI, and others.
- The region wide trials established by the Forest Nutrition Cooperative across that cover a wide variety of soils and landforms soils/landforms across much of the South.
- The series of studies established by The Stand Management Cooperative in the Pacific Northwest beginning in 1969 under the guidance of Stan Gessel. This provides one of the largest continuous studies of forest management impacts on growth that integrates soil properties into the study.

Additional studies like these are needed throughout North America. For example, an area of research that is increasing in importance is the long-term implications of management on carbon storage, physical properties, nutrient cycling, and tree growth. Well-designed long-term studies that contribute to a regional database are going to be the best places to address these questions. For example, in the Pacific Northwest, the USFS in cooperation with industry is expanding the network of trials across soil and climatic zones to determine the impact of organic matter removal (total-tree utilization versus conventional harvesting) and slash displacement (displaced with scarification but not removed) with and without intensive vegetation control. We need to know what the impacts of these treatments are across a range of sites from low to high moisture stress sites. And we need to monitor long-term impacts on carbon storage, water holding capacity, vegetation resiliency, such as species change over time.

This integrated research will require increased collaboration among industry, universities and the public agency scientists more so than in the past. However, the value of these large regional databases will not be fully realized unless we also increase the amount of collaboration among researchers and practicing foresters. Research results must be made available to forestland managers in a user-friendly format. Developing an effective extension program in forest soils remains a challenge. One improvement that needs to be made is to organize information into tools that foresters can use. Curran et al., 2003 (this conference) discussed how some of these tools could be better developed regionally; e.g., soil disturbance classification and monitoring tools, soil disturbance risk-rating.

However, large amounts of potentially useful information from well designed and executed research trials remains in a form that is not available to the practicing forester. Innovative use of the internet could revolutionize the transfer of information to those that need it, provided the information is organized and presented in a succinct, user friendly format. The problem today is often too much information available on the internet in its raw form, which can overwhelm practicing foresters and experienced researchers alike. There is a tremendous need for sites that synthesize and interpret the research results. A good example of the potential of this technology for disseminating information is the site on N management of Douglas-fir: http://depts.washington.edu/nitrogen/ and the PNW Stand Management Cooperative site: http://www.cfr.washington.edu/research.smc/. In the South, the Forest Nutrition Cooperative is attempting to create a website (http://www.forestnutrition.org/) where the results from its massive database are synthesized and condensed into a format usable by its industrial members. Sites that highlight information of particular interest are also very useful, such as: http://www.snr.missouri.edu/silviculture/online/ and http://www.forestsoils.org/s-7. Another issue with the internet is the limitations of current search engines. For instance, typing "Nitrogen management of Douglas-fir" into one of the popular search engines on the internet does not lead to useful sites already published on the internet. A great deal of use could be made of information already available, but the means of making it available will continue to challenge forest soil scientists.

As the evolution of the domesticated forest continues, we have entered into a new phase associated with precision, clonal forestry. Clonal forestry is being operationally implemented for conifers in the South and West as it has with eucalypts in South America for decades. This will bring new challenges in how to test the performance of clonal material on different soils and deploy it most efficiently to each site. Precision forestry that incorporates clonal deployment will require site specific silvicultural regimes to be developed at very fine spatial scales for individual clones to optimize water and nutrient availability throughout the rotation. Precision, clonal forestry will require interdisciplinary teams of geneticists, soil scientists, pathologists, and silviculturalists to properly implement it. The management of the domesticated forest will be even more agronomic in character.

Remote sensing techniques will be an essential component of precision clonal forestry, which attempts to make soil specific silvicultural recommendations and then apply treatments at the sub-stand level. For example, digital spectral analysis of stands obtained via remote sensing will help us better diagnose nutrient deficiencies and improve fertilizer prescriptions. Leaf optical properties, such as spectral reflectance, transmittance, and absorption, can be determined using remote sensing technology. These properties can be used to determine chlorophyll concentrations in the foliage and identify stress levels in plants (Carter and Knapp, 2001). Leaf area index can now be determined at the stand level or individual tree basis using remote sensing data (Fassnacht and Gower, 1997; Naesset et al., 2004).

The use of LiDAR to measure topography and tree heights will greatly improve our ability to track productivity at the micro-site and landscape scale level (Naesset et al., 2004). Incorporating these data into a GIS will permit larger scale studies that can then be conducted with treatments being replicated on an operational scale. Periodic flights would provide height growth from the same area on the ground, over a rotation, and from rotation to rotation. We still may have to measure tree diameters but trees per acre and heights will soon be reliably measured from the air. This technology can also help find slumps and faults that cannot be easily seen or mapped from the ground, thus greatly increasing our ability to identify unstable slopes and guide road building, maintenance, and harvest lay-out.

Maintaining soil quality is a fundamental aspect of sustainable forestry. Accurate, repeatable, and practical prediction of forest soil quality, site quality in the old vernacular, has been the "Holy Grail" of forest soils for over 50 years. Many well-known forest soil scientists spent their entire careers in pursuit of this goal. Unfortunately, in many ways we are no farther along than we were 20 or even 50 years ago. We "know", unless we are all guilty of theory tenacity, that properties, such as organic matter, nitrogen content (total, inorganic, mineralizable?), extractable nutrients, pH, CEC, texture, bulk density, aeration porosity, etc. must be related to forest soil quality. However, our ability to predict soil quality as it actually affects tree growth based on these parameters is still woefully inadequate. Recent efforts seem to have gone away from using site index or other measures of tree growth as the measure of soil quality. This is justified by the problems with ''variation'' in tree and stand growth that must be masking the true relationship. However, we must recognize that variability in forest soils is greater than in agricultural soils and develop better ways to account for this variability. We suspect that one of our fundamental problems in this regard is that we are not measuring the right variables or we are measuring them in the wrong way. This is probably a fault of our ''agronomic training'' as forest soil scientists. The agronomic model of soils assumes that soil is a homogeneous body (i.e., the concept of an acre furrow slice that dominates soils) and does not take into account the variability inherent in forest soils. It specifically does not take into account the important properties and processes of forest soils that separates them from agronomic soils. Some examples of how our agricultural bias may lead us astray include:

(1) In the agronomic model, we sample the bulk soil and analyze it. If a sample contains too many roots, rocks, chunks of buried organic matter, or many of the other factors common to forest soils, it is discarded as ''non-representative'' and a new sample is taken.
(2) Furthermore, we focus on the bulk soil and ignore the places that tree roots proliferate. How many times have we characterized the properties of old root channels, stumps, fractures, and ped faces where tree roots actually exist. It is not surprising that we find little correlation between tree growth and soil fertility indices from the bulk soil. Perhaps we need to better characterize the impact of coarse fragments, ped surfaces, old tree roots and stumps on water and nutrient supply. Although they may be a small percentage of the area, they could well be significant factors contributing to nutrient availability. We need to develop the correct weighting factor to account for these disproportionately important portions of the soil. We need to solve the problem of how to weight these areas when we come up with a whole-soil index of quality.
(3) In the agronomic model, the solum depth (rooting depth) is the soil above the C horizon parent material. We seldom sample below 50 cm. People that sample to 1 m are called ''heroic'' (or crazy). Yet we all see tree roots in the C material, or the saprolite, and even in fissures within the bedrock. How does this influence our description of solum depth?

None of this is new. Lutz and Chandler's (1946) text on forest soils has a picture of tree roots growing in an old root channel. Earl Stone has been a ''voice in the wilderness'' crying out for a better understanding of deep rooting of trees and how it affects our understanding of site quality for most of his career (Stone and Kalisz, 1991). We must challenge ourselves to devise the techniques and instruments needed to evaluate soil quality in a way that is relevant and specific for forestry and takes into consideration the unique properties of forest soils and the characteristics of trees as long-lived, deep rooted organisms. We then need to continue improving practical ways to evaluate soil quality in every stand so that we have a defensible way of evaluating management impacts on long-term sustainability.

Understanding what factors limit growth and the underlying mechanisms of treatment response will help define the most important indicators of soil quality and sustainability. These will be determined from well-designed research trials and they can be followed through repeated rotations if we have the foresight to do so. Tree growth and critical soil quality variables can be tracked in these trials to ensure operational prescriptions are going to be meeting our targets. Many excellent examples exist where detailed soil monitoring has been conducted on long-term productivity. Examples of these studies have been described by Allen et al. (1991), Morris and Miller (1994), Powers and Fiddler (1997) and Kelting et al. (1999). Information from these studies can be used to determine soil quality targets and to develop BMPs, while the larger set of operational stands should confirm that BMPs are operationally meeting productivity expectations.

In addition to enhancing our ability to define soil quality as an index of sustainability, we may also need to reconsider our basic approach to the problem. Finding improved ways to monitor and assess sustainability are high on everyone's list these days; e.g., ''sustainability metrics.'' Perhaps we spend too much time debating the metrics and too little time on assessing how well we are doing in each process step.

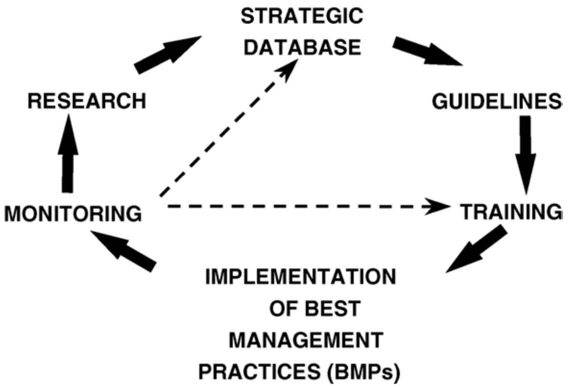

Fig. 3. Process components required to achieve sustainable site productivity.

The practice of sustainable forestry will demand that we use reliable processes in an integrated manner as illustrated in Fig. 3. Do we have the database we need to make decisions and define BMPs? Is there enough data for users to develop guidelines and decisions support tools to meet their objectives? We need to show that we have process steps in place directed at soil sustainability. Industry, agencies, and universities can work together at the region level to ensure that adequate systems are in place for sustainable soil management.

It is a lot easier to ensure that the BMPs have been implemented, and visual soil disturbance guidelines have been met, which are based on the research data, then to expect soil quality based on soil physical or chemical properties to be monitored on every management unit. Monitoring should be done for BMP treatment compliance, tree productivity, and other properties and processes in the forest ecosystem, such as vegetation, wildlife habitat. We need to maintain stand and silvicultural treatments histories across a matrix of soils/climatic zones. This data is not always maintained in inventory or stand management systems where it can easily be referenced back to stand boundaries through successive rotations. Geographic information systems make this possible and practical. In some cases detailed monitoring may be required on a sub-set of stands if diagnostic methods are available to guide prescriptions accordingly. A detailed subset needs to be established at the region level for forest productivity tracking. Sustainability can be assessed by monitoring growth performance of this matrix of stands, which have had BMPs implemented, across soil/climatic zones.

Many organizations are moving towards the use of reliable processes to ensure that their objectives are being met. Use of such processes is compatible with American Forest and Paper Association (AF&PA) SFI and with ISO 14001 environmental management system processes and standard requirements. ISO 14001 is an environmental management system developed by the International Organization of Standardization which helps organizations minimize detrimental environment impacts and improve overall environmental performance. These systems require reliable processes demonstrating how goals are to be achieved. The simple model illustrated in Fig. 3, often referred to as the adaptive management model, can be used successfully but it requires discipline, good planning and commitment in each step of the process. Too often we only do part of the process and eliminate its usefulness.

Finally, let us come back to integration of information. Tracking stand and culture history through time will be important component of precision forestry in the domesticated forest. If we take advantage of the full capabilities of existing GIS and remote sensing technologies, many of our research questions could be answered by data obtained from monitoring of operational plantations. We could easily track the impact of various treatments on stand growth and productivity and develop appropriate management guidelines based on those data. Just think of how forest management practices have changed since Earl Stone first described the domesticated forest in 1973, In the South we have seen genetic deployment, site preparation, vegetation control, and fertilization practices change drastically through time as research results are implemented in what in many areas is now the South's sixth forest (Fox et al., 2004). Even with the longer rotations in the west, in most locations we are now in the second rotation of plantations and similar changes in silvicultural practices have taken place. We must develop a strategy for keeping track of this information at the stand and landscape scale because without a good stand history it may be difficult to maximize the growth potential through successive rotations. To track productivity trends, information will be needed to be integrated from treatment prescription inventory information and final-harvest data. As in all endeavors of mankind, unless we learn from the past we are destined to repeat it. This is where some southern hemisphere operations are ahead of many of us. They have detailed records of what has been done and they track productivity very closely in every stand—they are already practicing "precision forestry." If we want to increase growth, optimize financial returns and demonstrate sustainability in the domesticated forests in North American we must do this as well.

Reference

Adams, J.L., 2001. Conceptual Blockbusting, fourth ed. Perseus Publishing, Cambridge, MA, 220 pp.

Ahrens, W.H. (Ed.), .1994. Herbicide Handbook. seventh ed. Weed Science Society of America, Champaign, Illinois, p. 352.

Allen, H.L., 2000. North Carolina State Forest Nutrition Coop, Annual Report, June 2000, 20 pp.

Allen, H.L., Morris, L.A., Wentworth, T.H., 1991. Productivity comparisons between successive loblolly pine rotations in the North Carolina Piedmont. In: Dyck, W.J., Mees, C.A. (Eds.), Long-term Field Trials to Assess Environmental Impacts of Harvesting. Proceedings of the IEA/BE T6/A6 Workshop, Florida, USA, February 1990. IEA/BE T6/A6 Report No. 5, Forest Research Institute, Rotorua, New Zealand, FRI Bulletin No. 161, pp. 125–136.

Allen, H.L., Weir, R.J., Goldfarb, B., 1998. Investing in wood production in southern pine plantations. Paper Age (April), 20–21.

Borders, B.E., Bailey, R.L., 2001. Loblolly pine—pushing the limits of growth. Southern J. Appl. Forestry 24, 69–74.

Carter, G.A., Knapp, A.K., 2001. Leaf optical properties of higher plants: linking spectral characteristics to stress and chlorophyll concentration. Am. J. Bot. 88 (4), 677–684.

Carter, R.E., McWiliams, E.R.G., Klinka, K., 1998. Predicting response of coastal Douglas-fir to fertilizer treatments. Forest Ecol. Manage. 107, 275–289.

Curran, M., Maynard, D., Heninger, R., Terry, T., Howes, S., Stone, D., Nieman, T., Miller, R.E., 2003. Progress towards more uniform assessment and reporting of soil disturbance for operations, research, and sustainability protocols. Paper Presented at this Conference.

Edmonds, R.L., Hsiang, T., 1987. Influence of forest floor and soil properties on response of Douglas-fir to urea. Soil Sci. Soc. Am. J. 57, 1332–1337.

Fassnacht, K.S., Gower, S.T., 1997. Estimating the leaf area index of north central Wisconsin forests using the LANDSAT Thematic Mapper. Remote Sens. Environ. 61 (2), 229–245.

Fisher, R.F., 1996. Broader and deeper: the challenge of forestry education in the late 20th century. J. Forestry 94 (3), 4–8.

Fisher, R.F., Garbett, W.S., 1980. Response of semimature slash and loblolly pine to fertilization with nitrogen and phosphorus. Soil Sci. Soc. Am. J. 44, 850–854.

Fox, T.R., 2004. Species deployment strategies for the southern pines: site-specific management practices for the Flatwoods of Georgia and Florida. In: Dickens, E.D., Barnett, J.P., Hubbard, W.G., Jokela, E.J. (Eds.), Slash Pine: Still Growing and Growing. GTR-SRS-076. USDA Forest Service, Southern Research Station, Asheville, NC, pp. 50–55.

Fox, T.R., Jokela, E.J., Allen, H.L., 2004. The evolution of pine plantation silviculture in the southern United States. In: Rauscher, H.M., Johnson, K. (Eds.), Forest Science: Past, Present, Future. GRT-SRS-75. USDA Forest Service, Southern Research Station, Asheville, NC, pp. 63–82.

de Gonçalves, J.L.M., Benedetti, V., 2000. Nutrição E. Fertilização Florestal Instituto de Pesquisas e Estudos Florestais, Piracicaba, SP, Brazil.

Heninger, R.L., Scott, W., Dobkowski, A., Miller, R., Anderson, H., Duke, S., 2001. Soil disturbance and 10-year growth response of coast Douglas-fir on nontilled and tilled skid trails in the Oregon Cascades. Can. J. Forest Res. 32, 233–246.

Ice, G., Binkley, D., 2003. Forest streamwater concentrations of nitrogen and phosporus—a comparison with EPA's proposed water quality criteria. J. Forestry 101 (1), 21–28.

Jenny, H., 1941. Factors of Soil Formation: A System of Quantitative Pedology. McGraw Hill, New York.

Jokela, E.J., 2004. Nutrient management of southern pine. In: Dickens, E.D., Barnett, J.P., Hubbard, W.G., Jokela, E.J. (Eds.), Slash Pine: Still Growing and Growing. Gen. Tech. Rep. SRS-076. USDA Forest Service, Southern Research Station, Asheville, NC, pp. 27–35.

Kelting, D.L., Burger, J.A, Patterson, S.C., Aust, W.M., Miwa S M., Trettin, C.C., 1999. Soil quality assessment in domesticated forests—a southern pine example. Forest Ecol. Manage. 122, 167–185.

Kirwin, J., 2005. Virginia wins big! Virginia Forests 40 (4), 17–21.

Lutz, H.J., Chandler Jr., R.F., 1946. Forest Soils. John Wiley & Sons Inc., New York, NY, 514 p.

Martin, R., Sexton, C., Franklin, T., Gerlovich, G., 2004. Teaching Science for All Children: An Inquiry Approach, fourth ed. Allyn and Bacon, Boston.

McKeand, S.E., Crook, R., Allen, H.L., 1997. Genetic stability on predicted family responses to silvicultural treatments in loblolly pine. Southern J. Appl. Forestry 21, 84–89.

Michael, J.L., Neary, D.G., 1993. Herbicide dissipation in southern forest ecosystems. Environ. Toxicol. Chem. 12, 405–410.

Miller, J.H., Zutter, B.R., Zedaker, S.M, Edwards, M.B., Newbold, R.A., 2003. Growth and yield relative to competition for loblolly pine plantations to midrotation—a southeastern united states regional study. Southern J. Appl. Forestry 27, 237–252.

Morris, L.A., Miller, R.E., 1994. Evidence for long-term productivity change as provided by field trials. In: Dyck, W.J., Cole, D.W., Comerford, N.B. (Eds.), Impacts of Forest Harvesting on Long-term Site Productivity. Chapman and Hall, London, pp. 41–80.

Naesset, E., Gobakken, T., Holmgren, J., Hyyppa, H., Hyyppa, J., Maltamo, M., Nillsson, M., Olsson, H., Persson, A., Soderman, U., 2004. Laser scanning of forest resources: the nordic experience. Scand. J. Forest Res. 19, 482–499.

Neary, D.G., Michael, J.L., 1996. Herbicides—protecting long-term sustainability and water quality in forest ecosystems. N. Z. J. Forest Sci. 26 (1/2), 241–264.

Powers, R.F., Fiddler, G.O., 1997. The North American long-term soil productivity study: progress through the first 5 years. In: Proceedings of the 18th Annual Forest Vegetation Conference, Sacramento, CA, January. Forest Vegetation Management Conference, Redding, CA, pp. 102–118.

Stone, E.L., 1975. Soil and man's use of forest land. In: Bernier, B., Winget, C.H. (Eds.), Forest Soils and Forest Land Management. Proceedings of the Fourth North American Forest Soils Conference, Les Presses de L'Universite Laval, Quebec, pp. 1–9.

Stone, E.L., Kalisz, P.J., 1991. On the maximum extent of tree roots. Forest Ecol. Manage. 46, 59–102.