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Construction of a rapid soil quality measurement framework and its use at the Alabama A&M bioenergy reserach site

Curtis Martin Jawdy

To the Graduate Council:

I am submitting herewith a thesis written by Curtis Martin Jawdy entitled "Construction of a rapid soil quality measurement framework and its use at the Alabama A&M bioenergy reserach site." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.

Daniel Yoder, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Daniel C. Yoder, Major Professor

We have read this thesis and recommend its acceptance:

Virginia R. Tolbert

Donald D. Tyler

Acceptance for the Council:

Vice Provost and Dean of Graduate Studies

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A Thesis Presented for the
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Dedication

'The earth is the Lord's and the fullness therof,' so dedicating this work to Him is redundant, but I do so nonetheless. My thesis is far from perfect, but that fact has only served to humble me and to help me realize how few of the creation's wonders are truly apprehended by man. Soil quality is only starting to be defined and cared for, and this lack of wisdom will continue to degrade our lands until we heed the advice of the true land manager,

> 'When you enter the land I am going to give you, the land itself must observe a sabbath to the Lord. For six years sow your fields, and for six years prune your vineyards and gather their crops. But in the seventh year the land is to have a sabbath of rest, a sabbath to the Lord. Do not sow your fields or prune your vineyards. Do not reap what grows of itself or harvest the grapes of your untended vines. The land is to have a year of rest.'

Acknowledgements

I would first like to thank my mentor Dr. Virginia Tolbert. Her support and guidance was invaluable to the successful completion of this project. She taught me how to conduct myself as a professional with class and integrity.

Many thanks also go to Dr. Daniel Yoder who taught me the value of a defined goal and focused work to reach that goal.

Professors Don Tyler and Mike Mullen were also of great help in teaching me about soil organic matter and nutrient cycling. They never hesitated to offer sage advice, even if it meant travelling a great distance to give it.

None of this learning would have been of any avail if it had not been for the encouragement of my wife, Sara. She kept me sane and focused through the entire project.

Abstract

This thesis evaluated multiple possible soil quality indicators in order to choose a small set for inclusion in a rapid soil quality measurement scheme. The scheme was developed to be used for examining soil quality changes caused by land use differences. A more rapid, albeit less detailed, assessment of soil quality will be valuable to researchers studying the effects of land-use change where evaluation of multiple widely scattered sites is necessary in order to understand soil quality changes over a wide range of treatments and site conditions.

Research projects sponsored by the United States Department of Energy are examining the environmental changes that occur when agricultural land is converted to bioenergy production. A small number of these sites are heavily instrumented and sampled in order document environmental changes on site. This work would be greatly enhanced if many more locations and treatments could be sampled rapidly and cheaply. The goal of this thesis was to determine which measurements should be included in a rapid soil quality measurement scheme and to develop the scoring structure to accurately reflect changes in soil quality as measured by a larger suite of indicators.

The experimental design utilized for indicator evaluation included four treatments: agricultural control, switchgrass, sweetgum trees with fescue cover, and sweetgum trees maintained with no cover crop. These treatments were replicated twice on severely degraded agricultural land near Huntsville, Alabama in 1995. The soil was sampled at planting and again in the fall of 2002 for each of the replicated treatments. The erosion rate was modeled based on the characteristics of the crops using the Revised Universal Soil Loss Equation (RUSLE).

After careful consideration of each indicator, the measurement framework was fashioned with only two simple parameters in order to make it easy to use, and thus widely employable by researchers and land managers. Soil organic matter level and erosion rate were chosen due to

their direct links to the health of the land, widespread use, ease of measurement or estimation, correlation to other important soil attributes, and sensitivity over the correct time frame.

In order to make the soil quality measurement more site-specific, the organic matter and erosion indicators were scaled between one and zero based on the values measured for a ~50 year old forest (1) and an extremely eroded agricultural plot (0) nearby. Multiplying the erosion score by the organic matter score yielded the overall site health score. In this way, both indicators must be fairly high in order for the site to be deemed healthy. The treatments scored as follows: tilled agricultural (.05), sweetgum (.21), switchgrass (.15), and sweetgum with fescue cover (.34). The bioenergy treatments scored significantly higher than the tilled agricultural treatment, but the site will clearly take many more years to approach the health of a forest. The other measured values of soil and plant characteristics yielded little information or were closely correlated to the chosen measurements and were thus not included in the scheme.

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I. AG-Agricultural treatment
II. DBH-Diameter at Breast Height
III. DOE-Department of Energy
IV. LTER-Long Term Ecological Research
V. MLRA-Major Land Resource Area
VI. NRCS-National Resource Conservation Service
VII. NT-No-Till corn treatment
VIII. ORNL-Oak Ridge National Laboratory
IX. RUSLE-Revised Universal Soil Loss Equation
X. S-Sweetgum with no cover treatment
XI. SC-Sweetgum with fescue cover treatment
XII. SCI-Soil Conditioning Index
XIII. SOC-Soil Organic Carbon
XIV. SOM-Soil Organic Matter
XV. SSSA-Soil Science Society of America
XVI. SQI-Soil Quality Institute
XVII. SW-Switchgrass treatment

Chapter 1: Literature Review

The project detailed in this thesis had dual goals - first to define and validate a measurement system that will be useful in rapidly examining soil quality effects due to land use changes, and to then use that scheme to determine how conversion of a degraded agricultural field to bioenergy production has affected soil quality. The following section reviews the need to maintain soil quality and published soil quality measurement schemes.

Importance of soil conservation

Examples of civilizations that neglected their soil and faded away because of it are numerous (Olson, 1981). Modern researchers and landowners are acutely aware of the importance of protecting the world's soil resources as productive land becomes more scarce.

Intensive-tillage based farming practices have produced plentiful harvests of food, but have also often degraded soil quality. This problem has generated much interest in the scientific community recently, but the decline of soil quality due to conventional farming practices has been recognized for many decades. In the early part of the twentieth century, conservationists such as H.H. Bennett and William Albrecht warned farmers that high intensity farming could lead to the breakdown of organic matter, erosion, and the loss of associated soil nutrition and physical health (Albrecht, 1938). The legacy of these early conservationists is carried on by the work of the National Resources Conservation Service (NRCS) in land management.

Warnings about loss of soil quality were sometimes ignored because yields were often increasing due to technological advances even as soil quality was being degraded. Crop yields per acre have risen steadily since the 1940's; and this trend is exemplified by the yield of corn displayed in figure 1.

Dire predictions of global hunger have been extended ever farther into the future as the "green revolution" in agricultural technology has produced greater and greater yields

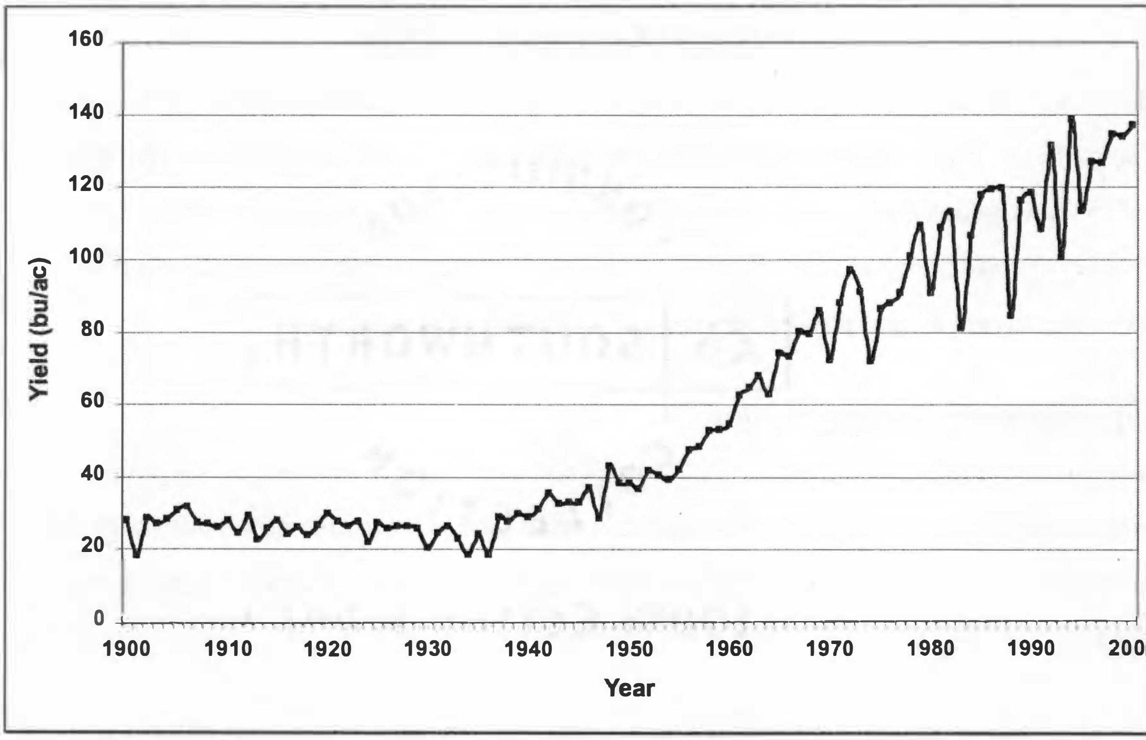


Figure 1: Historic yields of U.S. corn for grain

Adapted from NASS (2002)

per unit of land in the industrialized countries. Toy, Foster, and Renard (2002) state that overall agricultural yields per acre have tripled since 1935. In many cases, yield increases came from mechanization, improved crops (Reeves and Cassaday, 2002), chemical pest control and fertilization, and not from better soil management (Pearse, 1984). Non-conservation farming methods recommend frequent tillage and return little biomass to the soil, resulting in erosion and soil organic matter decline.

With intensive tillage and little crop litter return, a cycle of soil degradation can develop as follows. Farmers plow the soil in order to prepare a good seedbed for crops. After plowing, the organic matter that was previously protected by soil aggregation and lack of oxygen is broken down (Mann, 1986). This quick breakdown results in a flush of nutrients that is very helpful to the young crops (Hendrix, 1999; Kristensen et al., 2000). If the nutrients released in this way are not returned through fertilization, mineral weathering or atmospheric deposition, this process can lead to depletion of soil nutrient reserves (Van Duivenbooden, 1996).

Unfortunately, the intensive plowing results in breakup of soil covering litter and soil aggregates, allowing increased erosion. Soil nutrients and organic matter are lost in the eroded soil and through the metabolism of newly active microorganisms. Virgin soil usually loses approximately 20% of its organic matter within a few years of conversion to cropland (Mann, 1986). If modern soil conservation principles are not soon followed, the erosion and organic matter loss problems will only continue to worsen until a much lower equilibrium level of soil quality is reached. Similar scenarios are common, but we will consider only a few telling statistics detailing agricultural soil quality degradation in order to display the need for wise land management.

Prior to management, virgin land is in a state of relative equilibrium as measured by most soil health indicators. Once the land is plowed or otherwise disturbed, this equilibrium is lost and changes in the soil will occur until a new equilibrium is reached as a result of the management imposed upon it. For most soils, the soil will have lost health due to conventional cropping, as detailed below. The hypothesis being tested is that converting some of these degraded lands to bioenergy production will force the soil through a period of change into a higher equilibrium level of soil quality. These concepts are demonstrated in figure 2.

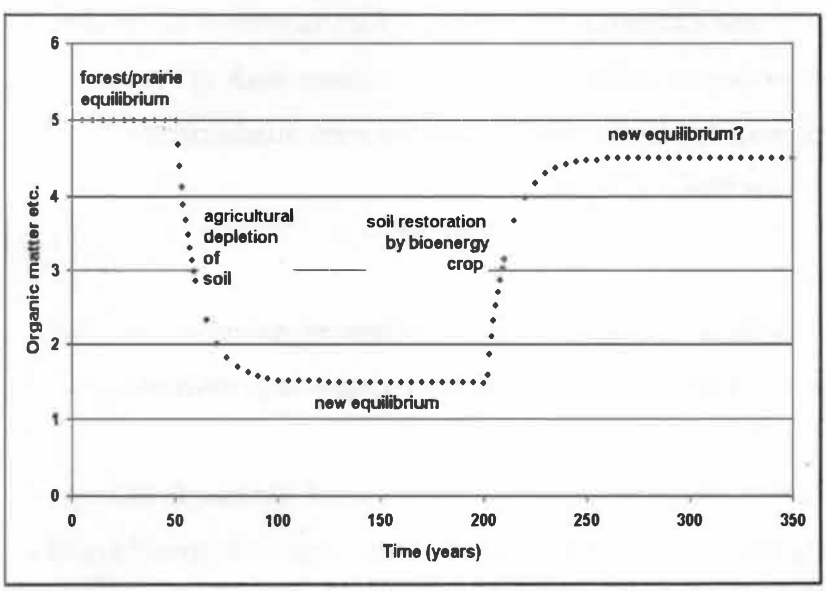


Figure 2: Theoretical depiction of soil quality with land use change

Measured by erosion

The soil quality and agricultural productivity of many soils have been harmed through careless farming practices that cause erosion. Toy, Foster and Renard (2002) state,

> On the basis of its temporal and spatial ubiquity, erosion qualifies as a major, quite possibly, *the* major, environmental problem worldwide.
>
> -and-
>
> There are 43.7 million hectares of cropland in the United States where the annual soil erosion rate exceeds the soil loss tolerance rate.

Erosion can degrade soil quality very quickly because it affects the most productive portion of the soil, the surface layer. The organic rich surface layer is critical for plant growth because plant roots depend on its loose texture, high porosity, and nutrient richness. If this layer is removed the soil quality can be severely impaired. The disproportionately large effect that the surface layer plays in soil quality was shown by Franzleubbers (2002), who derived a simple soil quality index based on stratification of organic matter. Erosion also reduces the depth of soil that plants can root in and draw water from. Subsurface layers such as fragipans and claypans that impede root growth are brought closer to the surface as erosion proceeds. In water-limited environments, this shrinkage of the rooting depth can be detrimental to crop growth and environmental health. Rhoton and Lindbo (1997) showed a high degree of correlation between effective soil depth and many other soil quality indicators, such as organic matter level, soil texture, and nutrient levels. Soybean yields were subsequently proven to have a high correlation to effective soil depth.

Measured by organic matter

Erosion often causes soil organic matter declines, and these declines are just as troublesome for soil quality as erosion. Reeves (1997) reviewed results from long-term continuous cropping experiments. and found,

> Soil organic carbon (SOC) is the most consistently reported soil attribute from long-term studies and is a keystone soil quality indicator, being inextricably linked to other physical, chemical, and biological soil quality indicators. Long-term studies have shown that continuous cropping results in decline of SOC, although the rate and

magnitude of the decline is climate and soil dependent and can be ameliorated by wise soil management practices.

Davidson and Ackerman (1993) reviewed changes in soil carbon storage following tillage of virgin soil and found an average decline of approximately 30%. Similar results were found by Mann (1986). Guo and Gifford (2002) reviewed the literature pertaining to land use change and its effects on soil carbon stocks. Forest-to-crop and pasture-to-crop conversion caused marked decreases in soil organic matter levels. Organic matter depletion is of concern due to the overriding influence organic matter exerts on soil quality through its nutritional, structural, and biological impacts (Reeves, 1997).

Measured by soil biological parameters

Many researchers have employed the rapid response of biological indicators to study the soil quality effects of differing soil management strategies. These soil microorganisms are necessary for the turnover of organic matter and nutrients in the soil and the preservation of soil structure. The health of soil microorganisms has also been adversely affected on many conventional cropping agricultural lands throughout the world (Caravaca et al., 2002; Yao et al., 2000). A number of factors can contribute to soil biological health decline, including lack of the organic residue they require as a substrate, poisoning by use of pesticides and herbicides, or breakdown of the good soil structure microorganisms need for proper aeration and moisture. Saviozzi et al. (2001) describes the very marked biological health advantage of forest and grassland soils compared with an adjacent conventionally cropped corn field in Italy. The measured parameters included total carbon, soluble carbon, total nitrogen, light fraction content, soluble carbohydrates, respiration, and the activities of six soil enzymes. Every parameter measured showed a considerable soil health advantage under the forest and grassland soils when compared to the cropped soil.

Measured by soil physical parameters

The declining soil organic matter and microbial biomass levels of many modern farmlands often lead to declines in the quality of physical soil parameters because of the fluffing and stabilizing effects of these fractions (Tisdall and Oades, 1982). When soils are tilled frequently, soil aggregates are dispersed and erosion potential increases (Curtin et al., 1994; Drees et al., 1994). Gardner and Clancy (1996) found significant decreases in aggregation and increases in bulk density when native North Dakotan prairie soils were converted to conventional cropping. Compaction problems caused by agricultural practice and machinery have also been reported in Barnes et al. (1971), Hakansson (1982), and Soane et al. (1981). The impairment of soil physical properties often leads to yield reductions (Raghavan et al., 1978; Eriksson et al., 1974), but slight compaction can cause no effect or even increase yields especially during dry years (Eriksson et al., 1974).

Reduced-till and no-till systems often vastly reduce these problems and problems with surface crusting and loss of soil organic matter by protecting organic matter from decomposition and soil structure from breakdown (Bruce et al., 1990; Karlen et al., 1994; Pikul and Zuzel, 1994). However, even no-till systems can be subject to soil compaction, reduced infiltration rate and aeration loss due to the compaction of the soil by heavy farm machinery (Hill and Meza-Montalvo, 1990; Horn et al., 1995; Soane and van Ouwerkerk, 1995).

Measured by soil chemical parameters

Finally, the chemical health of many soils has also been degraded by poor agricultural practice. Many soils have become nutrient deficient simply due to the export of nutrients in harvested food. These nutrient removals do not become troublesome as long as mineral weathering and atmospheric deposition of nutrients keep pace with removal through harvest. Modern high-yielding cultivars have provided cheap and plentiful food, but have also necessitated the use of chemical fertilizers to replace the nutrients removed in harvest. Experiments at two of the world's oldest agricultural trials serve to illustrate the point. At the Morrow plots in Illinois, trials of unfertilized and manure/lime/P fertilized corn plots showed declining yields on the unfertilized plots. Addition of inorganic NPK fertilizers to the previously unfertilized plots quickly restored their productive capacity, demonstrating that nutrient removal had depleted soil reserves (Vance, 2000). At the Rothamsted plots in England, extractable phosphorous and exchangeable potassium levels decreased in the unmanured, manured, and chemically fertilized plots over time (Jenkinson et al., 1987).

As soil degradation continues, losses of nutrients bound in the soil organic matter (C,N) are usually greater than the losses of nutrients that are bound to the mineral fraction (base cations) of the soil (Logan, 1990) because of the often rapid decline in soil organic matter that occurs in tillage-heavy systems with little residue return (Davidson and Ackerman, 1993). In order to maintain the chemical health of the soil, harvested, eroded, and mineralized nutrients must be replaced through deposition, weathering, or fertilization. Deposition and mineral weathering rates cannot be controlled, so for a given land use the nutrient status of the soil is largely determined by the amount of fertilizers applied and the availability of nutrients based on pH. Nonetheless,

> Some studies, usually on eroded soils, indicate that as SOC decreases it becomes increasingly difficult to obtain yields equivalent to those on un-degraded soils by the addition of fertilizer alone, albeit yields can be maintained at ca. 90% of potential (Loveland and Webb, 2003).

Nutrients are often applied in excess of crop needs due to the prohibitive cost of applying smaller amounts of fertilizer as crop requirements dictate. In cases where the fertility of degraded soils is maintained by excess chemical fertilization, nutrient leaching can occur. This leaching leads to eutrophication of waterways and is one form of non-point source pollution (Carpenter et al., 1998).

Soil quality measurement schemes rarely account for the forms in which soil nutrients occur (e.g., organic vs. inorganic), so the environmental consequences of fertilization strategy must be balanced with yield and profitability constraints through the use of nutrient management plans. Best management practices in this area include use of organic fertilizers which release bound nutrients more slowly as they are mineralized, crop rotations which include N-fixers, or crops which make more efficient use of nutrients (Carpenter et al., 1998).

Goal of land restoration

Lands degraded through careless agricultural practice, mining, site development and a number of other means can often be restored to health. A number of strategies have been employed to effect this restoration, including conversion to conservation tillage, mulching, cover cropping, green manuring, riparian buffers, and construction of erosion control structures (Troeh et al., 1999).

Because economic factors dictate that bioenergy crops will be planted mostly on degraded agricultural land (Wright and Tuskan, 1997; Mann and Tolbert, 2000), there is great potential for their use as soil restorers along with more conventional means of soil conservation. Researchers have hypothesized that bioenergy crops could make a significant impact in restoring such sites to health (Mann, 1986; Tolbert et al., 2000). The basis for such a hypothesis lies in the fact that tree crops compared to agricultural crops:

- tend to allow less erosion than conventional crops (Pimentel and Krummel, 1987; Kort et al., 1998);
- tend to add organic matter to degraded soil (Hansen, 1993; Tolbert et al., 2002; Post and Kwon, 2000; Richter et al., 1999);
- tend to increase the activity of soil microorganisms and fauna (Jimenez et al., 2002; Schipper and Sparling, 2000; Makeschin, 1994, Ma et al., 2000);
- tend to promote good soil structure (Tolbert et al., 2002; Devine, 2002; Singh and Singh, 1996);
- tend to recycle nutrients more effectively than conventional crops (Heilman and Norby, 1998; Wells and Jorgensen, 1979; Mann et al., 1988; Johnson and Todd, 1998).

The hypothesis that bioenergy plantations can restore the quality of soil degraded by poor agricultural practice will be tested in this thesis.

Bioenergy basics

A short review of bioenergy fundamentals is in order prior to examining the effects of bioenergy plantations on the environment. Renewed attention has been given to the use of biological materials for energy during the past three decades, beginning with the oil shortages of the 1970's. The United States Department of Energy (DOE) has been researching and promoting the use of domestically grown bioenergy fuels since 1979. The term "bioenergy" is used to describe heat, electrical, or liquid fuel energy derived from fresh plant material. Humans have been using bioenergy to heat their homes and cook their food for thousands of years, but the use of biofuels became impractical when the industrial revolution began to require vast amounts of concentrated energy in order to fuel the production of the creature comforts modern humans have come to expect. Society has begun to learn the lesson that the earth has finite fossil and environmental resources, however. This realization has lead to renewed interest in alternative forms of energy, including bioenergy.

The feedstocks used for conversion to bioenergy include agricultural residues, forest residues, mill waste, urban waste, and finally dedicated crops. These feedstocks are collected and converted to electricity and heat by combustion, or to liquid and gaseous fuels by various forms of fermentation and gasification. An example of this technology is the use of corn to produce the ethanol blended into many gasolines.

The choice of feedstock will be made mostly on the basis of availability and cost, but environmental factors must be quantified so that decision-makers can include this factor when deciding whether to use a biofuel or conventional fuels. Ultimately, the environmental benefits, if quantified and valued, may be one of the driving forces for adoption of biomass resources in energy production (Kuemmel et al., 1998). This thesis specifically examines the environmental effects of the two dedicated energy crop types that have been promoted by the DOE, short-rotation trees and grasses. These two cropping schemes were chosen for their high production rates of economical biomass with consistent combustion characteristics. The Biomass Feedstock Development Program (BFDP), the feedstock arm of DOE 's bioenergy production system, has selected and improved upon one or two model crops for each region of the United States.

The short-rotation tree system employs cultivars that have been selected specifically for extremely fast growth during the first decade of life. These trees are planted at close spacings and harvested after 4-12 years. This system capitalizes on the fast early growth characteristics of trees, without having to wait for the slower long-term growth needed to produce sawlogs. The DOE has singled out poplar as having the broadest production potential. Sycamore and sweetgum trees are being grown in the Southeastern region due to their wide site tolerances (Wright and Tuskan, 1997). The biomass produced on short-rotation plantations can be used for fiber as well as fuel.

The herbaceous system uses fast-growing grasses to produce the biomass used for fuel. The advantage of these crops is that they can be incorporated into existing crop rotations quickly, without the need of specialized machinery or significant investment of landowner money that would be tied up over the much longer rotation time of trees. Nearly any grass crop such as fescue or wheat could be used for this purpose, but the DOE has chosen switchgrass due to its extremely fast growth, site capture, lack of pests, and potential for soil improvement (McLaughlin and Walsh, 1998).

Agricultural sector models created at the Oak Ridge National Laboratory (ORNL) have predicted that most bioenergy crops in the Southeast will be, "grown on abandoned or excess bottomland agricultural sites..." (Wright and Tuskan, 1997) This land base of approximately six million acres is currently unprofitable or idle. Wright and Tuskan report 50,000 acres of short-rotation trees growing in the Southeast, with yields averaging three to four dry tons per acre per year on non-irrigated sites. Currently, this acreage is used primarily to provide fiber resources, but could also be used for energy production if the economics were competitive.

Early research has indicated that bioenergy crops can benefit the environment through increasing soil organic matter, bolstering soil physical structure, providing animal habitat, etc.

(Mann and Tolbert, 2000). The DOE has been monitoring a number of their dedicated feedstock research sites in order to test whether the crops are in fact increasing site health on the sites they were established. This thesis will report on the environmental monitoring results from the DOE plantation at Hazel Green, Alabama.

Need to study soil quality changes due to land use change

The BFDP has taken a wide range of soil quality measurements at their cooperative trials of agricultural sites converted to bioenergy plantations in order to fully understand the changes occuring on site. The work done at these sites is similar to that done at the 24 Long Term Ecological Research (LTER) sites scattered around the country (LTER, 2003). These sites, along with long term agricultural trials, chronosequence studies, and laboratory research are giving scientists new insight into the effects that land use have on soil quality and the environment as a whole. This large network of heavily instrumented sites is necessary to understand the changes occurring in the soil because of the large number of variables that affect the responses of the soil to treatment. For example,

> For each fall of 10° C in annual temperature, the average organic matter content of the soil increases two or three times, provided the precipitation-evaporation ratio is kept constant. (Albrecht, 1938)

The sites in the LTER network range from the arctic to the Everglades, but their goal is the same; to understand the response of ecosystems to land management. This knowledge is necessary so that extension agents, land managers and others can have the tools they need to make decisions that will benefit the health of the land under various circumstances. Just as the early soil erosion research led to the current trend toward conservation tillage (CTIC, 2003), the current work in monitoring the effects of land use on soil quality can possibly lead to future land managers employing new best management practices derived from LTER-type data.

Soil quality basics

Land use change researchers have examined many different aspects of environmental health including water quality (Jones, 2000), air quality (Offenberg and Baker, 1999), biodiversity (Pearson and Cassola, 1992), and a number of other areas. One area of interest is in the responses of soil quality to a number of different factors including cultivation (Mann, 1986), reforestation (Richter et al., 1999), timber harvest (Johnson and Todd, 1998), amendment with charcoal (Glaser et al., 2002), and a number of other factors. Before soil quality can be measured, however, it must first be defined. Soil quality can be defined in a number of ways depending on the goals for the soil and society as a whole. There is general agreement between soil scientists on the basics of soil quality, however. Soil quality fundamentals will be reviewed in the following section.

Broad statement of soil quality

"Poor land makes poor people, " according to Hugh Bennett, the first head of the precursor to the Natural Resources Conservation Service (SQI, 2002), but determining what makes land *poor* is not that simple. The task of defining soil quality and spreading good management recommendations has been ably undertaken by the Soil Quality Institute (SQI) within NRCS. The Institute defines soil quality as the capacity of a soil to "support plants and animals, retain and cycle nutrients, filter pollutants, regulate water flow, and support buildings." (SQI, 2002) This definition of soil quality will be assumed for the remainder of this thesis. The definitions of other research teams are similar, as demonstrated below;

> The capability of soil to produce safe and nutritious crops in a sustained manner over the long-term, and to enhance human and animal health, without impairing the natural resource base or harming the environment (Parr et al., 1992).

> The capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Doran and Parkin, 1995).

These definitions of soil quality are too broad to be useful for quantitatively measuring soil quality because they speak in unmeasurable terms. Most teams of researchers providing a definition for soil quality have also formulated a set of specific indicators for measuring soil quality. Table 1 displays the indicators formulated by the Soil Quality Institute (SQI, 2002) as an example of these frameworks. Similar lists can be found in

Table 1: Soil quality indicators

Indicator	Relationship to Soil Quality
Soil organic matter (SOM)	Soil fertility, structure, stability, nutrient retention; soil erosion.
PHYSICAL: Soil structure, Depth of soil, Infiltration and bulk density; Water holding capacity	Retention and transport of water and nutrients; habitat for microbes; estimate of crop productivity potential; compaction, plow pan, water movement; porosity; workability.
CHEMICAL: ph; Electrical conductivity; extractable N-P-K	Biological and chemical activity thresholds; Plant and microbial activity thresholds; Plant available nutrients and potential for N and P loss.
BIOLOGICAL: Microbial biomass C and N; Potentially mineralizable N; Soil respiration.	Microbial catalytic potential and repository for C and N; Soil productivity and N supplying potential; Microbial activity measure

Adapted from SQI (2002)

Doran and Parkin (1994), Romig et al. (1996), Mausbach and Seybold (1998), Karlen et al. (1994), and many other published articles.

Soil quality indicators

Nearly all soil quality frameworks break the chosen indicators down into 3-4 groups, including physical, chemical, and biological indicators, and sometimes organic matter as a separate category. Erosion is not usually directly considered, but only its effects on these categories. This thesis will also consider erosion due to its detrimental effects to local waterways and direct linkage to the other indicator categories.

State soil scorecards

Even detailed formulations of these indicator variables are too broad to assess soil quality, because local environmental differences and seasonal effects dictate which indicators have the most influence on soil quality for each situation. To remedy this, twelve states have partnered with SQI to formulate very specific sheets that can be used to determine the quality of a given soil (SQI, 2002). Specific soil problems can be diagnosed and remedied using the multiple indicators listed on the sheets. To date, 32 physical indicators, 12 biological indicators, 9 chemical indicators and 15 plant/residue indicators have been included in these state-specific cards. Each indicator typically has a measurement method described and a "healthy" range listed. The Georgia soil quality card is shown in figure 3 as an example of similar frameworks from other states.

These sheets are formulated with input from local farmers, and their ease of use gives them the potential to be widely employed. A review of the formulation and usefulness of the Wisconsin soil quality card can be found in Romig et al. (1996), which found initial farmer response positive. Values for all of the listed indicators are either estimated visually by the soil evaluator, or are taken directly from routine soil analysis done by the state soils lab.

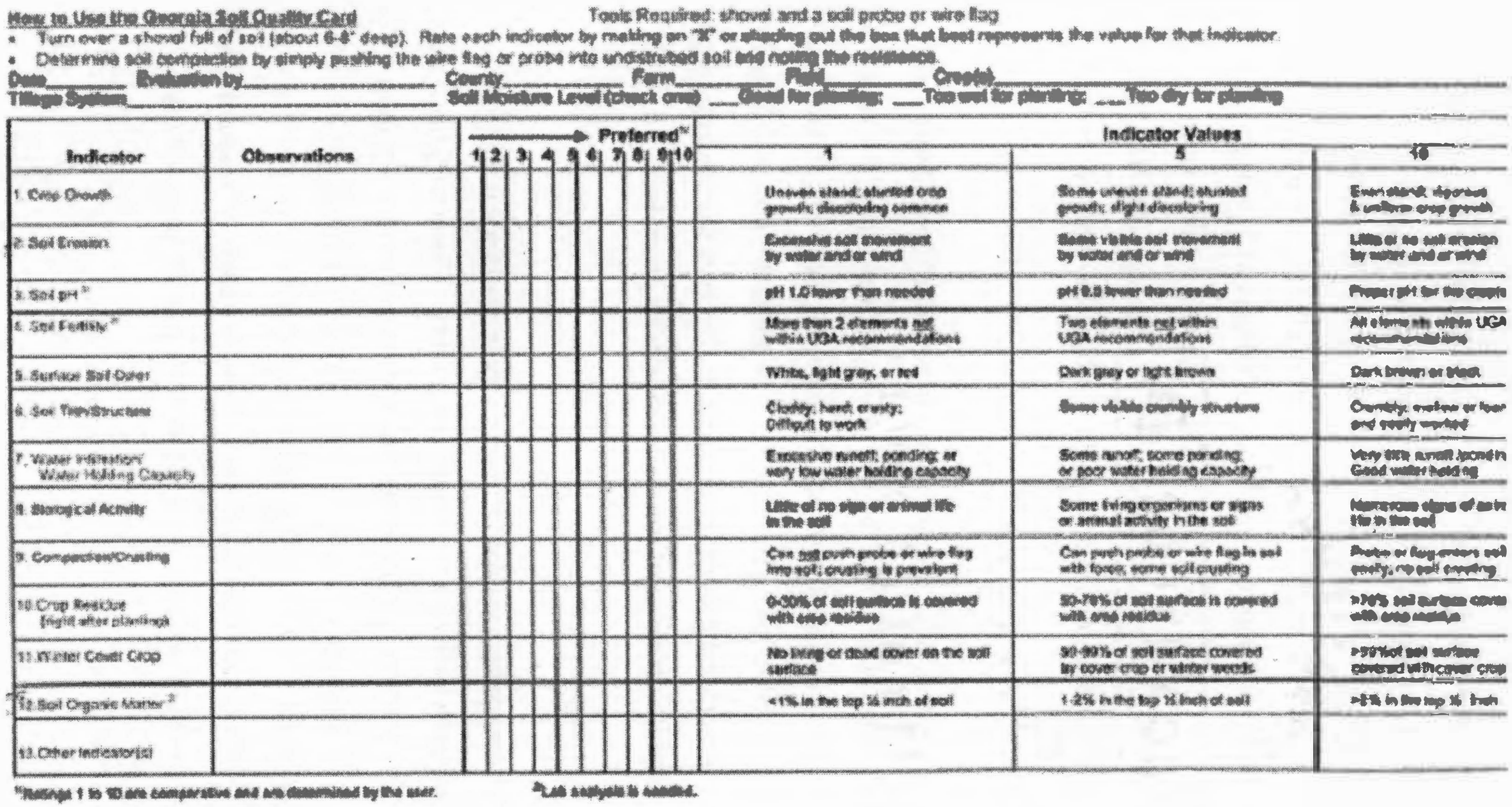
Romig et al. (1996) found that the major problem with these scoresheets is that,

> Pretests of the scorecard with farmers showed that farmers may be inherently biased when grading their own soils.... When judging any property they also may be judging the practices carried out on the field.

Accurate analysis of soil quality will be difficult as long as land-managers subjectively evaluate their own soils based on the treatments applied rather than on the actual results occurring in the soil. For example, many farmers assume that using cover crops will increase organic matter, and this expectation can be reflected when the farmer grades his soil, even if soil organic matter levels have not actually increased (Romig et al., 1996). The easy application of state soil scorecards should make them widely employed, but their subjective nature can make them hard to interpret and compare between sites.

<u>"Final score" sheets</u>

Several research teams have devised more quantitative measures of soil quality to correct subjectivity problems. These systems combine the results from several measured indicators into a "final score" for decision-making purposes. The final score format is useful for making decisions when management processes have increased soil quality in one category, but harmed it in another.



How to Use the Georgia Soil Quality Card — Tools Required: shovel and a soil probe or wire flag

- Turn over a shovel full of soil (about 6-8" deep). Rate each indicator by making an "X" or shading out the box that best represents the value for that indicator.
- Determine soil compaction by simply pushing the wire flag or probe into undisturbed soil and noting the resistance.

Date_______ Evaluation by_______________ County__________ Farm__________ Field__________ Crop(s)__________

Tillage System_______________ Soil Moisture Level (check one) ___Good for planting; ___Too wet for planting; ___Too dry for planting

Indicator	Observations	1	2	3	4	5	6	7	8	9	10	Indicator Values: 1	5	10
		——— Preferred[a]												
1. Crop Growth												Uneven stand; stunted crop growth; discoloring common	Some uneven stand; stunted growth; slight discoloring	Even stand, vigorous & uniform crop growth
2. Soil Erosion												Excessive soil movement by water and or wind	Some visible soil movement by water and or wind	Little or no soil erosion by water and or wind
3. Soil pH[b]												pH 1.0 lower than needed	pH 0.5 lower than needed	Proper pH for the crop
4. Soil Fertility[b]												More than 2 elements not within UGA recommendations	Two elements not within UGA recommendations	All elements within UGA recommendations
5. Surface Soil Color												White, light gray, or red	Dark gray or light brown	Dark brown or black
6. Soil Tilth/Structure												Cloddy; hard; crusty; Difficult to work	Some visible crumbly structure	Crumbly, mellow or loose and easily worked
7. Water Infiltration/ Water Holding Capacity												Excessive runoff; ponding; or very low water holding capacity	Some runoff; some ponding; or poor water holding capacity	Very little runoff /ponding. Good water holding
8. Biological Activity												Little or no sign or animal life in the soil	Some living organisms or signs or animal activity in the soil	Numerous signs of active life in the soil
9. Compaction/Crusting												Can not push probe or wire flag into soil; crusting is prevalent	Can push probe or wire flag in soil with force; some soil crusting	Probe or flag enters soil easily; no soil crusting
10. Crop Residue (right after planting)												0-30% of soil surface is covered with crop residue	30-70% of soil surface is covered with crop residue	>70% soil surface covered with crop residue
11. Winter Cover Crop												No living or dead cover on the soil surface	30-99% of soil surface covered by cover crop or winter weeds	>99% of soil surface covered with cover crop
12. Soil Organic Matter[b]												<1% in the top ½ inch of soil	1-2% in the top ½ inch of soil	>2% in the top ½ inch
13. Other Indicator(s)														

[a]Ratings 1 to 10 are comparative and are determined by the user. [b]Lab analysis is needed.

Figure 3: Typical state soil quality card

Adapted from SQI (2002)

Burger and Kelting (1999) proposed such a system. Their method combines multiple indicators into an overall score by which land management decisions can be made. The sufficiency of each indicator to promote healthy plant growth and site functioning is determined using curves with a maximum of 1 and minimum of 0. Each of these sufficiency scores is then multiplied by a scaling factor based upon the chosen importance of each indicator, with the scaling factors summing to one. In this way, a perfectly functioning ecosystem will achieve a score of 1. Karlen et al. (1994) proposed a similar method to determine an overall soil quality score. Figure 4 is taken from Mausbach and Seybold (1998), which expanded on the work of Karlen et al. (1994) by formulating sufficiency curves for the chosen soil quality indicators. Their proposed curves are shown.

Some curves, such as organic matter level, are of the "more is better" type. Some, such as bulk density, are of the "less is better" type. Some curves, such as nutrient levels, are of the "optimum" type. The score is scaled to one at the expected local best value and zero at the expected local worst value for each indicator. The indicator scores are made much more applicable to real world situations by this scaling, because the land manager can then see just where his soil lies in the continuum of soil health given local conditions.

The scaled indicator sufficiency scores are then multiplied by importance weights based on the relative importance of each indicator to overall soil quality. These weightings are based on the experience of the framework designer. The multiplied values are then summed to give the final score so that a perfect soil will be given an overall score of one and a worst-case soil will be given a score of zero. These concepts were applied by Mausbach and Seybold (1998) to compare Conservation Reserve Program, conventional tillage and no-till lands; the calculations used to determine the overall score for each land use are listed in figure 5.

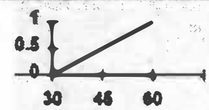
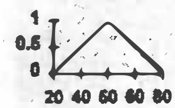
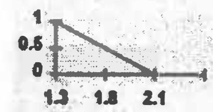
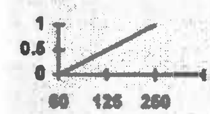
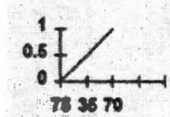
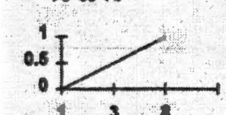
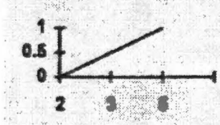
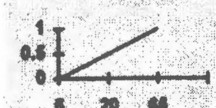
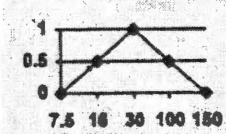
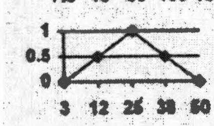
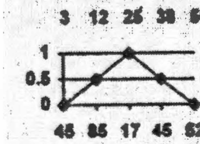
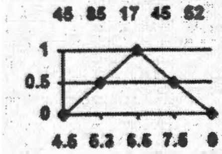
Indicators	Soil Functions	Range/Limits for Scoring Function	Scoring Function
Physical			
% Stable aggregate (*more is better*)	Regulating and partitioning water and nutrient flow	30–60 %	
Porosity—surface 75 mm (*optimum*)	Regulating and partitioning water and nutrient flow	20–80 %	
Bulk density (*less is better*)	Regulating and partitioning water and nutrient flow	1.3–2.1 mg/m³	
Rooting depth (*more is better*)	Biological activity	60–250 cm	
Biological			
Microbial biomass (*more is better*)	Biological activity, nutrient cycling, and filtering and buffering	75-700 mg C/kg	
Respiration (*more is better*)	Biological activity, nutrient cycling	0.5-8.0 mg C/kg	
Total nitrogen (*more is better*)	Biological activity, nutrient cycling	1.5 - 5.0 mg/cm³	
Total C in surface 75 mm (mg/cc) (*more is better*)	Storing and cycling nutrients and other elements, regulating and partitioning water and nutrient flow	15-50	
Chemical			
Plant available P (*optimum*)	Biological activity, nutrient cycling	7.5 - 150 mg/kg	
Nitrate nitrogen (*optimum*)	Biological activity, nutrient cycling	3 - 50 mg/kg	
Exchangeable K (*optimum*)	Biological activity, nutrient cycling	45 - 525 mg/kg	
pH Surface 250 mm (*optimum*)	Sustaining biological activity, diversity, and productivity, storing and cycling nutrients and other elements	5.5 - 8.2	

Figure 4: Indicator sufficiency relationships

Adapted from Mausbach and Seybold (1998)

Soil Function	Weight-1	Soil Indicator	Weight-2[d]		Weighted Index[b]	Soil Indicator Value (Score) CRP	Plowed	No-Till	Soil Quality Index[c] CRP	Plowed	N
Sustaining biological activity	0.40	Rooting medium	0.30								
		Rooting depth cm		(0.60)	0.072	150 (0.6)	100 (0.3)	125 (0.5)	0.043	0.022	
		Bulk density g/cm³		(0.40)	0.048	1.07 (1.0)	1.39 (0.9)	1.31 (1.0)	0.048	0.043	
		Water relations	0.30								
		Porosity %		(0.60)	0.072	60 (0.5)	48 (0.9)	51 (1.0)	0.036	0.065	
		Total carbon mg/kg		(0.40)	0.048	23.9 (0.6)	16.6 (0.3)	16.0 (0.3)	0.029	0.014	
		Nutrient relations	0.30								
		pH		(0.30)	0.048	6.3 (0.9)	6.4 (0.9)	6.4 (0.9)	0.043	0.043	
		Available P mg/kg		(0.10)	0.016	38 (1.0)	6 (0)	13 (0.5)	0.016	0	
		Exch. K mg/kg		(0.10)	0.016	267 (0.9)	137 (0.9)	167 (1.0)	0.014	0.014	
		Total carbon mg/kg		(0.40)	0.064	23.9 (0.6)	16.6 (0.3)	16.0 (0.3)	0.038	0.019	
		Nitrate nitrogen mg/kg		(0.10)	0.016	1.0 (0)	2.2 (0)	1.4 (0)	0	0	
Regulating and partitioning water	0.30	Aggregate stability %	0.60		0.18	40 (0.3)	19 (0)	26 (0)	0.054	0	
		Porosity %	0.20		0.06	60 (0.5)	48 (0.9)	51 (1.0)	0.08	0.054	
		Bulk density g/cm³	0.20		0.06	1.07 (1.0)	1.39 (0.9)	1.31 (1.0)	0.06	0.054	
Filter and buffer	0.30	Aggregate stability	0.60		0.18	40 (0.3)	19 (0)	26 (0)	0.54	0	
		Porosity	0.10		0.03	60 (0.5)	48 (0.9)	51 (1.0)	0.15	0.27	
		Microbial processes	0.30								
		Total carbon mg/kg		(0.50)	0.045	23.9 (0.6)	16.6 (0.3)	16.0 (0.3)	0.27	0.014	
		Total nitrogen mg/kg		(0.50)	0.045	2.9 (0.5)	3.6 (0.6)	2.9 (0.5)	0.23	0.027	
Totals					1.0				0.53	0.40	

Figure 5: Example overall scoring system

Adapted from Mausbach and Seybold (1998)

The final score method utilizes the objective measurements used by conventional state soils lab reports and the soil quality concepts used by farmer scorecards to give an accurate picture of soil health. It also removes the bias farmers have for their own soils by using objective measures of soil parameters, much like traditional soils lab reports. The final score method gives interpretive information about the role and importance of each soil attribute, much like the farmer scorecard. It also gives additional insight into soil quality by including measurements of soil characteristics typically excluded by soils labs such as respiration, aggregation and rooting depth.

Soil quality test kit

In order to bridge the gap between simple qualitative scorecards and intensive quantitative soil analysis, Dr. John Doran of NRCS developed the soil quality test kit. Ten soil quality indicators are measured with the kit, including soil respiration, earthworm number, infiltration rate, bulk density, water content, slaking, aggregate stability, pH, electrical conductivity, and nitrate level (SQI, 1999).

Testing with the kit showed good repeatability and no significant differences between kit and laboratory measurement, excepting respiration (Liebig et al., 1996). A study by Seybold et al. (2002) detected significant soil quality differences between paired tilled and no-till plots. Time required for sampling includes 1-2 hours in the field and 2-3 hours for drying, slaking tests, and calculation of values (Ditzler and Tugel, 2002).

SQI personnel conducted more than 20 training sessions for NRCS staff, conservation district staff, the Nature Conservancy, local governments, and universities. SQI staff found the kit a good tool to promote a broad understanding of soil quality and the impacts of management on it (Ditzler and Tugel, 2002).

Need for a rapid soil quality assessment scheme

The soil quality test kit is valuable to landowners who wish to improve the quality of their soil through conservation management (Liebig et al., 1996), and final score schemes are valuable to researchers who wish to study soil quality issues in depth at experimental sites (Mausbach and Seybold, 1998). However, there is a need for a soil quality measurement scheme that can be utilized to study the multiple widely scattered sites often necessary for land use studies in a time and cost-effective manner.

Although existing schemes are very adept at measuring soil quality when properly scaled to local conditions and administered by competent evaluators, their use may be hindered by three concerns. First, the measurement of multiple soil parameters that they require is too time-consuming and expensive to be used for researchers who study multiple widely scattered sites and who cannot use the SQI test kit because many funding agencies and publications frown on non-laboratory methods of soil analysis. Second, the measurement of some soil quality indicators is redundant due to the highly correlated nature of many indicators. Third, many of the included indicators cannot be interpreted in the same way for every site. Finally, many indicators, though contributors to soil quality, do not measurably respond to land use differences over the appropriate time scale. These concerns are detailed below.

Ease and speed of measurement

Desirable attributes for soil quality measurement schemes are the speed and ease of measurement. These attributes are even more critical when studying land use effects on soil quality because these studies are often prohibitively expensive due to travel and manpower costs even before the time and money for soil sampling and analysis is considered. Such studies are often not intended to fully explain the complex and dynamic nature of ecosystems, but to give a snapshot of differences in a much smaller set of attributes (e.g. SOM) over a wide range of treatments and locations (Mann, 1986; LTER, 2003, Glaser et al., 2002, Khaleel et al., 1981). Land use studies merely detect environmental changes due to land use differences, more detailed studies are then necessary to understand the dynamic processes leading from land use differences to environmental quality differences. These concepts were encapsulated succinctly by Schoenholtz et al. (2002),

> Adding complexity to soil quality models to improve their accuracy and forecasting ability must be balanced with the ability of practitioners to apply them to their management systems. To help the practitioner meet his or her goals, the best model would be conceptually simple, cheap to develop, and easy to apply. Soil quality assessment is a process of applying existing knowledge to achieve land management aims, namely sustainable forests and agro-ecosystems. This process should not be confused with the goals of forest science, a process of developing new knowledge for a deeper understanding of nature.

This thesis will attempt to produce a soil quality measurement scheme that can detect soil quality changes with a minimum of indicators.

Redundant indicators

The number of indicators can sometimes be safely reduced because of a high degree of correlation between many of the measured values. This correlation often makes it redundant to measure multiple values that are closely related to one another. For example, aggregation and soil organic matter are often correlated very strongly (~.8) (Chaney and Swift, 1984; Tisdall and Oades, 1982). Soil scientists have taken advantage of the observed relationships between soil attributes to produce several empirical equations used to estimate unknown soil properties based on known soil properties (Bell, 1995; Rajkai, 1996). The use of these pedotransfer functions can lessen the sampling and analysis required to determine soil quality. Where appropriate, indicators that are estimable using pedotransfer functions could be removed from existing soil quality measurement schemes. This thesis will attempt to choose the indicators that have the most influence over a range of soil quality attributes, and thus reduce the measurement of redundant indicators.

Difficult to interpret indicators

Regarding the difficulties of interpreting results, this thesis will attempt to select only indicators that can be interpreted the same way universally. For example, high soil respiration rates normally indicate a healthy microbial community, but could also indicate only that the soil has been recently tilled (Hendrix, 1999). A study by Sparling et al. (2000) demonstrated that different site conditions can lead to very different responses to land-use change. The study examined three soils that had been subjected to various land uses. The land uses examined were mature broadleaf-podocarp forest (50+ years), radiata pine plantation (20+ years), pasture (25+ years) and arable cropping (20+ years). A large number of physical, chemical and biological indicators were compared at each site whose soils differed only in land use, the soil series being the same at the closely spaced treatments. Cores were taken to 7.5 cm and the soils analyzed.

The pertinent result to note is that most indicators varied significantly within each soil type, but did not vary significantly when compared over all three soil types. Such results include bulk density, pore space, available water, hydraulic conductivity, pH, total C, total N, Olsen P, CEC, base saturation, and Ca. Responses to management for these indicators were site-specific, and thus use of these indicators would require additional expertise or testing to fully describe the change occurring at each location. Studies by Brejda et al. (2000a, 2000b) further confirm that many soil quality indicators cannot be used in the same way at different locations. Their studies, conducted over four different Major Land Resource Areas (MLRAs) evaluated hundreds of soil samples taken from each region for 20 soil quality attributes. Their factor and discriminant analysis showed that land use differences were effectively detected by a different suite of indicators for each area. Of all factors, only soil organic matter (SOM) level was sensitive to land use differences over all of the areas studied.

Indicators whose responses to land use differences are site specific should be used with care so that responses are correctly interpreted. This study will attempt to choose only the indicators that will be uniformly applicable and interpretable under nearly all soils and land uses.

Indicators that respond over the wrong time-scale

Finally, many indicators that have been used in published site health measurement schemes were rejected for this study because of their demonstrated lack of sensitivity to treatment changes over useful time scales. This study focused on medium-term (5-50 year) changes in site health, and many published site health indicators measure either shorter-term or longer-term changes. Medium-term changes in soil quality are the most useful to examine in land use studies, as detailed below.

Short-term changes often reflect not the *trend* of soil quality, but management and weather effects such as rainfall, fertilization, or residue removal. Short-term indicators are useful for gauging the effects of these operations, but provide little insight into whether the soil is gaining or losing quality. Biological indicators are usually of this extremely sensitive variety. For example, Franzluebbers (1999) dried and rewetted Piedmont soils and found soil respiration rate increases ranging from 70% to 250% over the equilibrium respiration rate. In order to fully understand the site with these parameters, many readings must be taken over time, an expensive and time-consuming proposition. If seasonal effects provide no real differentiation of soil quality, they simply become noise on the longer-term signal.

Long-term indicators are less sensitive to management changes, and can describe the trend of soil quality. Unfortunately, differences may not register between treatments for hundreds of years. For example, approximately thirty to one hundred years is required to produce one inch of productive topsoil from subsoil. This formation rate equals 11 metric tons ha^{-1} yr^{-1} (Morgan, 1986). Decision-makers, however, do not have hundreds of years to determine how they are affecting the environment. Indicators that are relatively unaffected by seasonal variations and yet sensitive enough to discern medium-term trends were chosen so as to avoid the time-scale pitfalls mentioned above. Moreover, the chosen indicators cover soil responses over the entire range of time scales; i.e., the sensitive period of one indicator covers the insensitive period of another.

Chapter 2: Methods

The usefulness of the soil quality indicators was tested in the field and using published literature. The field research was carried out at a BFDP site where the land use had been converted from conventional agriculture use to bioenergy production. The effects of the bioenergy crops on the soil were then evaluated based on the chosen indicators. The study site was one of four agricultural research facilities converted to bioenergy trials by the BFDP in the early/mid 1990's. These plantations were located in the Southeast and meant to test the viability of the program's model Southeastern bioenergy crops and their effects on the environment.

Site description

The plantation studied in this thesis was established in 1995 on heavily eroded agricultural land at Hazel Green, Alabama. The Winfred Thomas Agricultural Research Station sits on land that has been farmed for over 100 years, with at least the last ten years in a corn/wheat/soybean rotation. The soil is comprised of Decatur and Cumberland silty clays, in the severely eroded and eroded/undulating phases. These series are deep (>6 ft.) soils formed from limestone residuum and are fine, kaolinitic, thermic Rhodic Paleudults (NCSS, 2003).

Where the A layer still exists it is a dark reddish brown (5YR 3/2) silt loam and is moderately acid. Where the Bt1 layer exists, it can begin at 0 to 20 cm in depth and is a dark reddish brown with subangular blocky structure, shifting to a dusky red (10R 3/4) past 50 cm. In most places on site (>80% based on classification by soil scientist Don Todd), erosion has removed these layers and the Bt2 layer remains on the surface. The Bt2 layer is clay, sticky, plastic, and very strongly acidic. Chert fragments up to 10% can be found throughout. The top 50 inches contain less than 10% weatherable minerals in the 20 to 200 micron size (NCSS, 2003). For the full NCSS description of the soil please see the appendix.

This extremely poor (weathered, eroded, and acid) soil made it a perfect candidate to study the possibility of restoring soil quality with bioenergy crops in a side-by-side comparison with a tilled agricultural crop rotation. The study site is located within the circle of figure 6.

Treatment description

Five treatments were established: a conventional corn (*Zea mays*)-soybean (*Glycine max*) - wheat (*Triticum aestivum*) rotation (AG), no-till corn (NT), sweetgum trees (*Liquidambar styraciflua*) maintained with no cover (S), sweetgum trees with a fescue (*Festuca spp.*) cover crop (SC), and switchgrass (*Panicum virgatum*) (SW). These treatments were replicated twice, as displayed in the topographical map of figure 7. Replications were situated so as to remove the influence of slope and soil differences as much as possible by clustering the two replications along two areas of similar slope and soil characteristics. Average slope values are given in table 2. Site preparation included tillage for all plots. Trees were hand planted, and then fescue seeded between rows in the SC treatment. The S treatment was kept free of undergrowth through the use of glyphosate for the first two years. The agricultural plot was

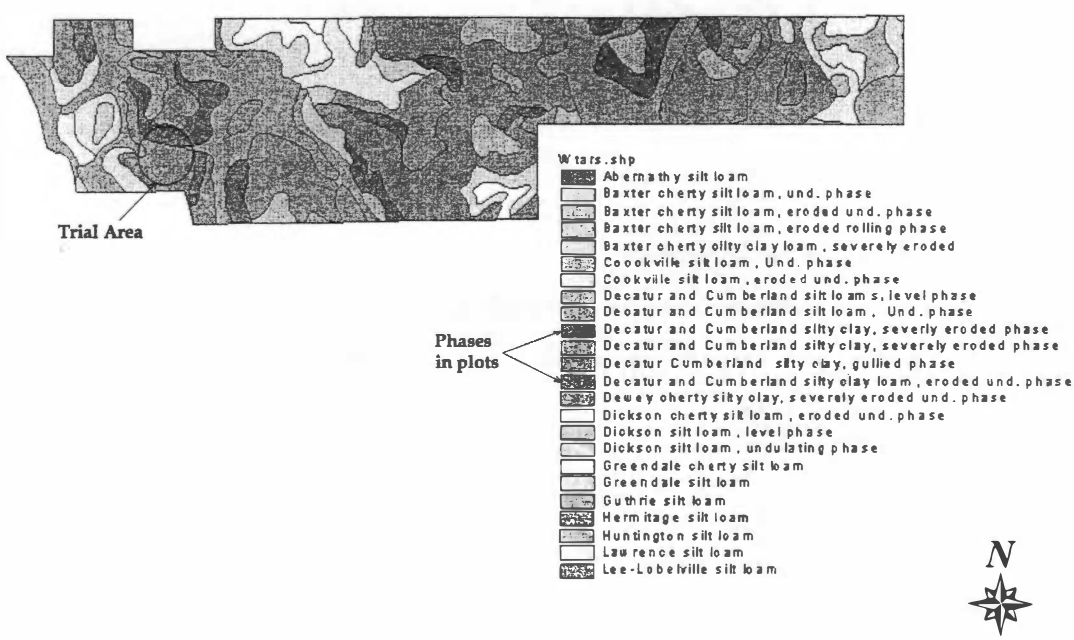


Figure 6: Research station soil classification

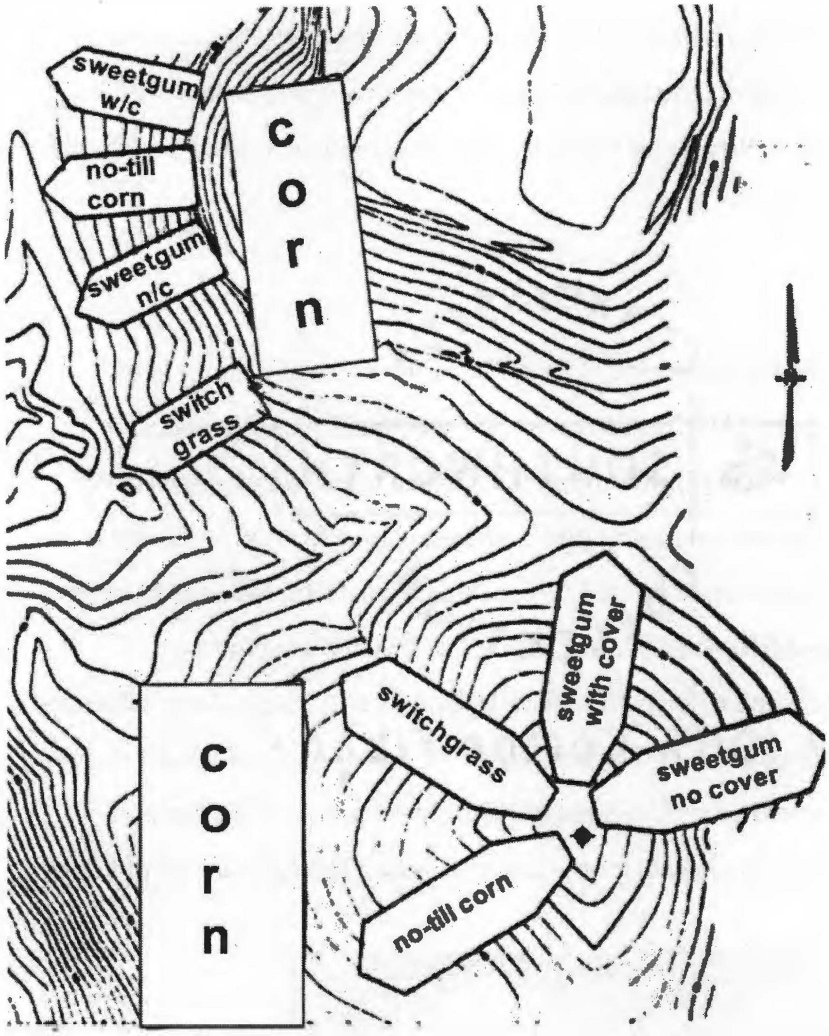


Figure 7: Site layout

Table 2: Average slope values by replication

Average slope for each replication (%)		
	Large (.5 ha) plots	Small (.25 ha) plots
AG	2.8	6.0
NT	2.2	6.3
S	3.5	6.0
SC	3.6	6.5
SW	2.6	4.8

managed roughly according to the state extension office recommendations for corn and soybeans (Mask and Mitchell, 2003; Monks and Delaney, 1998).

The trees received 84 kg ha^{-1} yr^{-1} of N in years 2 and 3 and 100 kg ha^{-1} of P in 1996. The switchgrass and agricultural plots received 134 kg ha^{-1} yr^{-1} of N and 67 kg ha^{-1} yr^{-1} of P yearly. The fertilization rate was determined based on soil samples taken at the time of establishment and the expected nutrient requirements of the specific crops. Lime was applied to the agricultural plots in April, 1999 at the rate of 2 tons ac^{-1} in order to keep the pH within the Alabama recommendations for corn and soybeans (Mask and Mitchell, 2003; Monks and Delaney, 1998).

All collected data were analyzed using the analysis of variance procedures within the SAS® statistical package. Crop and slope position were treated as fixed effects, while replication and subsamples were treated as random effects. Depth was included as a covariate for the soil analyses. Mean separation was performed at the $\alpha = 0.05$ level using the least significant difference procedure.

Sampling and analyses

At establishment, each plot was tilled and bermed in order to prevent any runoff interferences. Flumes and Isco® water samplers were installed at the outlet of each plot to monitor the runoff volumes, suspended solids, NH_4^+, NO_3^-, P, K, Ca, Mg, and pH. Event-based runoff samples were taken and analyzed until 1998. Suction lysimeters were also installed at each site and sampled after significant rainfall events. These samples were also analyzed for NH_4^+, NO_3^-, P, K, Ca, Mg, and pH until 1998. Rainfall measurements were also taken on-site until 1998. The water monitoring and modelling efforts are reported in Thornton et al. (1998). Because of the high variability in the runoff data from the smaller plots, the EPIC model was unable to adequately predict runoff differences that would be expected for the different experimental crop treatments.

Each plot was divided into five sub-plots in order to account for the gradient of soil properties along the slope, based on the assumption that erosion had caused differences in SOM levels and soil quality along the slope (Wan and El-Swaify, 1997). Five soil samples were taken for each treatment/slope position combination within both replications.

These cores were split into depths of 0-5 cm, 5-15 cm, 15-30 cm, 30-45 cm, 45-60 cm, 60-75 cm, 75-90 cm, and 90-120 cm. These plugs were then dried and sent to the University of Georgia Agricultural and Environmental Services Laboratories for analysis of carbon by combustion, total nitrogen, pH, K, Ca, Mg, and many micronutrients by the Mehlich I procedure. Phosphorous was determined using the Bray procedure (AESL, 2002). The micronutrient portion of the sampling showed no growth-limiting factors and will not be discussed here.

The soil was sampled in the year 2000 for saturated hydraulic conductivity, pH, dry bulk density, penetration resistance, and sand-silt-clay fractions according to standard methods (SSSA, 1994a). Twenty-five trees from each plot were measured at least once a year for height and diameter. The annual yields from the switchgrass and agricultural plots were recorded.

Intensive sampling of the tree plots occurred in the spring of 2002, prior to leaf-out. One tree was randomly selected from each of the five elevation locations within each treatment/replication combination. The chosen trees were cut down and measured for height and diameter at breast height (dbh). The wood of the trees was split into two fractions, bole and branch, roughly based on a diameter of 2.5 cm. These two fractions were weighed in the field and these wood samples were taken to the lab for moisture content determination. After drying and determination of moisture content, these wood samples were then ground and analyzed for carbon and nitrogen by combustion and P, K, Ca, and Mg using the Georgia Agricultural and Environmental Services Laboratory plant analysis procedure (AESL, 2002).

The dry weight of the wood from each tree was determined using the sampled moisture contents and green weights. These weights were then regressed against many combinations of the height and dbh measurements. The best fitting regression line was used to predict the total yield of the tree stands based on height and dbh measurements taken from one tree out of every row within the plantation.

Three random leaf litter samples were taken at each location where a tree was removed. The litter was sampled by placing a $0.5m^2$ ring randomly within the area occupied by the corresponding tree and collecting the leaf litter within the ring down to the mineral soil. These leaf litter samples were then weighed and analyzed for carbon and nitrogen by combustion. The Georgia Agricultural and Environmental Services Laboratory plant analysis procedure was used to determine P, K, Ca, and Mg levels (AESL, 2002).

After the litter was removed, a 2.5 cm diameter soil core was taken to a depth of 60 cm at each sampling location. These cores were then split using the same layers as in the initial sampling of 1995, namely; 0-5 cm, 5-15 cm, 15-30 cm, 30-45 cm, and 45-60 cm. The soils were refrigerated and one gram samples analyzed for β-glucosidase levels using the procedure of Eivazi and Tabatabai, which is based on the β-glucosidase catalyzed transormation of p-nitrophenyl-β-D-glucoside to p-nitrophenol. (SSSA, 1994b).

The remaining soil was dried and the moisture content determined. The dry soil was then crushed using a rubber mallet. Roots and rocks larger than 2 mm were removed and the remaining soil ground to pass a 60 mesh screen. The ground soil was then subsampled and analyzed for carbon and nitrogen using the combustion technique on the Leco Corporation LECO-2000CNS elemental analyzer. Five gram subsamples were also taken for N, P, K, Ca, and Mg analysis by the Mehlich I procedure (AESL, 2002).

The final sampling on the site occurred during late September, 2002. This was done on a mixed hardwood stand of approximately 60 years of age and also on the most eroded portions of a nearby soybean field. These areas were within 500 yards of the replicated study and on similar soils. The litter of the forested site was sampled, and 15 soil samples were taken using the same procedure as for the intensive study site. Seven soil samples were also taken from the degraded areas of the soybean field. All of these samples were analyzed for C and N by combustion as well as N, P, K, Ca, and Mg by the Mehlich I procedure (AESL, 2002).

Yearly erosion rate was modeled using the Revised Universal Soil Loss Equation (RUSLE). The RUSLE predicts erosion rate as follows, with values used in this study given in parentheses:

Soil loss = R*K*L*S*C*P

R = rainfall erosion index factor = (value for Hamilton county, AL)

K = soil erodibility factor = (.27) based on advice from county NRCS office and Dr. Dan Yoder

L = slope length factor = (150 feet) based on consultations with Dr. Dan Yoder

S = slope pitch factor = (based on measured slopes of table 5)

C = cover and management factor = (as given below)

P = cropping practice factor = (as given below)

The erosion model was initialized based on the following observations of the tilled agricultural (AG) plot:

- Summer 2002: Disked twice, soybeans
- Winter 2001: Disked twice, winter wheat
- Summer 2001: Disked twice, fallow
- Winter 2000: Fallow
- Summer 2000: Disked twice, soybeans
- Winter 1999: Fallow
- Summer 1999: Disked twice, corn
- Winter 1998: Moldboard plow
- This pattern was considered to repeat itself indefinitely into the past

The model was initialized for the other plots as follows:

- all treatments started out in the "agricultural" condition at the beginning of the study;
- the sweetgum with no cover (S) had very little if any weed growth, but was not disturbed by plowing following the initial year. The canopy closed in year three;

- the sweetgum with cover (SC) had poor-fair grass cover until year three, when it was shaded out. The canopy closed in year three;
- switchgrass (SW) had poor cover in the first year but was fully established at the end of the second growing season and did not have lush growth.

Indicator selection criteria

All of the measurements described above were taken so that they could be analyzed and the most useful ones for rapidly detecting soil quality changes chosen. Following is a list of the criteria used to choose indicators.

1. Must be highly correlated to site health as defined in the broad statement, so that they will be measuring soil quality
2. Must be easily and cheaply measurable, as well as widely-accepted so that multiple sites and treatments can be monitored effectively over time
3. Must be sensitive over the correct time/management scales, so that short-term noise is ignored, and so that longer-term trends are detected.
4. Must have a baseline value for comparison with future measurements, so that the progress soil quality indicators can be tracked
5. Must not be highly correlated to an already measured value, so that monitoring effort is not wasted on repetitive measurement

Chapter 3: Results and Discussion

Effect of blocking on slope position

The first analysis done was to test whether blocking on slope position achieved its goal of reducing the overall variability of the data. The hypothesis that position on the slope would affect soil properties was proven valid by many soil parameters, as displayed in table 3. Thus, use of slope position as a blocking term was justified. The soil carbon contents were enriched at the foot of the slope, most likely due to the movement of carbon-rich topsoil carried by erosion (Wan and El-Swaify, 1997). Preferential deposition of the larger silt particles may have also caused the relative silt enrichment at the foot of the slope. The higher carbon contents and silt fractions at the foot of the slope combined to form a more productive soil as evidenced by the wood yields. No other variables showed a consistent pattern across slope.

Crop yields

The wood yield calculations were based on the biomass regression that best fit the data for the harvested trees. The equation used was:

$$\text{Yield (Mg/ha)} = 0.0068 * \text{Diameter (in.)} * \text{Diameter (in.)} * \text{Height (ft.)} + .49.$$

The fit of the yield measurements was good, with an R^2 value of .89. The regression can be seen graphically in figure 8. Yields did not differ significantly between the plots with and without a fescue cover crop, as displayed in figure 9. The total calculated yield of wood was 41.1 Mg ha^{-1}, or 5.9 Mg ha^{-1} yr^{-1}. The trees only produced approximately half

Table 3: Effect of slope position

Position	Carbon content (%)	Silt (%)	Clay (%)	Wood yield (Mg/ha)
Top	.60 (a)	63.8(1.9)a	33.8(1.9)a	25.7(3.2)a
Upper	.61 (a)			36.0(3.3)ab
Middle	.66 (ab)	70.6(1.6)b	27.3(1.6)b	43.8(3.7)ab
Lower	.70 (b)			46.4(5.6)ab
Bottom	.76 (c)	77.9(1.1)c	19.9(1.1)c	53.7(13.4)b

Values within each column followed by the same letter do not differ at $\alpha = .05$. Wood yield is the average of S and SC treatments. Mean standard errors in parentheses.

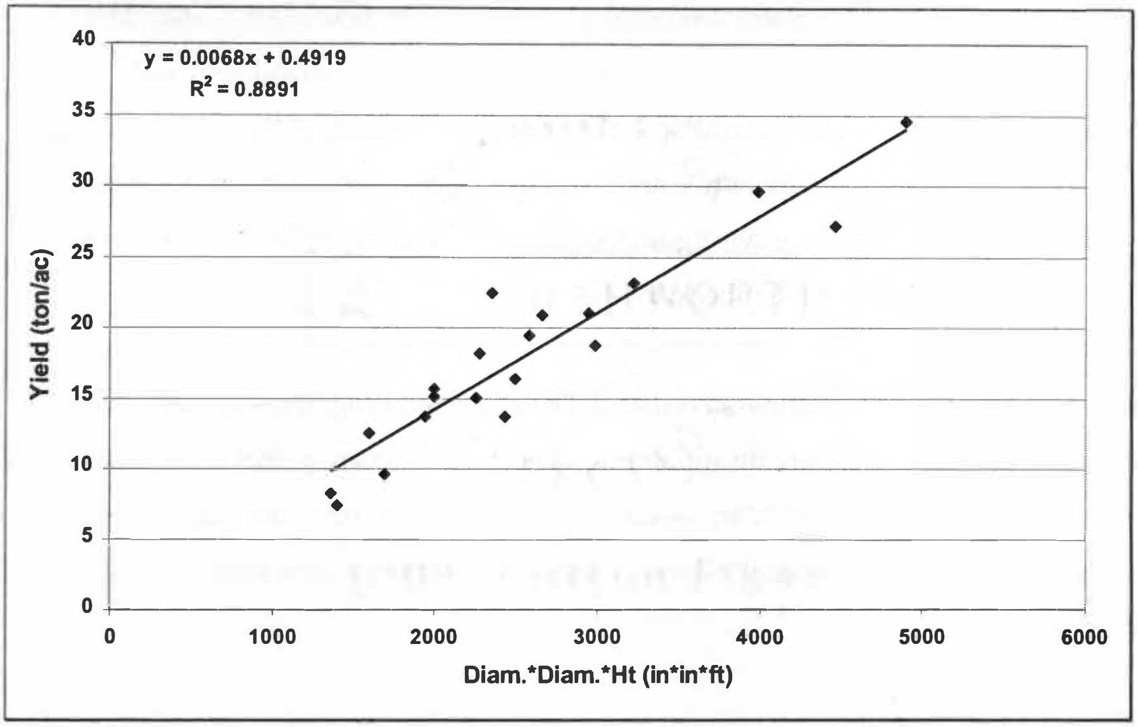


Figure 8: Sweetgum biomass regression

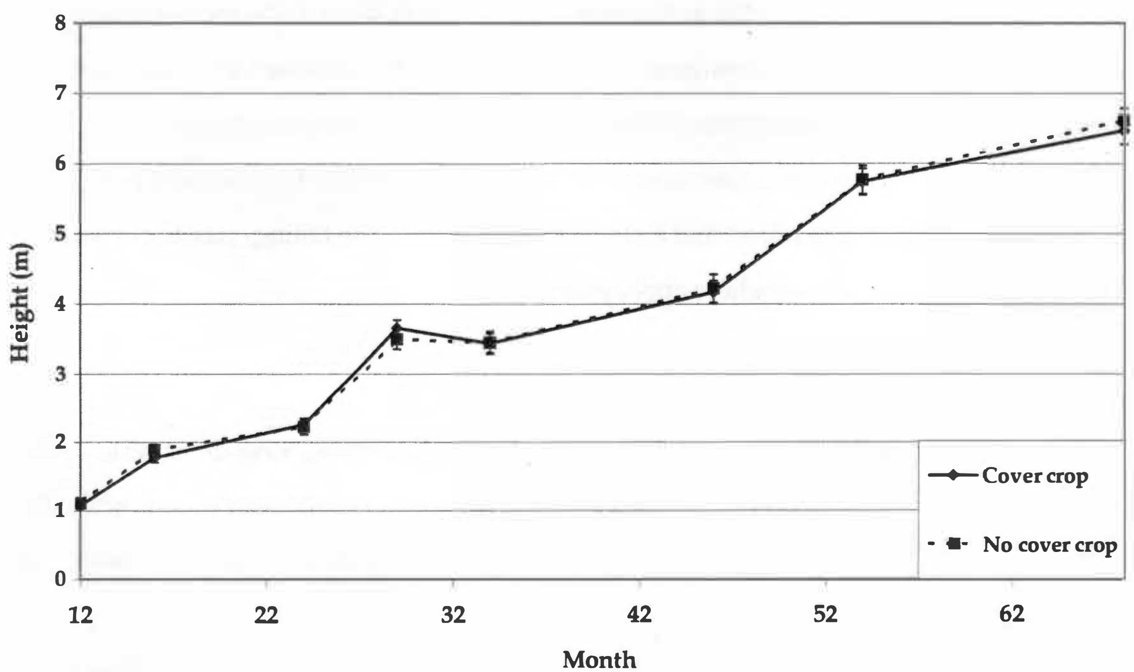


Figure 9: Effect of cover crop on tree growth

Bars represent mean standard error. No differences significant at $\alpha = .05$.

the biomass stated for typical short-rotation plantation in the Southeast as stated by Wright and Tuskan (1997), and were outperformed by both the agricultural and switchgrass crops, as displayed in table 4. The poor performance of the sweetgum can be attributed to the low quality of tree seedlings used, poor soil quality, and to the long establishment phase typical of sweetgum trees, after which they typically catch up to other high yielding species (Steinbeck, 1994).

Given that the goal of the Biomass Feedstock Development Program is to create *biomass*, the poor yields of the trees are disappointing. Their slow growth points to the need for careful matching of high quality tree seedlings to each site. With good soil and trees a similar DOE site in Mississippi produced yields over 5 times as great as the site under consideration.

Choice of indicators

Next, the indicators listed by the SQI were evaluated based on the results from the site and published literature according to the indicator selection criteria listed in the methods section. The results for each indicator are reviewed below, along with the reasons for rejection or acceptance. Naturally, the explanation for the rejected indicators is shorter than for the accepted indicators because only one failed evaluation criteria resulted in rejection, but acceptance as an indicator required that all five criteria be met. The failing/passing criteria number is listed in parentheses where appropriate.

Soil structure rejected

Detailed soil structural analysis was not done at the study site, because detectable differences in soil structure were not foreseen to occur on the sticky and plastic soils on site. This prediction was borne out by examination of the soil as samples were taken. A

Table 4: Crop yields

Crop	AG	S	SC	SW
Yield (kg ha^{-1} yr^{-1})	9200(900)a	5900(900)b	5700(600)b	9600(1400)a

Mean standard errors in parentheses. Within each depth, values with the same letter do not differ at $\alpha = .05$.

very distinct interface between the O horizon and the underlying Bt2 horizon soil was found in the tree plots, indicating that the coarse organic matter had not been incorporated into the mineral soil, and thus could not have affected soil structure as described in Tisdall and Oades (1982). The sticky and plastic consistence of the soil was unchanged. A longer time period will likely be necessary for soil structural changes to become evident on site.

Soil aggregation has been used as an indicator in many soil quality studies (Devine, 2002), but evaluation and interpretation of soil aggregation values is difficult. Evaluation of aggregation level involves hand shaking of the soil through a series of stacked sieves under water. The results are dependent upon the shaking intensity and subject to human errors.

Moreover, the high degree of correlation between soil structure and soil organic matter levels makes it possible to approximate soil aggregation changes with soil organic matter changes (Tisdall and Oades, 1982). This approximation is useful because the other major influence upon aggregation is soil particle size, a parameter that cannot be easily altered through land management. Changes in tillage and residue return practices will affect aggregation, but the aggregation change will be mirrored by an organic matter change. For these reasons (criteria 2, 5) soil aggregation does not make a suitable indicator.

Penetration resistance rejected

The difficulty in measuring soil aggregation has sometimes been sidestepped by the use of penetration resistance as an indicator of soil structure and compactness. Penetration resistance measurements were taken on the test site in order to test for changes in soil structure. Unfortunately, the measurements were plagued with difficulty. Rocks and dense root systems often gave falsely high measurements of penetration resistance that do not reflect the actual difficulty roots would encounter in penetrating the soil. Table 5 displays that the switchgrass treatment gave significantly higher penetration resistance

Table 5: Penetration resistance

Depth/Crop	AG	S	SC	SW
15 cm	6.59 (.57)b	4.07 (.39)c	4.39 (.45)c	10.69 (.65)a
30 cm	5.57 (.37)b	4.41 (.50)b	4.94 (.33)b	8.90 (.70)a
45 cm	4.54 (.31)b	4.49 (.42)b	4.89 (.30)b	6.74 (.69)a
60 cm	4.04 (.34)b	4.69 (.44)ab	4.32 (.24)b	5.83 (.73)a
75 cm	4.40 (.32)a	5.18 (.34)a	4.51 (.50)a	5.11 (.47)a
90 cm	4.64 (.48)b	6.70 (.43)a	4.57 (.61)b	5.97 (.74)ab
Total	4.96 (.18)b	4.91 (.19)b	4.60 (.17)b	7.31 (.34)a

Values reported in KN/m^2 Mean standard errors in parentheses. Within each depth, values with the same letter do not differ at $\alpha = .05$.

than the other treatments. This result was attributed to the density of the switchgrass root mass that stabilized the soil, yielding a high penetration resistance.

Stabilizing roots are not the only thing that may yield high penetration values, however. Plowpans, rocks, fragipans, soil crusts and a number of other heterogeneities of soil tend to add variability to averaged data, which makes finding significant differences between treatments sometimes difficult (Utset and Cid, 2001). Some researchers report penetration resistance functions with depth in order to give a fuller picture of the state of soil hardness. Statistical analysis and reporting of these functions is difficult, however, and the means can sometimes yield much different conclusions than the functions (Schrey, 1991). In the case of soil with zones of hardness (of whatever type), penetration resistance readings indicate that root growth will be difficult, when the roots may actually grow around the hard zones (Bingham and Bengough, 2003). Due to difficulties in measurement and interpretation, penetration resistance was rejected (criteria 2).

Despite the difficulties in measuring and interpreting penetration resistance, studies done after planting formerly agricultural land to cottonwood in Mississippi and to sycamore in Tennessee showed decreases in penetration resistance after the conversion (Tolbert et al., 2002; Devine, 2002). These two sites also showed increases in aggregation and decreases in bulk density after conversion. Based on these results penetration resistance could be included as an indicator when examining sites where soil physical quality could be expected to change (e.g., sites with less sticky and clayey soils than the study site in this thesis).

Soil depth rejected

In many cases, healthy plant growth is not dependent on the existence of an impeding layer (e.g., fragipan), but more on its depth. Averaged penetration resistance readings will indicate the existence of an impeding layer, but if the layer is deep enough root growth will not be hindered. Rhoton and Lindbo (1997) proposed soil depth as an indicator of soil quality along with the SQI (2002). Deep soil is indeed important to the roots of plants and plant water relations. However, soil depth changes are difficult to detect due to the slow rate of addition or subtraction of depth. For this reason, soil depth does not make a suitable indicator as echoed by Schoenholtz et al. (2000),

> Soil texture and depth are properties that would change little through time for a given soil, and so they would not be very useful for assessing management effects (criteria 3).

So soil depth makes a good indicator of processes that have already occurred on a site, but does not make a good indicator for tracking the soil quality of a site because it changes too slowly.

Bulk density rejected

One of the easiest soil physical measurements is bulk density. Bulk density is an indirect measure of soil porosity, which controls soil water and air relations. The measured bulk density values showed very little response to management (Table 6), and bulk density was rejected as an indicator because it is not very sensitive to management differences and not very predictive of site health.

Table 6: Bulk density

Depth/Crop	AG	S	SC	SW
15	1.67 (.02)b	1.62 (.03)ab	1.60 (.03)a	1.67 (.02)ab
30	1.59 (.04)a	1.59 (.03)a	1.51 (.03)a	1.54 (.04)a
Total	1.63(.02)b	1.60(.02)ab	1.55(.02)a	1.60(.02)ab

Values reported in g/cm^3. Mean standard errors in parentheses. Within each depth, values with the same letter do not differ at $\alpha = .05$.

As an example, Mckyes (1989) states that the optimum bulk density for silage corn growth depends on whether it is a wet or dry year. A similar observation was made by Bicki and Siemens (1991). The effect of compaction depends on the soil, crop, water content, weather, etc.

Additionally, Franzleubbers (2002) showed the high correlation between organic matter and bulk density ($r^2 = 0.82$). Based on this fact, bulk density can be roughly approximated through organic matter measurements, all else being equal.

Infiltration rate rejected

Difficulties in measuring infiltration rate exclude it as a soil quality indicator (criteria 2). Once again, roots were the culprit. The sweetgum tree treatments showed much higher infiltration rates than the agricultural and switchgrass treatments (Table 7), but this effect occured because the ring infiltrometers could not be properly seated into the soil full of woody tree roots (see Figure 12). Infiltration rate may make a good soil quality indicator for comparisons between annual crops without dense roots, but not for tree crops with their hard roots. Soil crusts can also lead to false and/or highly variable readings for soil water movement parameters (Hussen and Warrick, 1993; Logsdon and Jaynes, 1993).

The high variability of infiltration rate measurements (see the mean std. errors of Table 7) also makes the number of samples required to detect differences prohibitively high. The high variability of field infiltration rate measurements is mirrored by more controlled laboratory readings of hydraulic conductivity (2). In comparing widely different land uses, Schipper and Sparling (2000) state that,

> Unsaturated hydraulic conductivity had a CV of 48% and, on average, would need 147 samples from each site to be confident of detecting a 10% change in the mean.

Table 7: Infiltration rate

Crop	AG	S	SC	SW
Infiltration rate (cm/s)	0.45 (.07) a	1.24 (0.37) b	1.11 (0.25) b	0.45 (0.10) a

Mean standard errors in parentheses. Within each depth, values with the same letter do not differ at $\alpha = .05$.

Available water content rejected

A soil's water storage capacity is just as important to soil quality as the speed at which water can flow through a soil. Available water content could make a good indicator for this reason, were it not for the difficulty in measuring this value. Days are required to carefully set up and monitor the draining of a soil as increasing tension is applied (SSSA, 1994a). The labor-intensive nature of this measurement makes it unattractive for extensive land use studies examining soil quality (criteria 2).

Extractable nutrients rejected

Many farmers make good use of soil nutrient analyses, and these analyses are useful in scheduling fertilization and liming to maintain healthy soil. Unfortunately, extractable nutrient levels do not make good indicators in most agricultural situations because they reflect the previous year's fertilization more than the true health of the soil (criteria 1). The persistence of fertilizer nutrients in soil has been studied through the use of radioactively labeled fertilizers. Table 8 displays the percentage of applied nitrogen remaining in the soil one year after fertilization for a number of labeled-fertilizer studies.

Table 8: Fertilizer persistence in soil

Crop	% nutrient remaining after one year	Fertilizer and rate	Reference
Ryegrass	40	Nitrogen-various	Cookson et al. (2001)
Corn	16-40	Nitrogen-180 kg ha^{-1}	Sen Tran and Giroux (1998)
Barley	30	Nitrogen-various	Glendining et al. (1997)
Winter Wheat	24	Nitrogen-various	MacDonald et al. (1997)
Oilseed rape	29	Nitrogen-various	MacDonald et al. (1997)
Sugarbeet	25	Nitrogen-various	MacDonald et al. (1997)
Potatoes	21	Nitrogen-various	MacDonald et al. (1997)
Spring Beans	49	Nitrogen-various	MacDonald et al. (1997)
Wheat	55% after four years	Nitrogen-various	Hart et al. (1993)

Stecker and Brown (2001) found that year-old phosphorous fertilizer bands contained 35 times more extractable phosphorous than the bulk soil, and that after seven years phosphorous bands were still detectable in the soil. The persistence of fertilizers make the use of extractable nutrients as an indicator difficult.

The linkage between fertilization and nutrient levels was observed in the land use study as evidenced by tables 9-11. The higher levels of lime (2 t ac^{-1} vs. 0) and K added to the agricultural plot are evidenced by its more positive change in Ca, Mg and K levels. Nitrogen and phosphorous levels are not reported because different analysis methods were used in 1995 and 2002, making comparisons impossible.

Fertilization had no significant impact on tree growth, based on measurement of fertilized trees within the bermed plots and unfertilized trees around the perimeter of the plots. These data are shown in figure 10. The lack of response to fertilization indicates that fertilization of the trees was unnecessary and perhaps only added to off-site nutrient movement. The fertilizer may have been needed had the trees grown at the rate expected of them when the plantation was established.

Table 9: Calcium changes

	AG			S			SC			SW		
	1995	**2002**	**Δ**	**1995**	**2002**	**Δ**	**1995**	**2002**	**Δ**	**1995**	**2002**	**Δ**
5 cm	510 (80)	1300 (140)	790	610 (40)	510 (60)	-100	630 (60)	470 (70)	-160	650 (40)	450 (70)	-200
15 cm	580 (70)	810 (80)	230	710 (30)	640 (40)	-70	570 (80)	580 (30)	10	700 (20)	650 (50)	-50
30 cm	670 (60)	580 (50)	-90	690 (50)	580 (30)	-110	590 (70)	580 (20)	-10	720 (40)	700 (40)	-20
Total	590	900	310	670	580	-90	600	560	-40	690	600	-90
MSE	(40)	(100)		(20)	(30)		(40)	(20)		(20)	(40)	
LSD	a	a		ab	b		a	b		b	b	

Values reported in ppm. Mean standard errors in parentheses. Within each year, values with the same letter do not differ at $\alpha = .05$.

Table 10: Potassium changes

	AG			S			SC			SW		
	1995	2002	Δ	1995	2002	Δ	1995	2002	Δ	1995	2002	Δ
5 cm	125 (23)	135 (8)	10	110 (15)	78 (8)	-32	77 (19)	93 (3)	16	166 (27)	40 (4)	-126
15 cm	75 (20)	98 (12)	23	63 (14)	48 (4)	-15	43 (8)	71 (16)	28	57 (4)	36 (3)	-21
30 cm	37 (5)	72 (10)	35	45 (13)	38 (3)	-7	37 (8)	43 (3)	6	31 (2)	36 (2)	5
Total MSE LSD	79 (12) ab	101 (9) a	22	73 (9) ab	55 (4) b	-18	53 (8) b	64 (7) b	11	85 (14) a	38 (2) c	-47

Values reported in ppm. Mean standard errors in parentheses. Within each year, values with the same letter do not differ at $\alpha = .05$.

Table 11: Magnesium changes

	AG			S			SC			SW		
	1995	2002	Δ	1995	2002	Δ	1995	2002	Δ	1995	2002	Δ
5 cm	93 (5)	123 (8)	30	111 (7)	95 (10)	-16	107 (5)	106 (7)	-1	109 (6)	62 (5)	-47
15 cm	101 (8)	98 (7)	-3	115 (10)	86 (8)	-29	107 (8)	87 (5)	-20	104 (3)	67 (4)	-37
30 cm	121 (13)	111 (11)	-10	131 (10)	88 (7)	-43	114 (8)	100 (6)	-14	116 (5)	82 (4)	-44
Total LSD MSE	105(6) a	111 (6) a	6	119 (5) b	90 (5) b	-29	109 (4) ab	96 (4) b	-13	110 (3) ab	70 (3) c	-40

Values reported in ppm. Mean standard errors in parentheses. Within each year, values with the same letter do not differ at $\alpha = .05$.

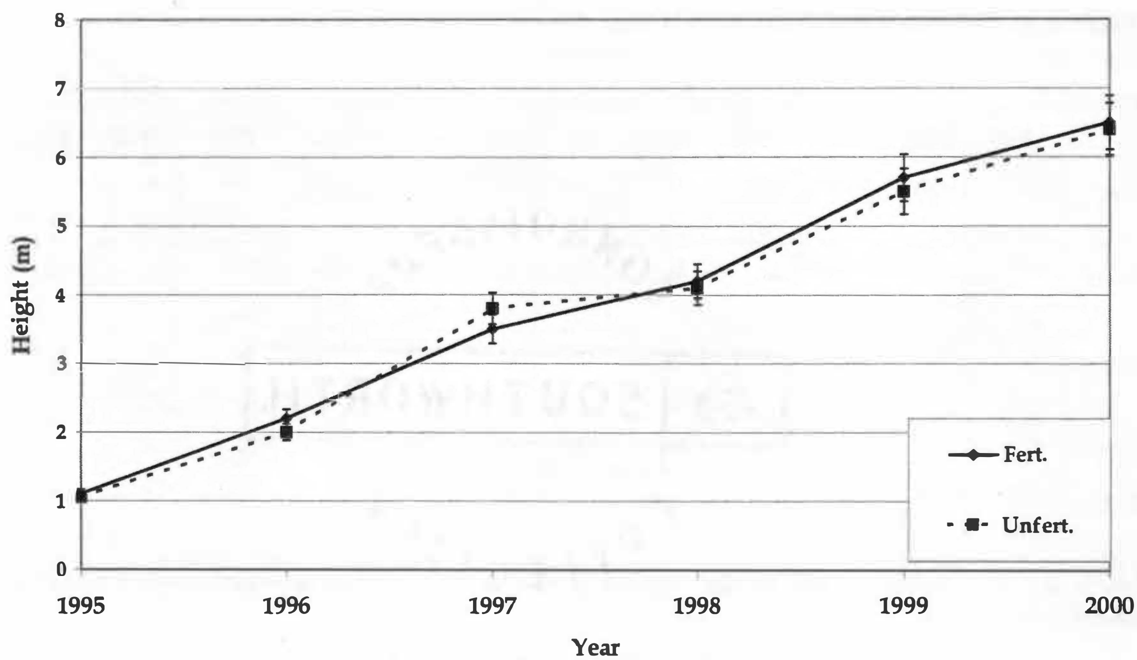


Figure 10: Effect of fertilization on tree growth
Bars represent mean standard error. No differences significant at $\alpha = .05$.

pH rejected

The results from soil pH measurements taken at plantation establishment and in 2002 are summarized in table 12. The 2 t ac^{-1} of lime applied to the agricultural plot in 1999 did not increase the pH of the AG treatment above that of the bioenergy crops. Due to the unequal liming applied to the plots, little can be inferred from the data, other than that pH levels dropped for all treatments, and that the agricultural treatment pH decline would likely have been more severe than the bioenergy crop pH decline had the liming not occurred.

Soil pH level has been proposed as a soil quality indicator but, once again, soil pH is more indicative of liming history than of soil quality trends and is therefore rejected (criteria 1). The effects of liming upon pH can persist for decades as shown by Peters et al. (1996). However, in cases where liming history is identical or pH differences due to liming can be accurately accounted for, the use of soil pH might be a more useful indicator.

Table 12: pH changes

Crop	AG			S			SC			SW		
	1995	2002	Δ	1995	2002	Δ	1995	2002	Δ	1995	2002	Δ
15	5.62 (.13)	5.18 (.10)	-.44	5.69 (.07)	5.15 (.08)	-.54	5.68 (.09)	4.96 (.05)	-.72	5.64 (.08)	5.03 (.04)	-.61
30	5.83 (.11)	5.22 (.12)	-.61	5.86 (.10)	5.19 (.09)	-.67	5.55 (.11)	5.08 (.08)	-.47	5.81 (.09)	5.05 (.08)	-.76
Total LSD group	5.70 (.07) a	5.20 (.08) a	-.50 a	5.76 (.05) a	5.17 (.06) a	-.59 a	5.62 (.06) a	5.02 (.05) a	-.60 a	5.71 (.05) a	5.04 (.04) a	-.67 a

Mean standard errors in parentheses. Within each year, values with the same letter do not differ at α = .05.

Biological indicators rejected

Biological indicators are very sensitive barometers of soil quality, as described by Rice et al. (1996), who state,

> Because of its rapid turnover, microbial biomass is a sensitive indicator of changes in climate, tillage systems, crop rotations and pollutant toxicity.

Studies examining land-use change have shown increased populations and activities of soil microorganisms after agricultural land is converted to forestry or pasture use. Indicators affected include respiration rate, microbial biomass and a suite of measured soil enzymes (Jimenez et al., 2002; Schipper and Sparling, 2000). Sparling et al. (2000) showed that microbial carbon levels and respiration rate also differed significantly across three different soils in the order forest>pasture>plantation>arable. These results indicate the larger and more active microbial populations under land uses similar to herbaceous and woody bioenergy crops.

Indicators can be too sensitive, however. Most biological measures of soil health are also affected by rain, recent plowing, and other factors not of interest when studying the longer-term effects of differing land uses. Some examples of factors that strongly influence soil biological properties are temperature (Yang et al., 2002; Bekku et al., 2003), moisture (Yang et al., 2002), and fertilization (Fisk and Fahey, 2001; Priess and Folster, 2001). Besides varying temporally, biological indicators have very high spatial variability (Parkin, 1993). This often makes it necessary to take a large number of samples in order to precisely determine values for biological indicators. These complicating circumstances make the use of biological indicators very difficult for soil quality monitoring purposes (criteria 1).

Moreoever, soil biological characteristics are often closely linked to organic matter levels. For example, in an old-field succession study, Zak et al. (1990) found a strong relationship between soil organic matter and microbial biomass (r^2= .87). Management changes such as conversion to no-till agriculture or addition of manure can cause measurable differences in soil organic matter within three to four years, and the biological activity of soil is often closely linked to this organic matter, so organic matter level should be able to roughly approximate these biological indicators in the longer term (criteria 5).

Nonetheless, the soil enzyme activities measured at the study site showed good separation between the treatments, though the data are puzzling. As expected, the AG treatment had the lowest activity at the 5 cm depth, as seen in table 13. But at the 15 cm depth, the AG treatment outperformed both tree treatments, possibly due to SOM incorporation from tillage that did not occur to the trees whose SOM profile was more stratified. Also, the switchgrass treatment had the highest activity at the 15 cm depth, but the lowest at 30 cm, where switchgrass would be expected to promote glucosidase activity through the turnover of its large and labile root mass. Further sampling for enzyme activity will obviously be necessary in order to fully understand the SOM turnover processes occurring under each treatment.

Two of the Soil Quality Institute (2002) indicators, erosion rate and organic matter level, explain a large proportion of a soil's quality (Toy Foster and Renard, 2002; Swift, 2001) .

Table 13: Soil Beta-glucosidase activity

Depth	AG	S	SC	SW
5 cm	43.5(3.1)a	54.1(2.0)ab	64.4(3.9)c	63.2(4.2)bc
15 cm	30.7(1.2)b	26.6(0.7)a	29.8(1.2)b	40.3(1.5)c
30 cm	17.2(0.8)ab	20.3(1.4)bc	21.4(0.8)c	14.3(1.3)a

Measured in µg p-nitrophenol produced g $soil^{-1}$ hr^{-1}. Mean standard errors in parentheses.
Within each depth, values with the same letter do not differ at α = .05.

The following section details the reasons that these two indicators were chosen as most applicable. Each of the specific criteria-passing statements are followed by the number of the selection criteria met in parentheses.

Erosion accepted

The RUSLE-modelled erosion rates showed very high sensitivity to treatment differences and can be seen in table 14. As expected, the rates for the eroded and forest reference soils effectively bracketed the values for the bioenergy and agricultural plots. The values for the agricultural plot (AG) varied on a four year cycle because of the four year cropping sequence utilized. The values for the tree plots were high in the initial year when soil cover was minimal, but declined roughly exponentially until they approached the value found for the forest plot as the trees captured the site. The trees with fescue cover (SC) reached this value more quickly than the trees without (S) due to the soil covering and stabilizing effects of the cover crop. The switchgrass (SW) followed a similar pattern to the trees as time progressed, but did not match the low erosion rate of the trees in the later years because of the modelled assumption that it did not establish a vigorous stand.

The modelled erosion rates for agricultural soils were compared to the USDA *T* value, which is defined as, "the maximum level of soil erosion that will permit a high level of crop productivity to be sustained economically and indefinitely." (Wischmeier and Smith, 1978) These values were set at a series of workshops in the early 1960's. T values range from 2

Table 14: Modelled erosion rates

	1996	1997	1998	1999	2000	2001	2002	Average
ER	68.44	68.44	68.44	68.44	68.44	68.44	68.44	68.44
AG	36.42	15.43	23.19	9.72	36.42	15.43	23.19	22.83
S	56.74	27.78	10.86	6.02	3.74	0.58	0.13	15.12
SC	17.79	5.80	1.77	0.31	0.09	0.04	0.04	3.69
SW	22.66	6.88	4.19	4.19	4.19	4.19	4.19	7.21
FOR	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03

Values reported in tons ac^{-1} yr^{-1}.

ton ac^{-1} yr^{-1} for fragile soils to 5 ton ac^{-1} yr^{-1} for soils not readily damaged by erosion (McCormack et al., 1982). The value for the site soils is 5 ton ac^{-1} yr^{-1} (Nyakatawa et al., 1999). The reference sites were markedly above and below *T*, as expected. The agricultural site allowed more than quadruple *T*, indicating that if agricultural production continues, it should be carried out using more conservation-oriented practices.

Of the bioenergy treatments, only the SC treatment allowed an erosion rate lower than *T* when averaged over the entire life of the plantation. The average erosion rates for the other two treatments were above *T*, due to the very high amount of erosion allowed during the initial two years of plantation establishment. If the plantation is allowed to continue growing, the average erosion rate on the switchgrass treatment will fall below *T* 26 years after establishment, and the sweetgum w/o cover will fall below *T* 16 years after establishment, assuming that the future rate is equal to the last modelled rate reported in table 15.

Erosion was chosen as an indicator because of its dominating influence on soil quality and its sensitivity to land use differences as shown through this study (table 15)(criteria 1). Toy, Foster, and Renard (2002) state in their overview of soil erosion that,

> According to the USDA, NRCS, soil erosion continues to threaten the productive capacity of nearly one-third of the cropland and at least one-fifth of all rangeland in the United States. Soil erosion reduces crop yields by reducing soil organic matter, water-holding capacity, rooting depth, and the availability of plant nutrients, as well as degrading soil structure and altering the soil texture.

The loss of soil quality after topsoil removal was succinctly shown through a study by Hart et al. (1999) which showed marked decreases in all soil quality indicators after removal of the top 30 cm of a pasture soil to replicate erosion.

American agronomists have taken a keen interest in the prevention of erosion because of its destructive effect on the land. Researchers and extension agents understand the harm that comes from soil erosion, and will readily subscribe to its use in the measurement of soil quality due to the ease of its estimation through models such as the Revised Universal Soil Loss Equation (RUSLE) (criteria 2). In a study by Romig et al. (1995), farmers were asked to rank soil and plant properties according to their importance to healthy land. Erosion was ranked third, behind only organic matter and crop appearance.

Researchers and land managers can compare these modeled erosion rates for different management practices with their current practice serving as an effective baseline value for future management decisions (criteria 4).

The measurement or prediction of soil erosion rate changes due to land use will not be a redundant exercise, because even though erosion is highly correlated to other soil indicators, it is generally the cause of change and not the effect (criteria 5). Humphreys and Groth (1999) studied a severely eroded site in Australia and looked at a chronosequence of soils. Erosion had a detrimental impact on a multitude of other possible soil quality indicators including organic matter, total nitrogen, total phosphorous, available potassium, available calcium, and cation exchange capacity. Eroded soil is also less able to support healthy microbial communities (Garcia and Hernandez, 1997).

Soil organic matter levels are strongly depleted by erosion because it removes the top layer of soil that is richest in organic matter. Light organic matter is preferentially removed by erosion (Wan and El-Swaify, 1997). For this reason, soil organic matter levels cannot be built up unless erosion is first controlled. Organic matter levels will not necessarily increase once erosion is stopped, however. Addition of biomass to the soil and protection of the biomass from fast breakdown by soil fauna and microbes is also necessary for organic matter buildup. For this reason, organic matter levels must also be measured in order to more fully understand the health of a soil, so these will be used as the second indicator in this study.

Organic matter accepted

The site soil carbon levels are displayed in table 15. Carbon is used as a surrogate for organic matter because most organic matter has approximately the same percentage of its weight made up of carbon, 56% (Nelson and Sommers, 1982). There were significant differences between the carbon contents measured under the various treatments. The bioenergy treatments all increased soil organic matter levels when compared with the treatment that remained in the agricultural treatment. Most of the SOM increase occurred in the top 5 cm of the soil, through the incorporation of residue from the crops.

Soil organic matter (SOM) levels were chosen as an indicator for the rapid soil quality assessment scheme due to the strong response of SOM to treatment differences and the overriding control it has over many other soil quality indicators (criteria 1). Swift (2001) states,

> Soil organic matter plays a crucial role in the development and maintenance of fertility, principally through the cycling, retention, and supply of plant nutrients and in the creation and maintenance of soil structure.

Studies by Brejda et al. (2000a, 2000b) chose SOM as the most important soil quality attribute in a study of hundreds of soil samples taken in the Northern Mississippi valley, Palouse and Nez Perce prairies, Central High Plains, and Southern High Plains. The samples were analyzed for a suite of 20 soil quality attributes using factor and discriminant analyses to find the indicators most sensitive to land use. Between four and six indicators were chosen for each area, but the only soil quality indicator that displayed significant sensitivity to land use in every area was SOM.

Table 15: 2002 Soil carbon levels

Depth	ER
5 cm	0.71(.03)a
15 cm	0.54(.03)a
30 cm	0.27(.02)a

Depth	AG
5 cm	0.76 (.03)a
15 cm	0.65(.01)a
30 cm	0.33(.02)ab

S						
Depth	Top	Upper	Middle	Lower	Bottom	Total
5 cm	0.94 (.07)	1.10 (.04)	1.02 (.07)	0.97 (.07)	1.08 (.06)	1.02(.03)b
15 cm	0.58 (.02)	0.65 (.02)	0.71 (.02)	0.68 (.02)	0.72 (.02)	0.67(.01)a
30 cm	0.34 (.04)	0.35 (.02)	0.35 (.03)	0.48 (.04)	0.47 (.06)	0.40(.02)b

SC						
Depth	Top	Upper	Middle	Lower	Bottom	Total
5 cm	1.18 (.13)	1.14 (.10)	1.05 (.05)	1.24 (.05)	1.20 (.10)	1.16(.04)b
15 cm	0.66 (.04)	0.68 (.02)	0.73 (.02)	0.75 (.02)	0.77 (.04)	0.72(.01)a
30 cm	0.32 (.05)	0.35 (.04)	0.61 (.06)	0.63 (.04)	0.50 (.06)	0.48(.03)c

SW						
Depth	Top	Upper	Middle	Lower	Bottom	Total
5 cm	1.17 (.10)	1.13 (.06)	1.06 (.10)	1.32 (.07)	1.09 (.06)	1.15(.05)b
15 cm	0.71 (.01)	0.70 (.02)	0.70 (.03)	0.69 (.01)	0.67 (.04)	0.69(.01)a
30 cm	0.37 (.02)	0.38 (.04)	0.36 (.04)	0.29 (.03)	0.42 (.03)	0.36(.02)ab

Depth	FOR
5 cm	2.57(.22)c
15 cm	1.38(.19)b
30 cm	0.92(.07)d

Values reported in % carbon by mass. Mean standard errors in parentheses. Within each depth, values with the same letter do not differ at $\alpha = .05$.

SOM levels are an attractive indicator choice for land use researchers because of the large amount of SOM data from experiments done under many different land uses, climates, and soil types (criteria 2). Reeves (1997) states that, "Soil organic carbon (SOC) is the most consistently reported soil attribute from long-term studies." The usefulness of SOM data is being utilized by scientists in the LTER network who made the study of, "patterns and control of organic accumulation in surface layers and substrate in relation to time or natural and induced stresses or disturbances." one of their five core research areas (LTER, 2003). The relative ease of measuring soil organic matter levels also makes their inclusion in soil quality frameworks desirable (criteria 2).

Soil organic matter responds to management changes over the medium/long-term, and will thus be useful for determining the effects of land use change over this time frame (criteria 3). Management changes such as switching to no-till or addition of organic amendments like manure will not produce measurable gains in soil organic matter for the first few years, and hence are not overly sensitive to short-term changes. If the management change is made permanent, however, the soil organic matter level is likely to respond and differences will be apparent after a period of five to twenty years if the soil organic matter equilibrium has indeed been changed. (Hansen, 1993; Bruce et al., 1990, Vance, 2000)

A change in organic matter level will only be noticed by a researchers and landowners if a baseline value is recorded before a change in management. As noted previously, SOM levels are the most common soil quality measurement and baseline information will be widely available (Reeves, 1997; LTER, 2003) (criteria 4).

Many soil testing labs measure and report organic matter level because, though it is correlated to many other measured soil indicators, it is usually the cause of changes and not the result (criteria 5). Guerra (1994) took samples from eroded and uneroded fields in Sussex, UK, and subjected them to 50-100 year rainfall events on a rainfall simulator. After the treatments, the soils were tested for many parameters, and the relationships between them were indicated by a correlation coefficient. With the exception of erosion, none of the soil indicators could have affected the organic matter level in an appreciable way; rather, the organic matter level drove the relationships between the parameters measured.

Once it was decided to use SOM levels as an indicator, more careful thought concerning exactly how to measure SOM was needed because,

> Attempting to hoard as much organic matter as possible in the soil, like a miser hoarding gold, is not the correct answer. Organic matter functions mainly as it is decayed and destroyed. Its value lies in its dynamic nature. A soil is more productive as more organic matter is regularly destroyed and its simpler constituents made usable during the growing season. Its mere presence in the soil is of value during certain stages of decay, when it influences soil structure and water relations and when it functions in holding plant food in readily available form much more effectively than does any mineral fraction of the soil. The objective should be to have a steady supply of organic matter undergoing these processes for the benefit of the growing crop. (Albrecht, 1938)

A healthy soil should therefore not just have a high organic matter level, but also have a fairly high input and turnover rate of fresh organic matter in order to supply nutrition to the soil microorganisms and growing plants. Albrecht (1938) recognized the function of two different fractions, and more recent research such as Garten and Wullschleger (2000) have linked these functions to physically separable components. Other research teams have separated the "active" SOM from the "inert" SOM by water dissolution (Martens and Frankenberger, 1992) or dissolution by weak oxidants (Bell et al., 1999). Some researchers have divided soil organic matter into five or more fractions; but the two-fraction model provides the clearest classification of organic matter pools because of its simplicity, and is the most commonly used (Tisdall and Oades, 1982; Carter and Stewart, 1996) (Table 16).

The more active pool of organic matter responds much more rapidly to environmental factors than the recalcitrant pool, and makes a sensitive indicator of soil quality (Ma et al., 2000;

Table 16: Soil organic matter fractions

	Active	Inert
Alternative names	labile	recalcitrant, inactive
Function	nutrient cycling, food source for microorganisms	soil structure, cation exchange, carbon sequestration
Form	organic debris, carbohydrates, exudates, soil microorganisms	humic substances, carbonates, strongly sorbed to clay particles
Turnover time	0-5 years	50+ years

Guggenberger and Zech, 1999). However, many soil studies remove the most "active" portion of the soil before sampling. These studies scraped away the O layer before sampling the mineral soil (Wang et al., 2003). By doing so, the layer most responsible for adding nutrients, increasing organic matter, and building soil structure is not included in the analysis of the soil. In a study of a re-establishing forest, Richter et al., (1999) found that the trees accounted for 80% of the site carbon accumulation, the litter 20%, and the mineral soil <1%. SOM changes would not be detected at this site if the O layer was scraped away.

In land use studies, the reasoning behind exclusion of the O layer is that if the soil is removed from a use which promotes O layer buildup (e.g., forest or prairie) and put in a tilled system, the O layer will quickly disappear (Mann, 1986). In order to take advantage of the importance of "active" organic matter, this thesis will include the O layer carbon with the mineral SOM.

Formulation of scheme

Erosion rate and soil organic matter level were the chosen indicators based on their high degree of control over soil quality and ease of measurement. A low erosion rate and high soil organic matter level are both necessary for a soil to be truly healthy. Different climates and soil types can have vastly different potentials for erosion and soil organic matter storage. Thus, the soil quality framework must be scaled to particular locations in order to make the framework uniformly applicable everywhere. This concept was utilized by Mausbach and Seybold (1998) as shown by figure 3.

This thesis takes the sufficiency curve concept one step further by analyzing the worst and best soils that can be found in an area to set the upper and lower bounds of erosion rate and soil organic matter level, rather than assuming these bounds. All possible land use treatments will then score somewhere between these two extremes, valued between one and zero. In so doing, local effects upon soil quality are automatically factored into the final score. Rather than try to model why different sites respond differently to similar land use changes using soil texture, climate, rainfall, and other measurements, the proposed method factors out all of these differences by local scaling. This method is appropriate where soil quality results due to land use change are being studied rather than the processes forcing the change.

The choice of reference values will obviously greatly affect the results obtained when land uses are scaled between them. The reference values should be chosen so as to reflect the goals for the land. If the goal is for the land to closely approximate the state of a virgin forest, a virgin forest should be chosen for the upper bound. If a more realistic goal, such as the restoration of degraded soil to match that of an older no-till plot or pasture is chosen, one of these areas should be chosen as the upper bound. Similar considerations apply to the choice of the lower bound.

In order to make overall comparisons between land uses these two scaled indicator scores must be combined into a final soil quality score. Previous "final score" frameworks have utilized a summation to compute this value. The system formulated in this research improves upon this by using a multiplication function instead. A multiplication function is necessary to capture this relationship, because if either indicator proved to be very poor, a low soil quality score would occur. Soil that is gaining organic matter but quickly eroding is not truly healthy. This truth is reflected in a multiplication function, but not an addition function. The scaling and multiplication steps are exemplified in the theoretical sites of table 17.

Table 17: Example of scaled soil quality framework

Land use	Erosion prevention score	Soil organic matter score	Overall score
Most degraded	0	0	0
Possible treatment A	.23	.41	.094
Possible treatment B	.45	.34	.154
Mature forest/prairie	1	1	1

The utility of this multiplication function is enhanced by the time-scale differences between soil organic matter and erosion rate changes due to land conversion. Soon after degraded land is converted to more environmentally friendly use, such as a pasture or a bioenergy plantation, erosion will be decreased, yielding a higher soil quality score. Later, erosion rate becomes insufficient to detect soil quality differences between treatments that have essentially halted erosion. At this time, soil organic matter level differences will begin to be seen between treatments (Hansen, 1993), because soil organic matter levels respond more slowly to treatment than do erosion rates. In this way, erosion differences control most of the soil quality score differences early in the land conversion process, but soil organic matter level differences control most of the score differences later in the process. The entire soil quality measurement process used in this project is detailed in figure 11. The broad statement of soil quality was refined until a simple measure that would quickly and easily quantify soil quality was found.

Comparison of treatments at site based on scheme

The soil quality model formulated in the previous chapter was applied to the data from the Alabama A&M field bioenergy trial. This study was done to determine whether bioenergy crops can be used to restore degraded agricultural lands.

Erosion modelling results

Erosion was visibly reduced in the bioenergy plots compared to the agricultural plot, where rills were often visible. A litter layer formed under the trees after the third year and remained in place throughout the remainder of the study. The switchgrass was slow to capture the site, but reached capacity by the end of the second year. The extensive rooting system of the grass was visible to a depth of 0.5 m when exposed with

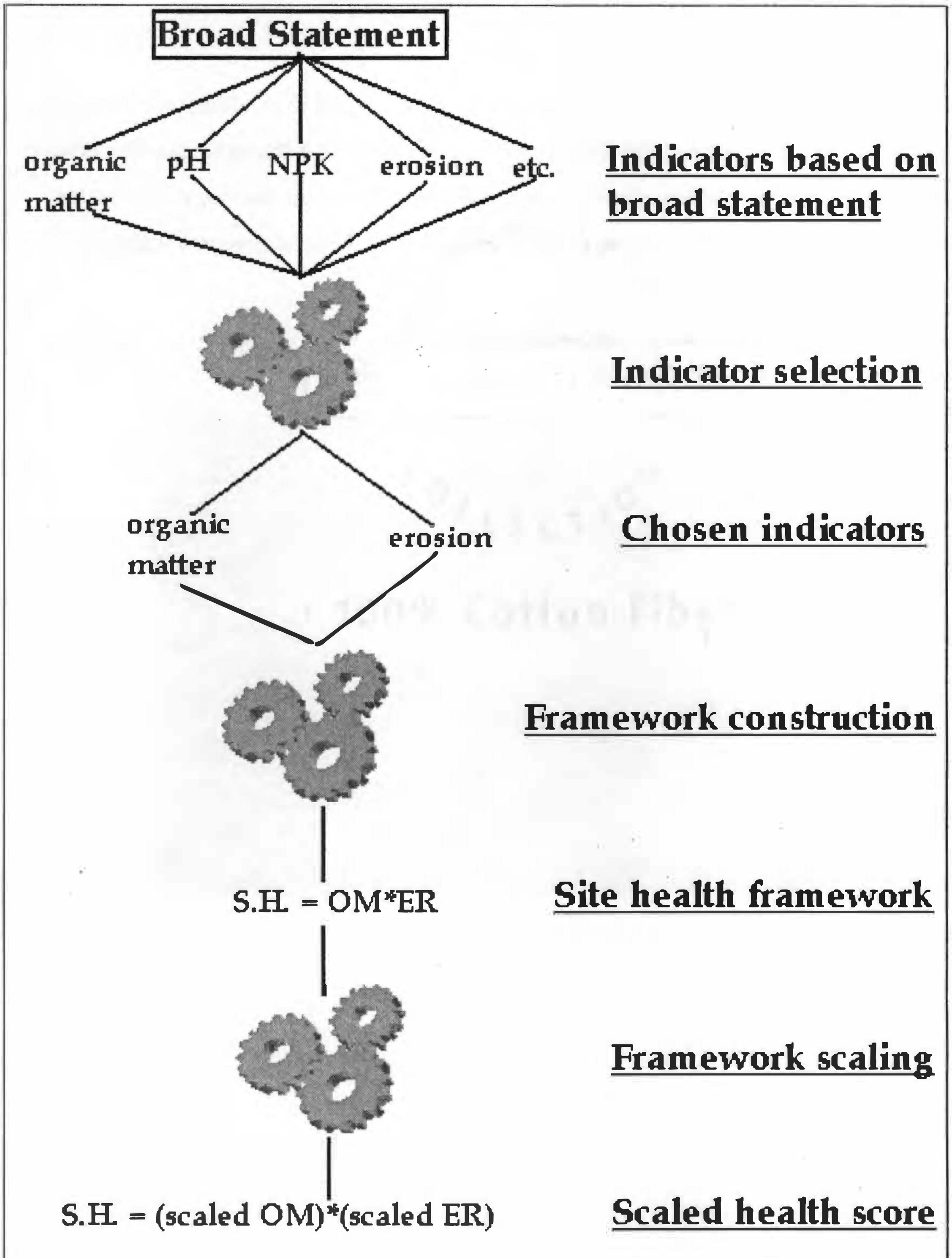


Figure 11: Soil quality measurement framework construction

a backhoe. The erosion-reducing root system of a sweetgum at the edge of one of the plots can be seen in figure 12.

The values for the RUSLE-modelled erosion rates are given by table 18, along with the values for the best and worst case scenario sites. A score of one represents the worst possible erosion and a score of zero represents negligible erosion. The best and worst case scenario C factor values were assigned scores of one and zero, respectively, and the other scores scaled in between according to the equation:

Erosion prevention score = (ER - x)/ (ER - FOR).

Figure 12: Sweetgum holding back erosion

Table 18: Modelled erosion rates and scores

	Average erosion rate	Score
ER	68.4	0.00
AG	22.8	0.67
S	15.1	0.78
SC	3.6	0.95
SW	7.2	0.89
FOR	0.03	1.00

RUSLE modelled rates given in t ha^{-1} yr^{-1}

The erosion values modelled for this site are higher than previously published data. Pimentel and Krummel (1987) estimated that erosion under bioenergy crops would be approximately 2 Mg ha^{-1} yr^{-1} on a 5% slope, compared to corn production with an erosion rate of 21.8 Mg $ha^{-1}yr^{-1}$ on a 4% slope. Ranney and Mann (1994) pointed out that this rate for bioenergy crops will likely only occur during the two year establishment phase of a short-rotation plantation and decrease after the trees establish their root systems and close canopy. The data from this study showed an establishment phase of five years for the trees without cover, and three years for the trees with cover.

Soil organic matter results

The initial soil sampling in 1995 showed negligible difference between the soil organic matter levels at each plot location, so all differences between treatments in 2002 were considered to be due to treatment effects. The soil organic matter (as represented by soil carbon) and litter carbon values for the treatments and best/worst case scenario sites are depicted in table 19.

The measured soil carbon levels were converted to weights by combining them with the measured bulk density values to generate total soil carbon storage to 30 centimeters of soil depth, for both 1995 and 2002 according to the equation:

Soil carbon mass = B.D. * column length * 100,000,000* 1/1,000,000 * C%/100
Mg/ha = g/cm^3 * cm * cm^2/ha * Mg/g * percent/100.

The carbon storage in the leaf litter of the tree plots and forest plot was also calculated according to the equation:

Litter carbon mass = dry weight in ring * 40,000 *C%/100
Mg/ha = $kg/.25m^2$ * $10,000m^2/ha$ *percent/100.

By comparing the 1995 and 2002 total soil carbon storage values, a change in soil carbon storage was computed.

Table 19: Site carbon changes

Crop	ER	AG			SW		
Year	2002	1995	2002	Δ	1995	2002	Δ
5 cm soil	5.0(.4)	6.0(.4)	5.0(.4)	-.6	5.9(.2)	8.1(.3)	2.2
15 cm soil	7.0(.4)	8.6(.4)	7.0(.4)	-.1	8.8(.3)	9.0(.1)	.2
30 cm soil	5.2(.7)	8.4(.7)	5.2(.7)	-2.0	8.4(.6)	7.1(.3)	-1.3
Litter	0	0	0	0	0	0	0
Total	17.2	23.0	17.2	-2.7	23.1	24.2	1.1

Crop	S			SC			FOR
Year	1995	2002	Δ	1995	2002	Δ	2002
5 cm soil	5.4(.2)	7.2(.2)	1.8	6.2(.4)	8.1(.3)	1.9	18.0(6.9)
15 cm soil	8.9(.3)	8.7(.2)	-.2	9.6(.4)	9.3(.2)	-.3	18.0(8.5)
30 cm soil	9.2(.7)	7.8(.4)	-1.4	8.8(.6)	9.3(.6)	.5	18.0(5.6)
Litter	0	4.6(.1)	4.6	0	4.9(.2)	4.9	3.1(.7)
Total	23.5	28.3	4.8	24.6	31.6	7.0	57.1

All measurements in Mg ha^{-1}. Mean standard errors in parentheses.

The total soil/litter carbon storage on the severely degraded site was set to a score of zero, and the carbon storage on the forest site was set to a score of one. The treatment plots were then scaled in between these two extremes in a manner similar to the scaling for the erosion plots. Values of this score are displayed in table 20.

The hypothesis that bioenergy crops would increase equilibrium soil carbon stocks when planted on formerly agricultural lands was tested by Hansen (1993) in the upper Midwest. The study sampled soils under hybrid poplar plantations spanning a range of ages and adjacent soils still in agricultural use. Results indicated that hybrid poplar plantations in the region added soil carbon at the rate of 1.6 Mg $ha^{-1}yr^{-1}$. This finding was based on measurements taken from 10-20 year old plantations that contained approximately 25 Mg ha^{-1} more soil carbon to 1 m than nearby agricultural land. Evidence of soil carbon increase after cropland conversion to switchgrass was found by Garten and Wullschleger (2000). Total soil carbon stocks had increased approximately 12% after a decade of switchgrass production.

The bioenergy crops in this study also increased organic matter stocks, but at a slower rate than that found by Hansen (1993) and Garten and Wullschleger (2000). Yearly accumulation rates were 0.7Mg ha^{-1} for sweetgum, and 1.0 Mg ha^{-1} for sweetgum with fescue cover. The increase of SOM under switchgrass was approximately 4% after seven years.

Overall score

The scaled erosion and soil organic matter scores were then multiplied to produce the overall site health score. The degraded site scored zero and the forest site scored one, by definition. The overall site health scores are depicted in table 21.

Table 20: Soil carbon scores

Totals	Overall Carbon Mg/ha	Sufficiency
ER	17.2	0.00
AG	20.3	0.08
S	28.3	0.27
SW	24.2	0.17
SC	31.6	0.36
FOR	57.1	1.00

Table 21: Overall score calculation

	Erosion score	SOM score	Total score
ER	0.00	0.00	0.00
AG	0.67	0.08	0.05
S	0.78	0.27	0.21
SC	0.95	0.36	0.34
SW	0.89	0.17	0.15
FOR	1.00	1.00	1.00

The bioenergy treatments increased site health based on the soil organic matter-erosion measurement scheme, as expected. All of the bioenergy treatments scored at least twice as high as the agricultural treatment. The sweetgum with cover (SC) treatment scored significantly higher than the other two treatments. The scores show that although conversion to bioenergy crops has improved the health of the soil, the site remains far from its potential, as exemplified by the forest site.

Chapter 4: Conclusions

The project detailed by this thesis had two goals, and both were met. The first was to create a rapid soil quality measurement scheme that is easy to use, sensitive to land use change, and applicable over a wide range of conditions. The second goal was to use the scheme to measure soil quality changes after a degraded agricultural plantation was converted to bioenergy production. Testing of the experimental scheme will be reviewed first, followed by the results obtained at the Alabama A&M bioenergy plantation.

Robustness of soil quality scheme

A wide range of indicators were evaluated in order to select only the most valuable for use in the soil quality framework. Many indicators published in previous soil quality frameworks were rejected because, though they affect soil quality, they present difficulties in measurement and interpretation when multiple widely scattered sites are sampled in the same study.

A few examples will show the type of indicators that are often included despite these difficulties. Some indicators, such as available water content, require a large investment of time and/or money to measure and are unlikely to see widespread use in land use studies. Other indicators, such as bulk density, rarely show a response to management differences and provide little information regarding soil quality, as shown by this study (Fig. 6). Yet other indicators, such as respiration rate, respond too quickly to factors such as rainfall and temperature, making their implementation dependent upon circumstantial factors (Parkin, 1993). Finally, some indicators are so closely related to already measured indicators that their inclusion in soil quality schemes is redundant. Soil aggregation closely follows organic matter level in this way (Tisdall and Oades, 1982). The results from the field site reinforced the decision to reject such indicators in every case. See the results section for a full description of the results for rejected indicators.

The two chosen indicators were scaled between the values measured at two adjacent plots representing the practical maximum and minimum soil quality to be encountered locally.

This scaling alleviates many of the interpretation difficulties typically encountered when attempting to draw broad conclusions about land use effects on soil quality from studies done under widely varying site conditions. Rather than modelling the effects of temperature, rainfall and soil texture, these factors are automatically included in the framework. The concept of scaling based on measured local maximum and minimum values builds upon the work of Mausbach and Seybold (1998).

The new scheme calculated a final score for each treatment by multiplying the scaled scores rather than adding them. This scoring system is an improvement over addition-based systems because it takes account of the fact that soils with only one attribute out of balance can be seriously degraded. For example, a soil scoring high in all categories but with zero hydraulic conductivity could score highly in an addition system, but not in a multiplication system.

Most importantly, soil organic matter and erosion rate were the only indicators included in the final framework because of the overriding control they exert upon soil quality. These two factors directly influence the majority of other possible indicators and are the most useful for determining soil quality changes due to land use change. See the results section for a more detailed account of the roles that erosion prevention and organic matter addition play in soil quality. They interact constructively because erosion rate tracks soil quality advancement through the early stages of site restoration, and organic matter level tracks soil quality through the latter stages of site restoration.

Erosion changes

Erosion modelling results show that bioenergy crops and agricultural crops controlled erosion to a similar extent during the two establishment years while the trees were small and no litter layer was present, and while switchgrass had yet to capture the site (Table 17). From year three forward, however, all of the bioenergy crops controlled erosion much more effectively than did the conventional agriculture. The sweetgum trees with fescue cover (SC) essentially allowed zero erosion from year six forward, mimicking the function of the natural forest ecosystem. The switchgrass reached an equilibrium erosion rate of 4.2 t ac^{-1} yr^{-1}. These reductions in erosion rate are significant and would make a large contribution to reducing stream loadings if bioenergy plantations become widespread.

The ecological benefits of bioenergy crops need not only be confined to large field plantations. Smaller plantings can have a substantial impact in soil quality restoration and protection if used strategically. The erosion prevention capabilities of short-rotation trees such as hybrid poplars have been recognized for over a decade (Kort et al., 1998). Many agricultural extension offices advocate the use of tree and grass crops as riparian buffers and erosion control strips. Use of narrow (~15m) riparian strips has been shown to greatly reduce non-point sediment and nutrient pollution from farms (Lee et al., 2000).

Agroforestry operations, where woody and conventional crops are planted together, can also often take advantage of synergistic environmental relationships between the two crops (Young, 1989; Schultz et al., 1995). In these systems, small rows or individual trees are used to provide shade, stability and organic matter to a much larger area of crops or pasture. Perhaps the slow introduction of farmers to bioenergy crops in this form could be used to give them the know-how and confidence to invest in the larger bioenergy plantations necessary to fuel dedicated energy facilities. Research into methods of mechanizing such systems has met some success and is ongoing.

The landscape-scale impact of large bioenergy plantations must be carefully considered before use. Erosion is much decreased through the use of these crops, and some of this erosion prevention is due to the evapotranspiration of water by the high-yielding trees. Local water tables have been drawn down by a meter or more by hybrid poplar trees, and this consideration should not be dismissed in water-poor areas (Perry et al., 2001). Where water availability is not a problem, however, bioenergy plantations can make a significant contribution to erosion prevention while providing a source of income from marginal land.

Organic matter changes

Bioenergy crops increased the soil organic matter level on the degraded land where they were planted. Because only two points in time were sampled for soil organic matter, little can be said about the rate of change of this indicator over time at the Alabama A&M site. However, starting from similar organic matter levels in 1995, the bioenergy crops added up to 7.0 Mg ha^{-1} carbon, while the agricultural plot lost 2.7 Mg ha^{-1} carbon. The buildup of soil organic matter levels accomplished by the bioenergy crops represents a significant increase in the quality of the soil, and if allowed to progress could lead to yield improvements in the impoverished soil on site and throughout degraded soils of the Southeast. However, under the tree crops much of the carbon was added in the O layer, and if the site is returned to tilled agricultural production, this layer will be quickly mineralized instead of incorporated into the mineral soil as humus.

The sweetgum trees without cover (S) treatment predictably stored less carbon than the trees with a fescue cover crop, due to the suppression of understory growth and exposure of bare soil. Early weed suppression allowed increased erosion and organic matter breakdown due to increased temperature. Lack of biomass input to the soil and erosion during the establishment phase did not allow significant organic matter buildup. As recommended by Tolbert et al. (2000), such systems should only be considered in areas with fierce weed competition that will significantly hinder tree growth (Malik et al., 2000). Proper site preparation, use of noncompetitive cover crops and good timing of planting can be used to help to augment chemical weed control in more environmentally friendly ways (Buhler et al., 1998).

The switchgrass added 1 Mg ha^{-1} of carbon, mostly in the top 5 cm of soil. It is significant to note that soil organic matter was actually lost at the 15-30 cm depth under the switchgrass, contradicting the notion that the extensive rooting system of switchgrass is the primary contributor to soil organic matter buildup. This effect could also have been caused by surface organic matter deposited in the deeper soil layers by tillage in the 1995 samples, and the slow establishment of the switchgrass plot. Plantations with shorter establishment times have shown more rapid accumulations of organic matter (Garten and Wullschleger, 2000)

The sweetgum trees with fescue cover crop added the most carbon, at 7.0 Mg ha^{-1}. Most of this accumulation was in the top 5 cm of mineral soil and due to litter additions, but a significant portion of the increase was found in the 15-30 cm layer and was likely due to root turnover. The increased organic matter addition in comparison with the plots without fescue was due to the erosion-preventing and organic matter-adding functions served by the grass.

Bioenergy plantations may eventually become a regular part of crop rotations as soil restorers, much as legumes and cover crops function today. Though they do not fix nitrogen, organic matter is added to the soil through litter and root turnover, as proven by this study and others. How long the increased soil organic matter will persist is unkown, but will be highly dependant on the cropping system used after the bioenergy crop and also on the climate. Because most of the added organic matter is labile, it will likely be quickly dissipated if conventional farming practices are again employed, especially in the hot and humid Southeast. The relationship of temperature and labile organic matter turnover rate was demonstrated by Garten and Wullschleger (2000) as shown by figure 13.

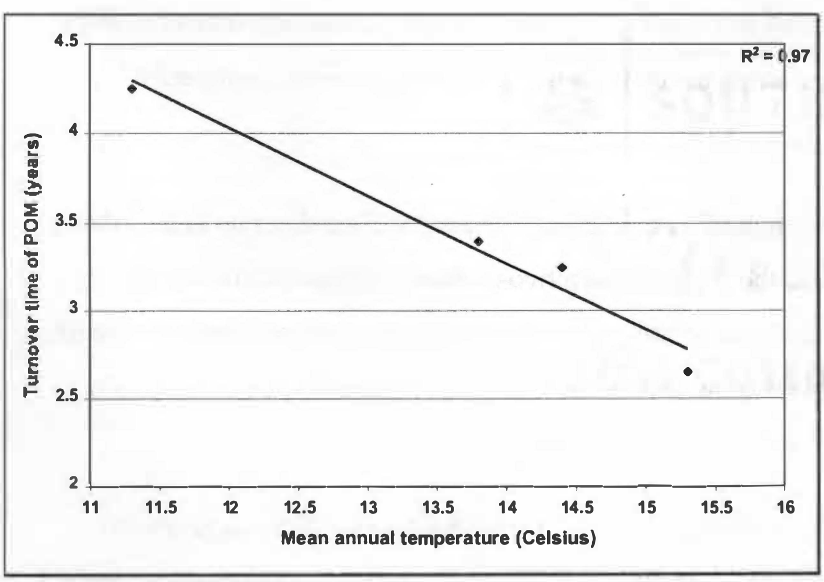


Figure 13: POM turnover dependence on temperature

Adapted from Garten and Wullschleger (2000)

The equilibrium level of organic matter is dictated by this turnover rate. Wet and cool areas such as the Northcentral region have much higher soil organic matter levels than the Southeast because the turnover rate is slower in the North. There exists much degraded land in the Southeast due to the speed of soil organic matter decomposition and high erosion potential from the region's high rainfall. This degraded soil represents an opportunity for reclamation using bioenergy crops, but the upper bound of soil carbon equilibrium level is fairly low in comparison to cooler portions of the country. The best areas for soil organic matter and soil quality improvement will likely be where the soil is farthest from the natural equilibrium level, and this fact was built into the soil quality management system by scaling it between the most degraded and healthiest sites nearby.

As the soil under a land-restoring crop such as switchgrass or trees approaches the natural equilibrium value, the soil quality will plateau. Such a point would be a logical time to consider returning the land to conventional crop production to utilize the newly healthy and profitable soil. In this type of rotation, bioenergy crops would be used as a restorative crop, much like cover crops are used in modern farm rotations. Research into the use of sycamores as restorative crops was done by Devine (2002) who found no problems planting into stumps. The potential for bioenergy crops to benefit soil quality and the broader environment in this way could be very large if and when the biofuels market develops more considerably.

Implications

The poor showing of the indicators other than organic matter and erosion rate in the Alabama A&M study lends credibility to the concept that a two-indicator soil quality measurement scheme can reliably be used to evaluate soil quality and make recommendations for specific sites. The scheme presented in this thesis should be applicable when making soil quality decisions between different land uses over the medium-term.

The overall soil quality scores for bioenergy were at least double that of the agricultural control treatment, indicating that soil quality at the Alabama A&M site was much improved over the seven-year life of the plantation (Fig. 19). The scores for the bioenergy treatments were much less than that of the second growth forest, however, indicating that many more years would be necessary in order to restore the site to a completely healthy state. Because the beneficial aspects of bioenergy crop production often do not begin until the second to third year and improve from there, the longest economically viable rotations should be used so as to make best use of the soil quality restoring aspects of these crops. Crops more well-suited to site conditions should increase the potential for organic matter additions.

This scheme only measures *soil* quality, however. Other environmental considerations, such as emissions of CO_2, nutrient leaching, and wildlife habitat are not included. Previous research has shown the advantages of bioenergy crops over conventional crops as measured by these additional environmental indicators not included in this study (Bransby et al., 1998; Tolbert et al., 2000; Makeschin, 1994). Measurement of these parameters could be added to this model to enable it to more fully depict changes in site health. These considerations were not included because the focus of the project was on soil quality as a starting point toward overall ecosystem health.

In order to be truly useful, any environmental model must be employed by the people who make policy decisions, in this case regarding land use and energy. Until environmental effects are taken into consideration, bioenergy will have a difficult time penetrating the energy market due to economic constraints. Simply because electricity generated from coal is cheaper than electricity generated from biomass does not make it the better alternative. Only once the external environmental costs of fossil fuels and the environmental benefits of bioenergy plantations are factored into the decision making process will the truly best decisions be made.

Research recommendations

Additional research is necessary in order to determine whether the results found at the Alabama A&M site are typical. Most importantly, the scheme formulated in this study must be used on other land use studies in order to gauge its effectiveness and refine it. This study has shown that rather than instrumenting one site heavily, as was done at the Alabama A&M site, future experiments could take more limited measurements (i.e., erosion and organic matter) at a large number of sites in order to determine the effects of climate, site, and crop on the restorative potential of bioenergy crops. This would allow for more efficient collection of useful information.

In order to make the scheme more sensitive, sites more representative of realistic upper and lower bounds could be found near the study site and used to recalibrate the system. Alternatively, the lower bound for erosion rate could be replaced by the RUSLE *T* value as a lower bound for erosion prevention.

Research also must be done in order to determine how long the soil quality improvements brought about by the bioenergy crops will last. The practical aspects of incorporating such crops into conventional agricultural rotations need to be explored before landowners will consider incorporating them into the crop rotation. Finally, no large scale plantings will ever be commercially successful until a profitable method of growing, harvesting, and converting the crops to energy is found. The bulk of bioenergy research should be directed to this end.

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Appendix

Decatur Series

The Decatur series consists of very deep, well drained, moderately permeable soils that formed in residuum derived from limestone. These soils are on level to strongly sloping uplands in valleys. Slopes are dominantly 1 to 10 percent but range up to 25 percent. Near the type location the mean annual temperature is 62 degrees F., and the mean annual precipitation is more than 49 inches.

TAXONOMIC CLASS: Fine, kaolinitic, thermic Rhodic Paleudults

TYPICAL PEDON: Decatur silt loam, 2 to 6 percent slope, cultivated. (Colors are for moist soil unless otherwise noted.)

Ap--0 to 7 inches; dark reddish brown (5YR 3/2) silt loam, dark reddish gray (5YR 4/2) dry; moderate fine granular structure; friable; few red-coated spherical chert fragments; few fine roots; moderately acid; gradual wavy boundary. (3 to 9 inches thick)

Bt1--7 to 12 inches; dark reddish brown (2.5YR 3/4) silty clay loam, dark reddish brown (2.5YR 4/4) dry; moderate medium and fine subangular blocky structure parting to very fine blocky; friable; thin patchy clay films on faces of most medium-sized peds; few soft dark concretions; few fine weathered fragments of chert; moderately acid; gradual wavy boundary.

Bt2--12 to 20 inches; dark reddish brown (2.5YR 3/4) silty clay loam, dark red (2.5YR 3/6) crushed; dry soil less than one-half unit of value higher; moderate very coarse subangular blocky structure parting to strong very fine blocky; firm; thin continuous dusky red (10R 3/3) clay films on faces of most peds; common fine pores lined with clay; few small soft dark concretions; few fine fragments of chert; very strongly acid; diffuse wavy boundary.

Bt3--20 to 45 inches; dusky red (10R 3/4) clay, dark red (10R 3/6) crushed; dry soil less than one-half unit of value higher; moderate very coarse subangular blocky structure parting to strong very fine blocky; firm, sticky, plastic; thin continuous dusky red (10R 3/3) clay films on faces of most peds; few small dark concretions; few fine chert fragments; very strongly acid; diffuse wavy boundary.

Bt4--45 to 72 inches; dusky red (10R 3/4) clay; dark red (10R 3/6) crushed; dry soil is less than one-half unit of value higher; moderate very coarse subangular blocky structure parting to strong very fine blocky; firm, sticky, plastic; thin continuous dusky red (10R 3/3) clay films on faces of most peds; common small dark concretions; few fine fragments of chert; very strongly acid; diffuse wavy boundary.

Bt5--72 to 120 inches; dusky red (10R 3/4) clay, dark red (10R 3/6) crushed; dry soil less than one-half unit of value higher; moderate very fine blocky structure; firm, sticky, plastic; thin patchy dusky red (10R 3/3) clay films on faces of most peds; few small manganese concretions; few fragments of chert; very strongly acid. (Combined thickness of the Bt horizon is more than 60 inches thick)

TYPE LOCATION: Limestone County, Alabama; 0.5 mile west of crossroads at Greenbrier and 200 feet north of county paved road in SW1/4SW1/4 sec. 21, T. 4 S., R. 3 W.

RANGE IN CHARACTERISTICS: Solum thickness is more than 72 inches. The upper 50 inches of the soil contains less than 10 percent weatherable minerals in the 20 to 200 micron size. The solum ranges from medium to very strongly acid. Any horizon may contain up to 10 percent fragments of chert and quartzite pebbles 2 mm to 3 inches in size and up to 3 percent fragments over 3 inches. Dark brown to black concretions range from few to many in each horizon.

The A horizon has hue of 5YR or 2.5YR, value of 2 or 3 and chroma of 2 through 4. Texture is loam, silt loam, or silty clay loam. Severely eroded pedons have Ap horizons of silty clay or clay.

Some pedons have BA or AB horizons less than 6 inches thick with the same hue, value, chroma, and texture range as the A horizon.

The Bt horizon has hue of 2.5YR or 10R, value of 3, and chroma of 4 or 6. Color value of the dry soil is less than 1 unit higher than that of the moist soil. Texture in the upper 20 inches is silty clay loam, silty clay, or clay that contains 35 to 60 percent clay and less than 20 percent sand. The lower part of the Bt horizon commonly contains 45 to 60 percent clay; however, the range includes clay loam below a depth of 60 inches. Structure grade is usually moderate but ranges from weak to strong, subangular blocky to blocky. In some pedons cherty limestone bedrock is at depths of greater than 6 feet.

COMPETING SERIES: These are the Anniston and Beckham series in the same family, and the Davidson, Greenville, Gwinnett and Lloyd series in closely related families. Anniston, Beckham and Greenville soils have more sand in the control section. Davidson soils have less clay in the lower Bt horizon. Gwinnett soils have sola less than 40 inches thick and are deep to paralithic contact. Lloyd soils formed in residuum from mafic igneous or high-grade metamorphic rocks and have few to common mica flakes. Additionally, Davidson, Greenville, Gwinnett and Lloyd soils have kandic horizons.

GEOGRAPHIC SETTING: Smooth level to strongly sloping uplands in limestone valleys at elevations ranging from about 430 to 1400 feet. Slope ranges from 1 to 25 percent, but is more commonly 1 to 10 percent. The soil formed in old valley fill material and residuum weathered from limestone. Limestone bedrock is at depths greater than 6 feet. The climate is warm and humid. Near the type location the average daily temperature is 44 degrees F., for January, and 75 degrees F., for July, the mean annual temperature is 62 degrees F. The average freeze-free season is 225 days. The mean annual precipitation is more than 49 inches.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Cumberland, Dewey, Fullerton, Minvale, and Talbott series. Cumberland and Talbott soils have base saturation greater than 35 percent. Dewey and Fullerton soils have color values of 4 or more in their argillic horizons. Minvale soils have less clay and 15 to 35 percent fragments throughout the solum.

DRAINAGE AND PERMEABILITY: Well drained. Runoff is medium, and permeability is moderate.

USE AND VEGETATION: Most of the soil is cleared and cropped to soybeans, cotton, hay, corn, small grain, and tobacco. Some is in pasture and a small amount in pine plantations.

DISTRIBUTION AND EXTENT: Alabama, Georgia, Kentucky, Tennessee, and possibly Arkansas. The series is of large extent.

MLRA OFFICE RESPONSIBLE: Lexington, Kentucky

SERIES ESTABLISHED: Greenville Area, Tennessee, 1904.

REMARKS: The 5/99 revision updates particle size class to fine. Competing series were also updated. Laboratory data indicates that kandic horizons commonly occur in areas mapped as Decatur and a separate series may need to be developed for these situations. The Geographic Setting section allows old alluvium for parent material, but this is not considered the main concept for this soil.

Diagnostic horizons and features recognized in this pedon are:

Ochric epipedon - the zone from the surface to a depth of 7 inches (A horizon).

Argillic horizon - the zone from a depth of 7 inches to a depth of at least 120 inches (Bt horizons).

Paleudults great group - do not have a decrease in clay of 20 percent of the maximum within 60 inches of the surface.

Rhodic subgroup - have within the upper 30 inches of the argillic horizon a hue of 2.5YR or redder, moist value of 3 or less, and dry value no more than 1 unit higher than moist value.

MLRAs: 122, 128

Revised: 12/88-CDB,GWH; 5/99-RLL,DHK

Vita

Curt Jawdy was born to Joseph and Janet Jawdy of Corry, Pennsylvania in the year 1977. There he attended Corry Area High School, graduating in 1996. He attended the Penn State University as a Schreyer scholar, studying Environmental Systems Engineering. As the outgrowth of an honors project on bioenergy he began research on the environmental effects of bioenergy crops on soil health, first as an undergraduate intern and then as a graduate student in the University of Tennessee Biosystems Engineering Program.