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by

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ABSTRACT

Global warming is becoming an ever-important topic in the world today. In 1998, it was estimated that 40.5 % of U.S. anthropogenic CO_2 emissions was attributed to the combustion of fossil fuels during the generation of electricity (U.S. Department of Energy 2000a). In an attempt to mitigate emissions, electric utility companies have become interested in the potential of forests to sequester large amounts of carbon in their above- and below-ground biomass as well as in the soils. It has been estimated that if the world's deforested lands were reforested and properly managed, they could have the potential to sequester five billion megagrams of carbon per year (Kimmins 1997b). To effectively manage forests to store carbon, it is important to study the role forest soils play in the carbon sequestration process. These soils have the potential to store up to 59% of the total carbon pool within a forest ecosystem (Birdsey 1992). This study examined the biological potential of storing carbon in the soils and the economic potential of storing carbon in the soils and trees grown on reclaimed lignite coal minelands in East Texas. Results show that up to stand age 16, these mine soils may be a net source of CO_2 rather than a net sink because lignite carbon, which is subject to microbial decomposition, exceeds modern organic carbon in the soil up to this point.

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INTRODUCTION

International concerns about increasing levels of greenhouse gas emissions and their impacts on climate change have led to the need for an understanding of carbon sequestration in forest ecosystems. It is estimated that CO_2 is 81% of total greenhouse gas (GHG) emissions in the U.S. (U.S. DOE 2000b). In 1992, the United Nations Framework Convention on Climate Change called for a "non-binding" voluntary effort from the industrialized countries to reduce their greenhouse gas emissions to 1990 levels by the year 2000. It became apparent that most nations would fail to meet this goal, and negotiations were made under the 1997 Kyoto Protocol in which the United States pledged to reduce its emissions 7% below 1990 levels by 2012 (Fletcher 2000, Hawk 1999). Reducing emissions would necessitate a large reduction in the use of fossil fuels. This may have a negative effect on the economy. President Bush has determined that the Kyoto Protocol is an unacceptable alternative and has called for new ideas to reduce greenhouse gases. The electric utility industry has the opportunity to respond to the administration by investigating new ways to capture and sequester CO_2.

Atmospheric CO_2 is the net result of emissions and uptake that occur through natural processes and human activities. Future atmospheric CO_2 concentrations can be reduced not only through the reduction of emissions, but also by increasing the uptake by natural systems, known as carbon sinks. It has been suggested by many scientists that the amount of CO_2 released into the atmosphere through natural processes is equal to the amount that is sequestered by these natural processes. Anthropogenic additions of CO_2 into the atmosphere far exceed that which is currently being sequestered, or taken up, by natural systems. It is estimated that natural processes on land and in the ocean absorb about half of the emitted anthropogenic CO_2, and that atmospheric concentrations of CO_2 are about 32% higher than they were 150 years ago (Fletcher and Justus 2000).

The U.S. is currently producing 20 percent of the world's greenhouse gases while it has only 4 percent of the human population. This is an estimated 1,511 million megagrams of carbon per year, mainly due to the combustion of fossil fuels for energy (U.S. DOE 1999). Researchers have only recently begun to address the need for atmospheric carbon removal and opportunities for significant reductions still exist.

While carbon sequestration through the use of trees has been given a thorough review, little is known on exactly how much carbon that soils can sequester, and their role as a carbon sink is controversial. The potential of forests to store large amounts of carbon lies not only in the above-ground biomass of trees but also in below-ground biomass, as well as in the soils (U.S. DOE 1999). Therefore, the U.S. Department of Energy has recognized forests as being potential viable carbon sinks. In attempts to offset their emissions, electric utility companies have become interested in the potential of establishing forests on their reclaimed coal mine sites to sequester carbon (Karpan 1999). Therefore, the major objective of this study will be to determine the biological and economic potential for storing carbon in the soils of loblolly pine (*Pinus taeda* L.) plantations on reclaimed lignite coal minelands in east Texas.

OBJECTIVES

The objectives of this study are:

1) To compare the amount of carbon stored in soils of loblolly pine stands on mined lignite coal land versus unmined land.

2) To determine the rate of carbon accrual in loblolly pine stands on mined lignite coal land across a range of stand ages.

3) To determine whether stand density of loblolly pine trees affects the rate of carbon sequestration in the soils of mined lignite coal land.

4) To determine how to manage the forest in order to maximize the financial profitability of the timber and the carbon stored in the soils and in the trees on lignite coal mined land.

LITERATURE REVIEW

Global Warming and Carbon Dioxide

It has been estimated that the Earth's average surface air temperature has increased by about 0.9° F over the last 110 years due to increasing concentrations of greenhouse gases (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6)), especially that of carbon dioxide (Fletcher and Justus 2000). For this reason, global warming is becoming an ever-growing environmental issue in the world today. However, these gases do occur naturally in our environment. These gases are responsible for trapping long wavelength solar radiation, which helps to maintain a temperature level suitable for sustaining life (Kimmins 1997b). Infrared (IR) active gases, such as water vapor, carbon dioxide, and ozone, absorb thermal IR radiation emitted by the Earth's surface and atmosphere (Ledley et al. 1999). Greenhouse gas concentrations are increasing and have the potential to warm the earth's surface and lower atmosphere above normal temperature levels.

It is predicted that by the middle of the 21st century, CO_2 levels will double current levels (Sedjo 1989). This rise is attributed primarily to emissions created from the combustion of fossil fuels. Over the last 60 years, emissions from the combustion of fossil fuels have increased CO_2 levels from 280 parts per million (ppm) to over 365 ppm (U.S. Department of Energy 1999). Land-use changes,such as forest land conversion, have also played a major role in changes to global atmospheric carbon levels. Conversion of forest lands to agriculture use results in as much as 50% loss of soil organic carbon (SOC) from surface soils (20cm), contributing a much larger release of carbon than that of forest harvests ($\pm$10%) (Johnson 1992, Post and Kwon 2000). A report by the IPCC (1990) showed that tropical forest depletion releases 1.6 billion megagrams of carbon annually. This has resulted in an increase of CO_2 levels from 35 to 60 ppm. Many are beginning to realize the potential of forests beyond that of simply agriculture use and timber production and have recognized their ability to sequester carbon and act as mitigating agents to carbon emissions.

Forests and Carbon Storage

Forests occupy approximately one-third of the world's land area, and most of the terrestrial organic C is stored within them (Richter et al. 1995). It is estimated that 1 hectare (ha) of forestland contains on a global average between 100 and 200 megagrams (Mg) of carbon, while 1 ha of afforested land can sequester carbon at rates of 5 to 10 megagrams of carbon per year (IPCC 1991). These potentials have allowed the U.S. Department of Energy (DOE) to recognize forests as being viable sinks for carbon storage which could achieve their net total sequestration goal of 1 billion Mg per year by 2025 and 4 billion Mg per year by 2050 (U.S. DOE 1999).

Forests have the ability to store atmospheric carbon for long periods of time.However, there appears to be a maximum amount of carbon that can be stored in any particular type of forest (Kimmins 1997a). The total carbon in a forest ecosystem increases until trees reach maturity, at which time total carbon in this ecosystem will roughly be in equilibrium as old trees die and new trees begin to grow (Plantinga et al. 1999). Old-growth forests often exhibit a period of stagnation where growth is slowed down and carbon is no longer stored as readily (Kimmins 1997a). This occurrence is infrequent though due to human disturbances, fire, weather and insects, which return the carbon stored in these natural ecosystems back to the atmosphere (Kimmins 1997a).

Although old-growth forests usually have a larger total carbon store than younger forests, there is a potential for a greater release of carbon during and after the harvesting of old-growth forests versus younger forests (Kimmins 1997a). If the harvested old-growth logs are used to produce long-lived products versus disposable wood products, the carbon release accompanying timber harvesting will be limited (Cannell 1996, Kimmins 1997a, Plantinga et al. 1999). This is because the carbon that would have been released to the atmosphere from disposable wood products will be captured in those long-lived products, therefore limiting the amount of carbon released into the atmosphere. Also, if an old-growth forest is harvested and the land is immediately reforested and then subsequently harvested for lumber, the old-growth carbon that was released into the atmosphere through decomposition and manufacturing will be sequestered again over the first rotation (Kimmins 1997a). With the potential of forests acting as carbon sequestration sinks, it is important to focus on and study how these sequestration rates are affected by differing forest management practices (Sharpe and Johnson 1981).

Brown et al. (1996) has proposed three methods by which forest management may be used to mitigate the rate of CO_2 emissions into the atmosphere. These three categories are management for carbon conservation, management for carbon storage, and management for carbon substitution. The goal of carbon conservation is to maintain current carbon pools in forest vegetation and soils by reducing deforestation rates, protecting forests currently under conservation, and using forests for sustainable timber production. Carbon storage management is aimed at increasing the current carbon pool in existing forest vegetation and soil through various silvicultural treatments, increasing carbon storage in durable wood products, and using agroforestry to increase tree cover on cultivated lands. Over the long term, management for carbon substitution has the greatest mitigation potential. Substitution management is gained by extending the use of forests for wood products and fuels through the establishment of new forests or plantations and/or using silvicultural treatments to increase the growth of forests that have already been established (Brown et al. 1996, Moura-Costa and Stuart 1998). In time, the use of fossil fuels will be displaced either directly or indirectly through the production of "low-energy-intensive" wood products (Brown et al. 1996). Over a fifty-five year period, it has been estimated on a global scale that 60 to 87 billion Mg of carbon could be sequestered and conserved at a cost of $247 billion to $302 billion using the forest management techniques described above (Brown et al. 1996).

Richter et al. (1995) conducted a study in South Carolina estimating the rate of carbon accumulation over the first three decades of development in an old-field loblolly pine forest. These estimates included above- and below-ground (biomass, forest floor, and mineral soil) carbon accrual. Also, carbon cycling in relation to soil acidification down to a depth of 6 m was examined. It was found that over a 34-year period, the total carbon accumulation in the ecosystem was 271.5 Mg/ha, of this, the total above- and below-ground biomass was 140.6 Mg/ha. Almost all of the carbon that accumulated in this stand was found in plant biomass and in the forest floor. Carbon accumulation in the mineral soil was 96.0 Mg/ha, or 35% of the ecosystem total. About 80% of the carbon storage in the soil was in the upper-half of the 6-m profile. It was found that, on average, the ecosystem stored carbon at a rate of 5.16 Mg/ha/annum. Soil C inputs in the surficial horizon (0.075m) can be as high as 3 Mg/ha/annum (Kinerson et al., 1977), but in this study it was found that over three decades only about 2 Mg/ha of carbon accumulated. This was found to be a result of rapid turnover and decomposition rates in coarse textured surface soils (Richter et al. 1995). Also, it was found that CO_2 and carbonic acid increased with soil depth (Richter et al. 1995). Many authors have given the subject of carbon sequestration in forest ecosystems a fairly thorough review, but little is known about the true potential of carbon storage in soils.

Soils and Carbon Storage

On a global scale, approximately 1500-1600 $\times 10^{15}$ g of carbon are contained within the soil organic matter (SOM) (Johnson and Henderson 1995). This amount of carbon is more than what is contained in either vegetation (500-800 $\times 10^{15}$ g) or in the atmosphere (750 $\times 10^{15}$ g) (Johnson and Henderson 1995), making soils as a carbon sink an important issue. Of importance is the "missing sink" of carbon, which is the difference between CO_2 released by fossil fuels (approximately 6 $\times 10^{15}$g) and the annual increase of CO_2 into the atmosphere (approximately 3.4 $\times 10^{15}$g). While it is difficult to identify the missing sink, it has been suggested that soils are a major global source or a sink for carbon (Johnson and Henderson 1995).

One of the setbacks in determining total organic content in soils on lignite coal minelands is that the composition of the lignite-rich mine spoil is different from that of natural soils (Rumpel et al.1998b). This is due to mining techniques that do not allow for the separation of the overburden from small coal seams that may become incorporated into the overburden during the mining process. Therefore, an unknown amount of carbon is contributed to the new soil by lignite. This makes it difficult to determine the amount of carbon contributed from recent additions from plant material (Rumpel et al.1998b). Recent studies have been completed by Rumpel et al. (1998a, 1998b, 1999, 2000) in the Lusatian mining district of the Federal Republic of Germany in which the organic matter composition of lignite derived materials was analyzed. Under the assumption that the soil samples contained recently formed soil organic matter from plant litter and ancient organic carbon from lignite, Rumpel et al. (1998a, 1998b, 1999, 2000) determined the amount of carbon derived from lignite as a percentage of total organic carbon. This was accomplished through radiocarbon dating using the macro-technique of liquid scintillation as described by Becker-Heidmann et al. (1988). It was concluded that lignite must be considered as a carbon source due to its high carbon content and because of the potential for microbial decomposition of the lignite (Rumpel 1998b).

It has been suggested that the sequestration of carbon in soils could significantly decrease atmospheric CO_2 (Schlesinger 1999). One problem in evaluating carbon levels in soil is that most of the information available is for leaf litters, which may only contribute a minor part (Agren et al. 1999). A 1977 experiment conducted in West Virginia found that soil organic carbon (SOC) content in a strip-mined spoil was increased from 0.11 to 1.17% over a 4-year period (Lal et al. 1998). A similar study observed an increase in SOC content by

30g/kg after a 7-year reclamation period (Lal et al. 1998). Assuming that SOC is not removed, added, or redistributed through soil movement, the rate of SOC input and loss typically converge over time (MacDonald 1999). But because of agricultural practices (burning, harvesting, plowing and tilling), the balance between SOC inputs (plant and animal residues) and losses (decomposition) in natural systems is usually disrupted (MacDonald 1999).

In a recent study by Johnson and Henderson (1995), the effects of harvesting techniques and nitrogen fixers were examined to determine their effects on soil carbon content. It was found that little change could be seen in soil carbon due to harvesting. On the other hand, it was found that the presence of nitrogen fixers almost always resulted in an increase in soil C and N (Johnson and Henderson 1995). Rogers et al. (1999) discovered that in loblolly pine plantations, with elevated CO_2 levels in which supplemental nitrogen was provided, there was a general increase in photosynthetic rates and growth rates. Enhancing plant growth can lead to a greater delivery of carbon to the soil, potentially increasing the amount of carbon stored within the soil.

Vogt et al. (1995) analyzed soil carbon data from 90 forested sites globally. It was found that soil organic carbon was greatest in temperate forests, followed by tropical forests. The lowest SOC occurred in boreal forests. The dominant tree species present in each site were noted and, within each biome, it was found that soil C levels were highest in those forests dominated by deciduous tree species. But when looking at dominant tree species alone, soil C was highest in mixed species (deciduous and coniferous) forests as compared to those dominated by deciduous or coniferous species alone.

Lal et al. (1995) suggests 3 ways of sequestering carbon in soils: (1) increase total soil organic carbon content, especially within the sub-soil horizons, (2) increase micro-aggregation, and (3) increase soil biodiversity. An increase in soil organic carbon content can be achieved through soil, water, and vegetation management (i.e., erosion control, water conservation, soil fertility management, and increased biomass return to the soil). Growing vegetation with deep root systems can enhance the soil organic carbon content of the sub-soil. Also, carbon stored within the sub-soil is less susceptible to disturbance by wind and soil erosion and cultural practices. An increase in micro-aggregation can be achieved by (1) increasing soil biotic activity and (2) through the addition of biomass and organic material to the soil. Increasing the total aggregation can immobilize large quantities of carbon, making these micro-aggregates and clay domains inaccessible to microorganisms. An increase in soil biodiversity can be achieved through afforestation, soil fertilization, and cover crops. Not only does the enhancement of soil biodiversity increase soil structure and aggregation, but it also increases active carbon content in soils (Lal et al. 1995).

MacDonald et al. (1999) conducted a study on the effects of elevated soil temperatures on C losses from a forested Spodosol. Soil samples were taken from surface and subsurface horizons and were incubated at two seasonal temperature regimes. One regime simulated those temperatures normal to northern lower Michigan and the other simulated soil temperatures representing an amount of warming that might occur under global warming theory calculations. It was found that increased soil warming resulted in higher microbial respiration rates, which in turn resulted in increased cumulative C respired and greater losses of carbon from the soil. The greatest carbon losses were present in the surface soils (50 mg C g^{-1}C) as compared to subsurface horizons (25 mg C g^{-1}C).

Mineland Productivity and Carbon Storage

The combustion of fossil fuels has been the greatest contributor to the rise of CO_2 concentrations in the atmosphere. The United States is the largest contributor of the world' s fossil fuel emissions (Uzama 1991). Because of this, utility companies in the United States, have become involved in the carbon mitigating process. One approach is through the establishment and productivity assessments of forests on their reclaimed minelands (Karpan 1999).

The establishment of forests on reclaimed minelands in some areas (mainly in the west) have shown establishment costs as high as $1,000 per acre (Finkenbinder 1999). Finkenbinder (1999) found that this contrasted with Texas Utilities, which found that it is cheaper to plant trees than to establish pasturelands. It was found that this discrepancy in the willingness of landowners to plant trees has to do with a combination of state regulations, whether the land is owned by the mining company or is leased, and the geography of the mine (Finkenbinder 1999). Hawk (1999) performed an analysis on the different options and costs for reducing CO_2 emissions in the power generation industry. Hawk (1999) analyzed options ranging from fuel switching of coal to natural gas in existing plants, producing new and improved plants to replace the older ones, and sequestration achieved through forestation or technological sequestration (i.e. deep ocean disposal). This study concluded that because forest carbon sequestration allows for the continued use of utility companies' existing coal-fired power plants, it is the lowest cost emission-reduction option. It reduces the need for new plant construction and the use of more expensive fuels. Using forests to meet the carbon reduction targets gives utility companies time to develop lower cost and more efficient carbon management methods for meeting long-term goals (Hawk 1999).

Results reported in a study by Bussler et al. (1984) determined the suitability for reforestation on reconstructed mine soils in southwestern Indiana, according to specifications of Public Law 95-87. It was found that the chemical properties of mine soils were more favorable for plant growth than unmined reference soils, while the physical properties such as rooting zones were less favorable for mine soils versus unmined soils. It was concluded that methods of redistributing topsoil to reduce the degradation of soil physical properties should be investigated.

Willett (1978) conducted a study on unmined lands in northeastern Texas to determine the effects of the A horizon on height growth of loblolly pine given soils of similar parent materials but differing A horizon thickness. Age and height data for loblolly pine stands grown on Bowie, Fuquay, Sacul, and Troup soils were gathered using stem analysis. Site index ratings at 50 years for Fuquay, Sacul, and Troup soil series were 80 feet and for Bowie soils it was 83 feet. The depth of surface soil effects tree growth but these soils have very different surface soil thickness; yet their site indices are relatively constant. It was found that at 5,10, 15, 20, 25, and 30 years of age, stands on Bowie soil series had the greatest heights on average. Those trees on Fuquay and Troup soils were intermediate and those on Sacul soils were the shortest. It was determined that standard loblolly pine site index curves based on index age 50 years overestimate site index at young ages, causing the projected site index to be slightly less at each successive 5 year interval from ages 15 to 30. However, a localized site index table based on index age 25 years was more accurate and suitable for the northeast Texas area. At all ages, height increased with an increase in fine material content (silt-plus-clay) of the surface soil while it tended to decrease with increased fine material in the subsoil. An increase in fine material improves water holding capacity. Therefore, those soils with more fine material in the subsoil horizons (i.e., Sacul series) often became waterlogged during the wet season (Willett 1978).

Schroeder and Vining (1993) studied how compaction by heavy equipment during mine reclamation affects soil physical parameters. With an increase in bulk density and a decrease in porosity and pore size during compaction, it was hypothesized that water infiltration and permeability would decrease and rooting depth would be restricted. It also was found that subsoil tillage treatments applied prior to topsoil respreading did not successfully reduce bulk densities because the subsoil materials were recompacted during topsoil respreading. Finally, the study showed that there was an increase in subsoil bulk densities and soil strength over time due to reconsolidation.

Soil compaction can also result in lower oxygen diffusion due to a reduction in porosity (Hons 1978). It has been found that an increase in soil oxygen content is beneficial to increased root production while a deficiency in soil oxygen levels decreases root penetration. Therefore, adequate soil aeration and adequately available soil oxygen will promote plant uptake of nutrients such as N, P, K, Ca, and Mg (Hons 1978).

Another problem encountered on reclaimed minelands is the acidification of soils caused by the oxidation of ferrous sulfides (pyrite and marcasite) (McCallister 1981). When high amounts of acidity are produced, certain clays and minerals are solubilized and release toxic amounts of iron, manganese, and aluminum into the soil making it unsuitable for plant growth (Hons 1978). High amounts of acidity can also produce direct toxicity to the roots of plants. A study conducted by McCallister (1981) looked at the effects of acidity on the exchangeable cation status of mine soil. It was found that the pH of older sites was lower than those younger reclamation sites. This finding suggested that more acid was produced due to the additional time of exposure. Both soils where found to have the lowest pH values at the surface where the zone of most intense oxidation occurs.

A study conducted by Moss et al. (1989) showed how different reclamation techniques affect productivity. This study evaluated, with respect to tree growth and survival, the productivity of third-year height, diameter, volume, and survival of pitch X loblolly pine (*Pinus rigida* Mill. X *P. taeda* L.) on amended mine soils in Virginia. The treatments used were a control, topsoil only, sawdust plus a slow-release N source, and sewage sludge at 22, 56, 112, and 224 Mg/ha. The most productive treatment was the sawdust plus a slow-release N source. After 3 years, this method yielded a height of 74.3 cm, a diameter of 23.1 mm (at the root collar), a volume of 192.4 cm^3, and 92% survival. The least productive treatment was the sewage sludge at 224 Mg/ha. This treatment produced a height of 50.2 cm, a diameter of 10.0 mm, a volume of 18.5 cm^3, and a 10% survival rate.

Kee (1984) conducted a study at the Martin Lake mine site in Panola County, Texas. The objective of the study was to determine the effects of cover crop and nitrogen (N) and phosphorus (P) fertilizer rates on loblolly pine growth and survival when planted on mine spoils. It was found that those plots with cover crops that competed greatly with trees for moisture and nutrients during periods of drought had the lowest tree survival compared to those plots with cover crops such as subterranean clover that did not compete with the trees. Overall, tree survival was greatest in plots fertilized at 50 kg N/ha because those plots fertilized at higher rates (100 kg N/ha) had extreme competition with Coastal bermudagrass. In those plots fertilized with P, needle nitrogen increased versus those not fertilized with P. Tree height increases were greatest in those arrowleaf clover and N fertilized plots, ryegrass plus N, and no cover plus N, due to the N input from fertilization and legumes. Although these plots had the greatest height increase, they had the lowest rate of tree survival because in these plots the cover crops competed excessively with the trees for sunlight, water, and nutrients.

Shupe (1986) determined the optimum amount of nitrogen and phosphorus which promotes the maximum growth of loblolly pine on lignite mine spoils. The study was conducted on a 7 ha, two-year old loblolly pine plantation at the Martin Lake lignite mine in Texas. Nitrogen was applied at rates of 0, 56, 112, 224, and 448 kilograms per ha combined with phosphorus at rates of 0, 28, and 84 kilograms per ha. It was found that height growth increased slightly in plots of combined N and P where the phosphorus level increased. Diameter growth increased as height class increased across all levels of phosphorus application rates. Overall, an increase in diameter growth and foliar nitrogen content was found due to the application of nitrogen during the first year, and increased foliar nitrogen during the second year. It was determined that although diameter responses were significant due to the application of fertilizers, the growth was not enough to justify fertilization expenses. Shupe stated that fertilizers added during site preparation were sufficient to promote satisfactory loblolly pine growth, and the further addition of N and P would not increase profits enough to justify their application.

Hons (1978) studied the yield and reclamation potential of various grasses and legumes on lignite mined spoil in Freestone County, Texas. The mixing of the entire overburden in the mining process resulted in soils of intermediate textures (silty clay loams and clay loams). The higher silt and clay content, as compared to adjacent unmined sites, increased the moisture holding capacity of the mined soils. Kleingrass and Coastal bermudagrass produced the highest yield of the grasses and of the legume species, Yuchi arrowleaf clover produced the highest yield. The use of NO_3^- form of N fertilizer was more effective than NH_4^+ -N in the production of grass. This form of N fertilizer (NO_3^- -N) proved to be most effective when applied during the establishment period (before dense root systems were formed). Phosphorus was found to produce maximum grass and legume yields when applied at rates less than 134 kg P/ha/yr and 224 kg P/ha/yr, respectively.

Toups (1986) conducted a study comparing the average total height growth, and soil physical and chemical properties for loblolly pine plantations on mined and non-mined soils in East Texas. Although trees on both land types were growing at increasing rates, the average total height for trees on the reclaimed sites were significantly lower than the height growth on the unmined sites. Total height and stem diameter for the reference sites averaged 267 cm and 6.1 cm, respectively. The reclaimed sites showed an average total height of 178 cm and an average stem diameter of 4.7 cm. Soil P, K, Ca, and Mg were all significantly greater on the mined site versus the unmined site. The mined sites had the advantage in terms of soil fertility due to the greater supply of plant available macro- and micro-nutrients. It was determined that compaction and the occasional deficiency of nitrogen and/or phosphorus may have caused the trees on the mined site to grow slower. It was concluded that loblolly pine can be grown successfully on reclaimed mine sites (Toups 1986, Wood 1985).

Carbon Credit Market

It is possible that in the future, the amount of CO_2 that utility companies are emitting and sequestering each year will be monitored by government agencies. A tax may eventually be imposed on the amount of carbon emitted by utility companies, which could increase utility bills for consumers by as much as 86% by the year 2010 (DOE 1998). On the other hand, if these companies are able to meet the DOE goal of sequestering carbon at $10 or less per ton by 2015, utility bills will increase by less than 1 cent per kilowatt hour (Environmental News Network 2000). Since sequestering carbon in forests is currently the lowest cost option, utility companies will either store carbon on reclaimed minelands or pay landowners to store carbon for them. This transaction between companies and private landowners will create what is known as a carbon credit market in which "carbon credits" (1 ton of carbon=1 carbon credit) can be bought and sold on the open market (Huang and Kronrad 2002).

On the European market, carbon is currently being traded for $16 per ton of C and is expected to triple. In the U.S., companies are already putting a shadow price of $17 per ton of carbon emitted (Totten 1999). Utility companies are beginning to take part in this growing market, in which the demand for 1 billion tons of carbon per year is currently being created (Totten 1999).

JUSTIFICATION

Global warming concerns are increasing and this is mainly due to the release of carbon dioxide caused by the combustion of fossil fuels. In an attempt to mitigate this problem, utility companies have begun to look at the carbon sequestration potential of forests on their reclaimed mined sites. In order to quantify carbon sequestration rates, utility companies must determine how productive these lands are. The purpose of this study is to quantify the amounts of carbon in the soil and conduct financial analyses to determine the optimal management regime that should be employed to maximize the financial return from timber and from the carbon sequestered in the soil and trees. By doing this, the possible potential of carbon sequestration on mined lands can be evaluated.

METHODS

Study Area

The study area contained loblolly pine plantations located on the reclaimed mined lands at Martin Lake Mine, near Beckville, Texas. In addition, samples were also collected from nearby pine stands, on unmined land, with soils similar to those that existed on the pre-mined sites.

All samples from the loblolly pine plantations were collected at the same time and from the same plots used by Jason D. Morton (2002). Morton determined the impacts of stand densities on carbon sequestration rates in the trees. Morton's data was used in this study to determine whether stand density affects the rate of carbon sequestration in the soils on mined sites.

Litter Layer and Mineral Soil Sampling

In all, 11 stands were sampled (litter layer and mineral soil) using the point sampling cruising method. At each plot on which Morton gathered tree density information, three samples were collected from the litter layer (organic surface horizon) using a 0.0625 m^2 (625 cm^2) microplot. Overall, approximately 194 litter layer samples were collected. For each of the samples, the microplot was placed on the ground at a point located in a random direction, 3 meters from plot center.

All of the organic surface horizon material contained within the microplot was collected and taken to the lab for analysis.

Next, three samples were collected from the mineral soil (0 to 30 cm), using a sharp shooter, at the same location on which litter layer samples were taken. Approximately 194 mineral soil samples were collected. These samples were then taken to the laboratory and analyzed for carbon content with a Leco carbon-nitrogen analyzer.

Litter layer and mineral soil samples were collected across a range of sites:

1) Two sites that were recently mined but had not been planted with grasses. In order to determine how much lignite carbon was present in samples immediately after mining, data from recently mined sites was needed. The assumption is that on sites recently mined (time 0), there should be no carbon from recent additions (modern organic C). This data was used to check this assumption through radiocarbon dating.
2) Two sites that had been recently planted with grasses. In order to determine how much carbon was present in the soils before pine trees were planted, data was collected from sites that had been recently planted with grasses.
3) Eleven sites that had been reclaimed as loblolly pine plantations. Data on these soils were collected from plantations on reclaimed mineland of different ages, site indices, and stand densities. Mineral soil and

organic surface horizon samples were collected from a stand of loblolly pine planted in each year between 1983 and 1990.

4) One, fully occupied, unmined loblolly pine plantation that was established in 1988 on existing native soils located at Martin Lake. These samples were used to show a graphic representation of where carbon from an unmined site falls in relation to that on the mined sites.

Litter Layer Analysis

MacDonald (1999) suggests the following steps in order to determine the carbon content within the organic surface horizon:

(1) The whole sample collected from the microplot was oven-dried at 70°C and weighed to determine dry biomass.

(2) A subsample was weighed and ashed in a muffle furnace at 525°C using the Loss on Ignition (LOI) procedure.

(3) After complete combustion of all organic material the subsample was re-weighed.

(4) The loss in mass from combustion provided an estimate of organic matter content.

(5) By assuming that half the organic matter present is representative of organic carbon, the following equation was used: (percent organic matter / 2) = percent organic carbon.

Mineral Soil Analysis

During the mining process at Martin Lake Mine, the topsoil is not set aside and then replaced before planting trees. Instead the topsoil is mixed in with the overburden and placed back onto the pit before tree planting. During the mining process there are "rider" seams, containing thin layers of coal, which are brought to the surface and become incorporated into the overburden. One of the problems encountered in determining actual organic carbon on these sites, is that lignite is not distinguished from organic carbon in soil testing procedures. Therefore, organic carbon would be grossly overestimated if carbon from lignite is not taken into account. Soil samples were gathered from the Beckville mine site and the following steps were performed on each sample:

(1) The samples gathered from the Beckville mine site were dried and ground.

(2) From the ground samples, 0.25 grams of soil were analyzed using the Leco carbon-nitrogen analyzer.

(3) Of the 194 soil samples, 20 soil samples were chosen and sent to the Radiocarbon Laboratory at the University of Arizona in Tucson. These samples were analyzed using carbon-14 dating. The 20 samples comprised of, 2 samples from each stand ages 12 to 19 (16 total), 2 samples from bare sites that had recently been mined but not reclaimed and 2 samples from sites planted with grasses.

Carbon-14 Dating

Radiocarbon dating (carbon-14 dating) was used to determine the amount of carbon in the soil from recent additions and the amount of carbon in the soil from lignite. Lignite is composed of carbon that is devoid of carbon-14 activity, making it possible to use C^{14} dating to determine lignite C as a percentage of total organic carbon (Rumpel et al. 1999). The following equation was developed by Rumpel et al. (1998a) and was used in this study to determine lignite C, using radiocarbon results:

$$f(x)=1-\exp(-(t_r-t) \times \ln 2/T)$$

where, t_r= C^{14} age (determined by radiocarbon dating)

t= C^{14} age of soil= 0

T=Libby half-life of C^{14}= 5,730 years

Due to the expense of carbon-14 dating, a small sample size (2 samples per stand age) was sent to the radiocarbon lab. To compensate for this small sample size, the results of radiocarbon dating were used to create a correction factor to correct all 183 data points. Each stand age had a different correction factor. First, using total organic carbon (obtained from the Leco carbon-nitrogen analyzer) and lignite carbon (obtained from C^{14} dating and Rumpel's equation), an equation was used to determine the percent of total carbon that was modern.

$$\frac{\%\text{Total organic carbon - }\%\text{Lignite carbon}}{\%\text{Total organic carbon}} = \%\text{ of total carbon that is modern}$$

This equation was used for each of the 2 samples at all stand ages, and the 2 samples were then averaged at each stand age. The average of the 2 samples was the percent that total organic carbon was reduced by to obtain modern organic carbon. Then, by subtracting the average percent of total carbon that is modern from 1, the percent of total organic carbon that is from lignite was obtained. In order for this correction factor to be used, the assumption had to be made that at the time of mining, lignite was evenly distributed throughout the overburden.

Data Analysis

Total organic carbon storage was calculated by adding the modern organic carbon content of the soil horizon to the carbon content of lignite. Bulk density data was determined to allow for conversion of the C data from a percent by weight basis to weight per hectare basis. Soils data gathered from unmined adjacent stands and mined stands was used to graphically serve as a baseline comparison of how much carbon would have been stored in the soils had the site not been mined and how much carbon the mined site actually stores. To determine the rate of soil carbon accrual over time, soil carbon was measured on sites being prepared for planting and on plantations of different ages. The affect of stand density, site index, and stand age on carbon sequestration was determined by measuring soil carbon in stands of different planting densities, site indices and stand ages.

Statistical Analysis

The independent variables in this project are stand age (time), planting density, and site index, while the dependent variables are total organic carbon in the soil, modern organic C, and lignite C. These independent and dependent variables were statistically analyzed using multiple regression. Using Student-Newman-Keuls test (SNK), significant differences in mean carbon at the 0.05 level were determined. Regressions were developed for each of the following: modern organic carbon, litter carbon (L.C.), lignite carbon, and total organic carbon (lignite carbon + modern organic carbon). All results are reported using a 95% confidence interval.

The relationship between carbon accrual on mined versus unmined land was presented graphically but not statistically. A single variable regression model was formed for total organic carbon versus time on mined land, and a line was plotted along the y-axis representing total organic carbon on unmined land. This line provides an indicator of where total organic carbon on unmined lands falls in relation to that on mined lands.

To determine modern soil carbon (excluding lignite), a correction factor was applied to all of the data using the results from carbon-14 dating. Each stand age has a different correction factor. The 183 observations were multiplied by the correction factor corresponding to the stand age associated with that point. A graphic representation was used to look at data gathered from carbon-

14 dating. These numbers were plotted on two graphs, each representing modern and lignite soil carbon in order to compare the amount of carbon contributed from recent organic inputs versus ancient organic carbon (lignite carbon).

Economic Analysis

Under the assumption that carbon is a tradable commodity, the question to be answered was how to manage the forest in order to maximize the value of the timber and the carbon stored in the trees and in the soil. A true economic analysis could not be carried out because the statistical data did not prove to be significant. Therefore, based on the data that was gathered, some observations were made about the potential for earning money through carbon storage on the Martin Lake minelands in Beckville, TX.

RESULTS AND DISCUSSION

Carbon Storage on Mined Verses Unmined

The first objective of this study was to determine and compare the amounts of carbon stored in the soils of mined sites versus the soils of unmined sites (Figure 1). The soils gathered from stand ages 12 to 19 and those gathered from the unmined site were used to address this objective. Significant differences in total organic C in the soils were found between stand ages 12 to 19 (Table 1). Total organic C storage, including lignite, decreased with increasing stand age (Figure 1). While the regression model is significant (Table 2, and 3), only 4.7% (r-square) of the variability in total carbon storage is explained by stand age (Figure 1). This model does not represent the normal pattern exhibited by soil carbon, as stand age increases, in a loblolly pine plantation. Mining practices specific to Martin Lake Mine in Beckville, TX, allow for thin layers of coal to be incorporated into the replaced overburden. The additional carbon from lignite incorporated in the mining process caused total organic soil C to be higher in these plantations.

Total organic C in the unmined site is lower than the predicted values for organic carbon in the mined sites (Figure 1) and is slightly higher than mean total organic carbon at stand age 19. Commonly, between stand ages 15 to 20 in unmined loblolly pine stands, the rate of litter accretion begins to approach the

Table 1. Mean total organic carbon in the soil to a depth of 30cm for stand ages 12 to 19 in mined sites and in an unmined forest.

Stand age	Mean total organic carbon ($Mg\ ha^{-1}$)*	s	n
12	75.5a	22.0	12
13	49.7b	39.2	30
14	50.5c	31.3	18
15	114.8d	34.5	12
16	28.8e	21.6	39
17	49.8f	17.4	15
18	50.2g	35.0	45
19	19.5h	6.8	12
Unmined	21.3	2.2	9

*Means followed by a common letter are not significantly different at $\alpha \leq 0.05$ level using Student-Newman-Keuls test.

Table 2. Regression statistics for predicting total organic carbon in the soil from various stand ages (12 to 19 years).

	Coefficients	Standard error	t-statistic	p-value
Intercept	107.81	19.64	5.49	0.0001
Stand age	-3.70	1.24	-3.00	0.0031

Table 3. Analysis of variance for total organic carbon in the soil under various stand ages (12 to 19 years).

Source	Degrees of freedom	Mean square	F	Pr > F
Regression	1	11,497.77	8.99	0.0031
Error	181	1,278.91		

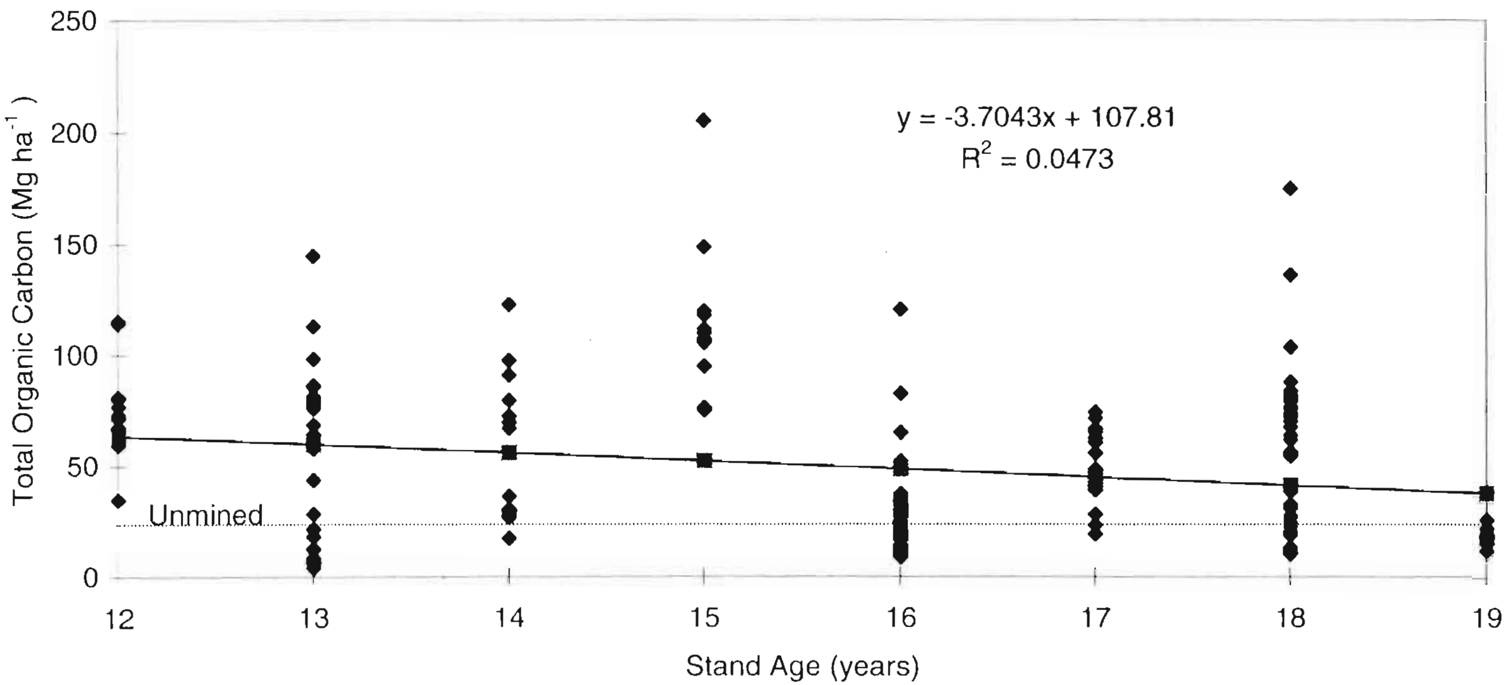

Figure 1. Total soil organic C (Mg ha^{-1}) to a depth of 30 cm in stand ages 12 to 19 and a graphic representation of total C on an unmined site under loblolly pine plantations on TXU minelands in Beckville, TX.

rate of litter decomposition (Switzer and Nelson, 1972). At stand age 19, the mined site is probably approaching this point of equilibrium. This is why mean organic carbon at stand age 19 is approaching mean organic carbon in the unmined site, which has already reached the point at where inputs equal decomposition.

Significant differences were found in mean organic carbon in the litter layer at all stand ages except for 13 and 16 (Table 4), and the regression model is significant (Table 5 and Table 6).

Carbon Accrual on Mined Sites

The second objective of this study was to determine the rate of carbon accrual in the soil of mined sites in stands ages 12 to 19. Two different scenarios were looked at in this objective: (1) total carbon storage, including lignite; and (2) total carbon storage, separating lignite carbon and modern carbon.

Radiocarbon dating produced results showing that the percent of total organic carbon, in stand ages 12 to 19, attributed to lignite ranges from 0% and 83% or 0 Mg ha^{-1} to 106 Mg ha^{-1}, respectively (Table 7). Also, it was observed that at stand age 0 (recently mined site with no grasses), total C from lignite ranged from 134.7 Mg/ha to 35.7 Mg/ha (Table 7). These soil samples were taken from the same site, which shows that there was high variability in the amount of lignite mixed into the overburden on minelands. Once correction factors were applied to the original data (Table 8), it was found that modern organic C increased with

Table 4. Mean organic carbon in the litter layer for stand ages 12 to 19 in mined sites and in an unmined forest.

Stand age	Mean organic carbon ($Mg\ ha^{-1}$)*	s	n
12	3.6b	1.1	12
13	3.2a	1.3	30
14	3.9c	0.8	18
15	5.3d	1.8	12
16	3.3a	1.1	39
17	6.4e	2.7	15
18	4.6f	2.2	45
19	4.9g	2.5	12
Unmined	4.0	0.5	9

*Means followed by a common letter are not significantly different at $\alpha \leq 0.05$ level using Student-Newman-Keuls test.

Table 5. Regression statistics for predicting organic carbon in the litter layer from stand age (12 to 19 years).

	Coefficients	Standard error	t-statistic	p-value
Intercept	0.22	1.04	0.22	0.8293
Stand age	0.25	0.07	3.83	0.0002

Table 6. Analysis of variance for organic carbon in the litter layer under various stand ages (12 to 19 years).

Source	Degrees of freedom	Mean square	F	Pr > F
Regression	1	52.13	14.68	0.0002
Error	181	3.55		

Table 7. Modern and lignite carbon contributions to total carbon in the soil (depth 0-30 cm), which were determined by carbon-14 measurements.

Stand age (years)	Total carbon ($Mg\ ha^{-1}$)	Modern carbon (% of total)	Lignite carbon (% of total)	Modern carbon ($Mg\ ha^{-1}$)	Lignite carbon ($Mg\ ha^{-1}$)
0	136.6	1.4	98.6	1.9	134.7
	37.9	5.8	94.2	2.2	35.7
12	115.2	39.2	60.8	45.1	70.1
	71.4	18.6	81.4	13.3	58.1
13	80.2	17.3	82.7	13.9	66.3
	43.6	46.8	53.2	20.4	23.2
14	72.3	34.0	66.0	24.5	47.8
	36.2	79.8	20.2	28.9	7.3
15	94.8	34.9	65.1	33.1	61.7
	148.6	28.4	71.6	42.2	106.4
16	52.1	56.2	43.8	29.3	22.8
	34.6	75.6	24.4	26.1	8.5
17	65.3	52.6	47.4	34.4	30.9
	55.7	21.6	78.4	12.0	43.7
18	55.9	100.0	0.0	55.9	0.0
	73.7	36.7	63.3	27.1	46.6
19	25.4	68.5	31.5	17.4	8.0
	38.0	75.7	24.3	28.8	9.2

Table 8. Correction factors used to convert total organic carbon (including lignite) to modern organic carbon (without lignite) at each stand age.

Stand age (years)	Correction Factor (%)
12	29
13	32
14	57
15	32
16	66
17	37
18	68
19	72

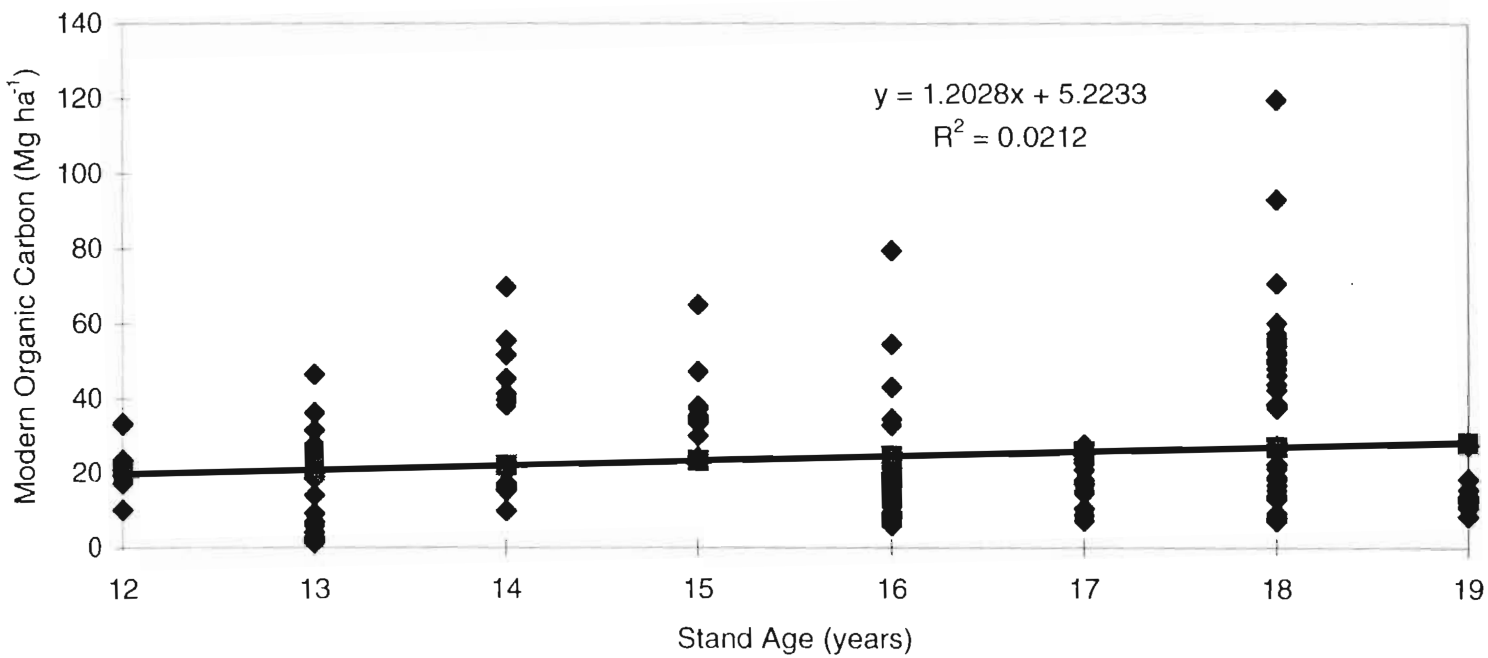

Figure 2. Total modern organic C (Mg ha^{-1}) to a depth of 30 cm from stand ages 12 to 19 under loblolly pine plantations on TXU minelands in Beckville, TX.

increasing stand age (Figure 2). The predicted values for modern carbon storage, excluding lignite carbon, do represent the normal pattern exhibited by soil carbon in which carbon increases with increasing stand age. Significant differences in mean modern organic C were not found between stand ages 15 and 18, and between stand ages 12, 13, 16, 17, and 19 (Table 9). While the overall regression is significant (Table 10, and 11), the intercept (modern carbon) is not significantly different from zero ($p=0.5892$), and only 2.1% (r-square) of the variability in modern carbon storage is explained by stand age (Figure 2). Due to the initial small sample size (20 samples) of soils sent to the radiocarbon lab, a significant regression could not be created.

In addition to modern organic carbon, it was important to look at trends exhibited by carbon from lignite. Significant differences in mean lignite carbon were found between all stand ages except for ages 13 and 17 (Table 12). While the overall regression is significant (Table 13, and 14), only 19% (r-square) of the variability in lignite carbon is explained by stand age (Figure 3). This r-square is slightly higher than that produced from modern organic C and stand age. The higher r-square indicates that there is a stronger relationship in this model between stand age and carbon from lignite than in the model with modern organic carbon as the dependent variable. Total carbon from lignite is decreasing with increasing stand age (Figure 3). This may indicate that soil microbes are breaking down lignite in the soil, and releasing CO_2 into the atmosphere as it is broken down. This theory may be validated by an

Table 9. Mean modern organic carbon in the soil to a depth of 30cm for stand ages 12 to 19 in mined sites and in an unmined forest.

Stand age	Mean modern organic carbon ($Mg\ ha^{-1}$)*	s	n
12	21.8b	6.4	12
13	15.9b	12.6	30
14	28.7c	17.8	18
15	36.3a	10.9	12
16	19.0b	14.3	39
17	18.5b	6.5	15
18	34.3a	23.9	45
19	14.1b	4.9	12
Unmined	21.3	2.2	9

*Means followed by a common letter are not significantly different at $\alpha \leq 0.05$ level using Student-Newman-Keuls test.

Table 10. Regression statistics for predicting modern organic carbon in the soil from stand age (12 to 19 years).

	Coefficients	Standard error	t-statistic	p-value
Intercept	5.22	9.66	0.54	0.5892
Stand age	1.20	0.61	1.98	0.0491

Table 11. Analysis of variance for modern organic carbon in the soil under various stand ages (12 to 19 years).

Source	Degrees of freedom	Mean square	F	Pr > F
Regression	1	1,212.29	3.92	0.0491
Error	181	309.02		

Table 12. Mean lignite carbon in the soils to a depth of 30 cm in stand ages 12 to 19.

Stand age	Mean lignite carbon ($Mg\ ha^{-1}$)*	s	n
12	53.7b	15.60	12
13	33.8a	26.63	30
14	21.8c	13.50	18
15	78.5d	23.59	12
16	9.8e	7.38	39
17	31.3a	10.97	15
18	15.9f	11.08	45
19	5.4g	1.89	12

*Means followed by a common letter are not significantly different at $\alpha \leq 0.05$ level using Student-Newman-Keuls test.

Table 13. Regression statistics for predicting lignite carbon in the soil from stand age (12 to 19).

	Coefficients	Standard error	t-statistic	p-value
Intercept	102.58	11.98	8.56	0.0001
Stand age	-4.91	0.75	-6.51	0.0001

Table 14. Analysis of variance for lignite carbon in the soil under various stand ages (12 to 19).

Source	Degrees of freedom	Mean square	F	Pr > F
Regression	1	20,176.97	42.41	0.0001
Error	181	475.71		

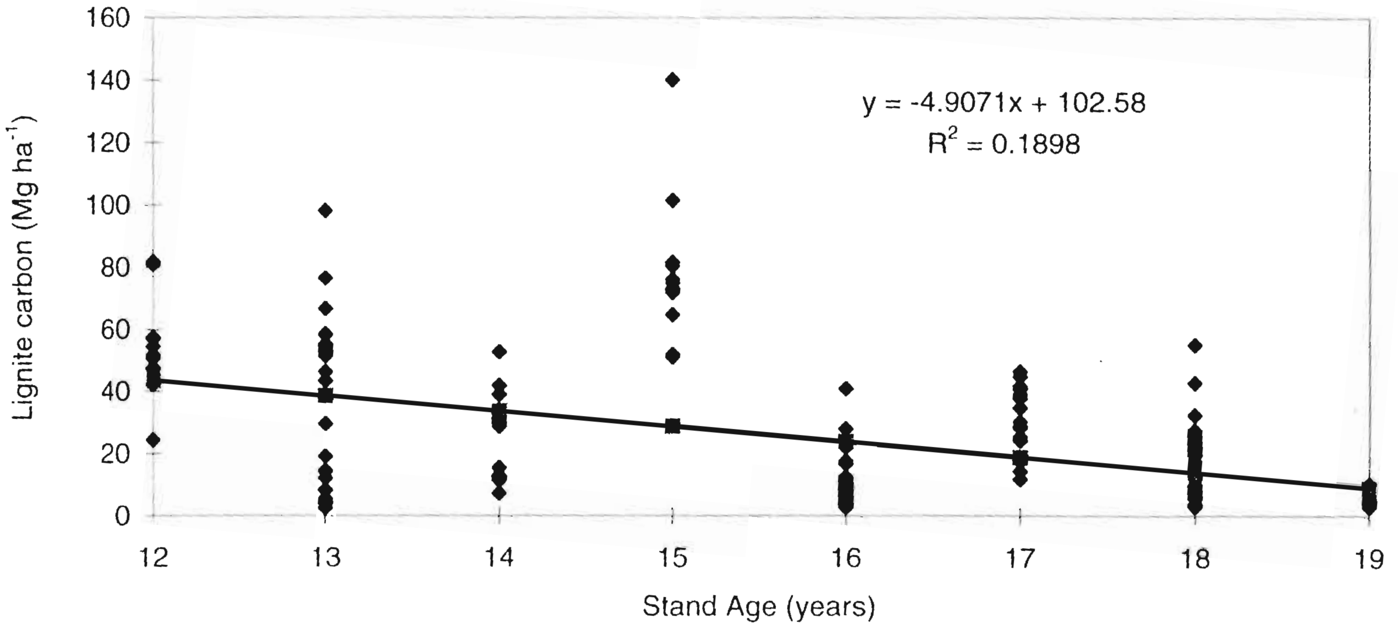

Figure 3. Total carbon from lignite (Mg ha^{-1}) to a depth of 30 cm in stands ages 12 to 19 under loblolly pine plantations on TXU minelands in Beckille, TX.

unpublished study by Stapleton (2003), which showed higher than expected CO_2 respiration rates in wetlands that also have been mined at Martin Lake Mine in Beckville, TX. Soil respiration in plots sampled by Stapleton (2003) were as low as 14 g CO_2/m^2/day at wetland age 0 up to 34 g CO_2/m^2/day at wetland age 18.

Carbon Storage – Effects of Stand Density, Site Index, and Stand Age

The third objective of this study was to determine whether stand density affects carbon storage in the soils of mined sites. All of the models for this objective were built using modern organic carbon. When planting density is the only independent variable used, the overall is not significant (Table 15, and 16). Using multiple linear regression, 8 stand ages (12 to 19), 3 site indices (50, 60, and 70), and 2 planting densities (5X10 and 6X10) were used to build a regression model. The overall regression is significant (p=0.0091) when the independent variables planting density and site index are added to the original independent variable stand age (Table 18). Even though planting density alone was not significant, when added to the overall model, it became important in explaining the variance in modern organic carbon. This indicates a correlation between all three independent variables when trying to predict the dependent variable modern organic carbon. No significant differences in mean modern organic C were found between the two planting densities (Table 19). Significant differences in mean modern organic carbon were found between the 3 site

Table 15. Regression statistics for predicting modern organic carbon in the soil from planting density (5X10 and 6X10).

	Coefficients	Standard error	t-statistic	p-value
Intercept	50.77	16.27	3.12	0.0021
Stand density	-0.03	0.02	-1.64	0.1026

Table 16. Analysis of variance for modern organic carbon in the soil under various planting densities (5X10 and 6X10).

Source	Degrees of freedom	Mean square	F	Pr > F
Regression	1	837.62	2.69	0.1026
Error	181	311.09		

Table 17. Regression statistics for predicting modern organic carbon in the soil from stand age (12 to 19 years), stand density (5X10 and 6X10), and site index (50, 60 and 70).

	Coefficients	Standard error	t-statistic	p-value
Intercept	19.07	19.17	0.99	0.3211
Stand age	0.64	0.72	0.89	0.3745
Site index	0.43	0.22	1.95	0.0522
Stand density	-0.04	0.02	-1.91	0.0574

Table 18. Analysis of variance for modern organic carbon in the soil under various stand ages (12 to 19 years), stand densities (5X10 and 6X10), and site indices (50, 60 and 70).

Source	Degrees of freedom	Mean square	F	Pr > F
Regression	3	1,186.86	3.96	0.0091
Error	179	299.36		

Table 19. Mean modern organic carbon content in the soil under two planting densities (5X10 and 6X10).

Planting density	Mean modern organic C ($Mg\ ha^{-1}$)*	n
5X10	20.3a	42
6X10	25.3a	141

*Means followed by a common letter are not significantly different at $\alpha \leq 0.05$ level using Student-Newman-Keuls test.

Table 20. Mean modern organic carbon content in the soil under 3 site indices (50, 60, and 70).

Site index	Mean modern organic C ($Mg\ ha^{-1}$)*	n
50	24.9a	42
60	18.8b	96
70	34.9c	45

*Means followed by a common letter are not significantly different at $\alpha \leq 0.05$ level using Student-Newman-Keuls test.

Table 21. Site index, stand density, stand size, and sample size for each stand age sampled.

Stand Age	Planting density	Site index	Stand size (acres)	Sample size
12	6X10	50	13	12
13	6X10	60	38	30
14	6X10	50	14	18
15	6X10	60	13	12
16	6X10	60	14	12
	5X10	70	14	15
	5X10	50	13	12
17	5X10	60	17	15
18	6X10	70	39	30
	6X10	60	24	15
19	6X10	60	16	12

Table 22. Predicted values for lignite carbon in the soils to a depth of 30 cm in stand ages 12 to 19.

Stand age	Predicted lignite carbon ($Mg\ ha^{-1}$)
12	43.7
13	38.8
14	33.9
15	29.0
16	24.1
17	19.2
18	14.3
19	9.4

Table 23. Predicted modern organic carbon in the soil to a depth of 30cm for stand ages 12 to 19 in mined sites.

Stand age	Predicted modern organic carbon ($Mg\ ha^{-1}$)
12	19.7
13	20.9
14	22.1
15	23.3
16	24.5
17	25.7
18	26.9
19	28.1

indices (Table 20). While stand density did not appear to play a significant role in carbon accrual, site index does have some effect on modern organic carbon storage. While there was a slight decrease in the amount of mean modern organic C at site index 60, this may be due to the uneven sample size for each site index (Table 20). The site index, planting density, and size of the stand sampled is presented in Table 21 for each stand age. There were more samples for site index 60, which probably produced a more accurate estimate of modern organic C. With that aside, there was still a larger gap between modern organic C in site index 50 and site index 70, than that between site index 50 and 60. The data suggests that poor sites generally store carbon more slowly than higher sites (Table 20).

Economic Analysis

After analysis of the data, it was not feasible to do an economic analysis. Significant regressions could not be built because of a small sample size due to the high expense of radiocarbon dating. However, using data from this study and Morton's (2003) study, some important observations were made. Morton predicted tons of carbon sequestered per acre for one rotation, using TXU's current management regime, with the PTAEDA2 program. PTAEDA2 is a forest stand growth simulator used to predict stand growth and yield data. He found that between 30.5 tons/acre of carbon at site index 50 (5X10 spacing) and 51.9 tons/acre (site index 70, 5X10 spacing) of carbon were stored over one rotation.

At stand age 12, the predicted value for total carbon from lignite (Table 22) stored in the soils was 43.7 Mg/ha (119 tons/acre). This lignite is a net source of CO_2 to the atmosphere as long as it is being broken down by microbes in the soil. At stand age 15, the predicted value for total C from lignite (Table 22) is 29 Mg/ha (79 tons/acre), which is already over 2 times the amount of carbon sequestered over one rotation in the lowest site index of 50 (30.5 tons/acre), and approximately 20 tons/acre higher than the amount in the highest site index of 70 (58.2 tons/acre). While at stand age 15, carbon from lignite exceeds the carbon stored in the trees over one rotation, it is beginning to approach the point where modern organic carbon in the soil exceeds lignite carbon in the soil. At stand age 16, predicted lignite C (Table 22) is 24.1 Mg/ha (65.6 tons/acre). At this point, predicted values for new organic inputs (Table 23) to the system (24.5 Mg/ha, or 66.7 tons/acre) exceed lignite carbon, making predicted modern organic C in the soil a net sink rather than a source of C (Table 23). Also, radiocarbon results for stand ages 12 to 19 support this conclusion (Table 7). From stand ages 12 to 15, the majority (9 out of 10) of the samples contained a higher percentage of lignite than modern carbon (Table 7). While in stand ages 16 to 19, the majority (8 out of 10) of the samples contained a higher percentage of modern carbon than lignite carbon. It could be said that only after stand age 16, can TXU begin to claim carbon credits from C stored in the soils.

CONCLUSION

Significant regressions could not be built due to a small sample size of radiocarbon results, and the high variability in total organic carbon due to the presence of lignite in the soil. The high variability in the amount of lignite mixed into the overburden was seen in the radiocarbon results. Two samples, taken from the same site, produced results indicating that between 134.7 Mg/ha and 35.7 Mg/ha of lignite was on one site. This high variability could explain why using correction factors to correct all 183 samples produced low r^2 values, and this indicates that the assumption that lignite is evenly distributed in the overburden is not correct. Significant differences in total organic carbon were found among stand ages, while modern organic carbon exhibited no significant differences. The correction factors used may have biased the modern organic C data set because only one factor could be used to correct every data point in each stand age. Mean lignite carbon appears to be decreasing as stand age increases, suggesting that it is being broken down by soil microbes. No significant differences were found in modern organic C between the two planting densities, while significant differences were found between site indices. Mean modern organic C was lower at site index 50 than it was at site index 70. This suggests that a higher site index may lead to higher quantities of carbon stored. Sites with higher site indices may exhibit soil properties that promote tree growth, and therefore contribute to a faster growth of biomass above and below-ground.

This leads us to the question at hand. Can TXU claim carbon credits for the soils, or on the land in general, of reclaimed loblolly pine plantations? If it were economically feasible to have all 184 samples analyzed by radiocarbon dating, there would be a greater understanding of actual carbon accrual on these sites. Since this cannot be done, the small sample size analyzed in this study will have to suffice. According to the data gathered in this study, carbon from lignite at stand age 16 is not completely broken down. While lignite has not completely broken down by stand age 16, at this point in the stand, modern organic carbon exceeds lignite carbon. The data suggests that up to stand age 16, the soil should be considered as a net source of CO_2 to the atmosphere and it is not until after this point that the soils and the land in general may be considered as a sink.

FURTHER RESEARCH NEEDED

Future research on TXU loblolly pine plantations at Martin Lake Mine in Beckville, TX, should cover a few areas. First, the current mining practices, which allow for coal to be incorporated into the replaced overburden, should be reconsidered. Second, determine if the profits that could be made from sequestering carbon in these soils are greater than the cost of setting the overburden aside and then replacing it before planting trees. At approximately \$250 per sample (183 samples = \$45,750), the costs of radiocarbon dating for this study alone may be too high to even consider taking credit for the carbon in Martin Lake Mine soils. Even 184 samples may not be sufficient to understand the rate of carbon sequestration in these soils.

A moving average sampling method could be used to estimate the number of samples needed to determine modern organic carbon on these sites (Coble 2003). Knowing now the great degree of variability on these sites, this method could be used to determine approximately how many soil samples should be gathered at each stand age. The following steps should be carried out for each stand age. First, take approximately 3 soil samples from a site and analyze them using radiocarbon dating to determine modern organic carbon. Then, plot the mean modern organic carbon of these 3 samples on a figure that should be labeled with the number of samples (n) on the x-axis and mean modern organic carbon on the y-axis. Next, collect and analyze 4 additional samples, and plot those on the same figure. Continue with this process until the mean value for modern organic carbon begins to stabilize, and this will be the optimum number of samples that should be gathered from that site. Once the number of samples is decided upon, regression analysis should be used to analyze modern organic carbon. It is also suggested that further research include analysis of these 4 scenarios at each stand age.

1) A low planting density (5X10) on a low site index (50).
2) A low planting density (5X10) on a higher site index (70).
3) A higher planting density (6X10 or 7X10) on a low site index (50).
4) A higher planting density (6X10 or 7X10) on a higher site index (50).

This would allow for studying the affect of densities and site indices across a range from low to high.

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