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Carbon Sequestration in the Forests of East Texas

by

Joyce Almaguer-Reisdorf

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APPROVED, THESIS COMMITTEE:

[Signatures and titles]

Paul Harcombe, Professor
Ecology and Evolutionary Biology

Arthur Few, Professor
Physics and Astronomy

Ron Sass, Professor, Chair
Ecology and Evolutionary Biology

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ABSTRACT

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Increasing levels of atmospheric CO₂ threaten to change the earth’s climate and diversity in numerous adverse ways. This thesis explores aspects of two potential types of terrestrial sinks in East Texas, plantation rotation management and reforestation. I used a simple method of employing government GIS and tabular data for calculating and visualizing the size of those sinks, which could store an additional 2.3 to 98 million Mg C aboveground. The uncertainty of these values is high because of data inadequacies and also uncertainty about future land use trends. The mitigative powers of these sinks are discussed, as is their potential application in newly forming carbon credit programs such as the Chicago Climate Exchange.
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CHAPTER I. INTRODUCTION & LITERATURE REVIEW

Section 1.01 Introduction: A Context in Science and Policy

Increasing levels of atmospheric CO₂ threaten to change the earth’s climate and diversity in numerous adverse ways. To help mitigate this change, the parties to the UN Framework Convention on Climate Change (UNFCCC) agreed in December of 1997 to limit and reduce 1990 levels of greenhouse emissions by an average of 5% between 2008 and 2012 (1998a). The Kyoto Protocol, as this agreement came to be known, urged developed countries to reduce net CO₂ emissions by both decreasing fossil fuel consumption and/or increasing anthropogenic uptake through managed terrestrial sinks. This thesis explores aspects of two potential types of terrestrial sinks in East Texas, and uses a simple method of employing government data for calculating and visualizing the size of those sinks and the impact they might have.

To enter into effect, the Protocol needed to be ratified by enough signatories to represent at least 55% of the CO₂ emissions of 1990 (UNFCCC 1998b). In 2001, however, the Bush Administration of the United States decided not to pursue ratification of the Kyoto Protocol, greatly reducing the likelihood of it passing. Instead, the Administration developed an alternative, voluntary emissions reduction plan. This Global Climate Change Initiative recommends the emissions intensity¹ of CO₂ and other greenhouse gases be reduced by 18% over the next ten years, despite a projected economic growth of 30% over those same ten years.²

¹ Emissions intensity considers the greenhouse gases emitted per million dollars GDP. According to the Global Climate Change Policy Book, “the 183 Mg of emissions per million dollars GDP that we emit today will be lowered to 151 Mg per million dollars GDP in 2012” (Anon 2002).
² This statistic given in a speech at the USDA Carbon Symposium on Natural Resource Management to Offset Greenhouse Gas Emissions, November 19, 2002, by Jim Mahoney, Assistant Secretary of Commerce for Oceans and Atmosphere and Director of the Climate Change Science Program of the Interagency Working Group on Climate Change Science and Technology.
Despite the near-certain failure of the Kyoto Protocol, public and private agencies worldwide, including the World Bank BioCarbon Fund, US Natural Resources Conservation Service, USDA, and Chicago Climate Exchange are still working to find methods to reduce atmospheric CO₂.

The Kyoto Protocol authorized greenhouse gas emissions trading systems to help decrease net carbon dioxide outputs. The Chicago Climate Exchange is one such system; additionally, the UK and Denmark have both recently established international carbon credit exchanges to bring such a system into effect (Department of the Environment, Transport, and the Regions 2000, Danish Energy Authority 2002). The Bush administration Global Climate Change Initiative program “Climate VISION” encourages the voluntary development and use of such exchanges (Karey 2003). Similar to the way the New York Stock Exchange was established for trading and purchasing shares of companies, the new carbon credit trading systems allows for trading and purchasing of carbon credits. Each credit represents a reduction in CO₂ emissions, or an increase in CO₂ sequestered, according to a previously-established baseline.

Carbon credits, typically measured in Megagrams (Mg) of carbon sequestered, are commonly awarded via exchanges for carbon storage for reforestation and afforestation processes. The Chicago Climate Exchange is expected to begin trading in Spring 2003. Richard Sandor, Chairman and CEO of the exchange, suggested at a meeting in March 2003 that credits should be worth approximately $20/Mg C (personal communication).

East Texas, like many places throughout the south United States, could possibly utilize at least two opportunities for carbon credits. First, the many hectares of plantation

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iii The term reforestation typically refers to the anthropogenic establishment of forest on non-forested lands that were forested previously, whereas afforestation describes the growth of forest on lands that have not historically, at least in the past 50 years, been forest (Schlamadinger et al. 2000).
forests in East Texas can be used to accumulate biomass. Second, open areas may be encouraged to revert to forest, and present forest preserved.

As this carbon credit market develops, however, timber markets, sprawl, industry, and agriculture continue to divert stored carbon from forests, plantations, and other and other sequestration land uses to other purposes, decreasing their ability to extract and store atmospheric carbon. To compound the problem, forests, when clearcut, release large amounts of vegetative and soil carbon into the atmosphere. This negates any positive effects of carbon storage efforts elsewhere. How much carbon, then, is currently stored in this dynamic landscape? How much carbon is gained, and how much lost, as it experiences land use change? These questions are difficult to answer; as will be explained in Section 1.05, estimating carbon storage is a complex and uncertain process.

This thesis seeks to explore aspects of the relationship between forested land uses and carbon storage in East Texas. The lessons learned from these Texas forests will be applicable to the similar forests throughout the South; it is hoped that these lessons will also affect how carbon storage in this region is viewed as a mitigation tool. Some questions addressed are as follows:

1) How is land use change likely to affect regional carbon storage?

2) Are existing pine plantations a potentially significant carbon sink?

3) Where can storage occur?

The following chapter will provide a context for carbon storage in Texas by briefly reviewing the carbon cycle and its connection to greenhouse gas emissions. After evaluating carbon storage and potentials for increasing carbon storage for the United States, carbon storage in East Texas will be discussed. For the sake of simplicity, I will
focus on above-ground carbon in forest vegetation. Soil and litter carbon estimates, though not well-described in the literature, can generally be approximated from this first estimate (Birdsey 1992a). This work relies heavily on forest inventory data, simple spreadsheet models, and biomass estimates developed from a marriage of fieldwork and remote sensing. The goal in using these techniques is to provide insight into national carbon estimates, which are currently based on survey data.

Section 1.02 The Global Carbon Cycle and the Possibility of Climate Change

The carbon cycle has 3 main components:

1) a terrestrial component, which includes the carbon in geologic formations, soil, and vegetation,

2) an oceanic component, which includes carbon in the form of dissolved CaCO$_3$, CO$_2$, and CO$_3^{2-}$, and

3) an atmospheric component, which includes carbon in the form of CO$_2$, CH$_4$ and other, less common, organic compounds.

Carbon flux occurs naturally among these components via combustion, photosynthesis, respiration, decomposition, dissolution, sedimentation or burial, and vaporization.

By changing land cover and land use patterns, human activities are changing the sizes of pools and fluxes between terrestrial ecosystems and other carbon cycle components. Between 1850 and 1998, for example, 155 ± 55 Gt of carbon were released into the atmosphere as a result of land-use change (Bolin and Sukumar 2000).

The pools and fluxes of the geologic portion of the carbon cycle are changing, as well. Carbon dioxide is emitted into the atmosphere from cement production at rates much higher than the natural dissolution of geologic limestone (Schlesinger 1997).
Fossil fuels, extracted from geologic deposits millions of years old, release large amounts of CO\(_2\) and other carbon compounds when extracted or burned for energy and heat. These emissions, now at 6.3 ± 0.6 Gt C globally every year (Boer et al. 2001), have led to CO\(_2\) levels unprecedented in the past 200,000, perhaps even 20 million years (Schimel 2000). Climate scenarios predict increases to as high as 766 ppm by 2100 from 260 ppm in the pre-industrial age (Boer et al. 2001, Wigley et al. 1997).

Throughout the earth’s history, increases in levels of greenhouse gases like CO\(_2\) have corresponded to increases in global average temperatures and corresponding changes in climate. Current fossil-fuel emissions scenarios and modern climate models predict global mean temperatures may rise 1.4° to 5.8° C by 2100 in the absence of serious policies to dramatically limit greenhouse gas emissions (Folland et al. 2001). In an independent probabilistic analysis of the climate projections of the IPCC Third Annual Report, Wigley and Raper (2001) reinforced the severity of the issue by calculating the 90% probability interval of climatic warming by 2100 to include temperatures from 1.7° to 4.9°C.

Now almost certain to occur, such a global shift in temperature will impact regional climate and vegetation patterns worldwide. The diversity of many ecosystems could change, positive feedback mechanisms might occur with the soil and ocean, and agricultural productivity could decline (Borken et al. 1999, Schneider et al. 2001, Melillo et al. 2002).

To begin working toward an agreement to mitigate significant anthropogenic climate changes, 100 countries have signed the Kyoto Protocol (UNFCCC 1998b). If Russia ratifies the document, the Protocol will enter into effect. This will require
signatory countries to examine their emissions and uptake fluxes to determine compliance with the emissions reductions. These fluxes—particularly in North America—are the topic of the next section.

**Section 1.03 The Terrestrial Carbon Cycle and North America**

Only about 43% of the emissions released from anthropogenic processes remain in the atmosphere (Bolin and Sukumar 2000). This indicates that one of the components of the carbon cycle is a sink (i.e., it takes up more carbon than it emits). Several methods, each with its own strengths and weaknesses, have been developed and used to locate and quantify these sinks. Some of the more common methods include atmospheric transport models, land-use models, and forest inventories.

Atmospheric transport models using $^{13}$C/$^{12}$C ratios, O$_2$ concentrations, and inverse modeling techniques$^iv$ have consistently shown that the sink is primarily terrestrial (Tans et al. 1990, Ciais et al. 1995, Keeling et al. 1996, Fan et al. 1998, Pacala et al. 2001). Tans et al. (1990) infer a sink that is not only terrestrial, but that is almost certainly in the Northern Hemisphere. The presence of a northern sink is supported by work by others who suggest that regular seasonal changes in the amplitude of atmospheric CO$_2$ fluxes are evidence of a large sink in the Northern mid latitudes (Keeling et al. 1996, Randerson et al. 1997).

More specific information about the terrestrial sink, such as its size or location, vary widely. Suggested Northern Hemispheric sink strengths range from .5 - 2.2 Gt C/yr, depending on the models and time periods used (Fan et al. 1998, Ciais et al. 2000, Prentice et al. 2000). While Schimel et al. (2000) challenge a very large North American

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$iv$ Inverse modeling is a process by which available data from concentration and vertical flux measurements are used to estimate surface fluxes of CO$_2$ (Fan et al. 1998).
sink, there are still reasons to support North America as a substantial sink, even if it does not contain the only or even largest sink.

There are two major reasons why the results calculated by these atmospheric models vary so widely. First, each model mathematically simulates atmospheric mixing differently. Second, some models use different stations from which to inversely model atmospheric transport than do others (Tans et al. 1990, Ciais et al. 1995, Keeling et al. 1996, Fan et al. 1998, Pacala et al. 2001). To add to the apparent differences, not all models base their estimates on the same time period (Fan et al. 1998, Ciais et al. 2000, Prentice et al. 2000). As a result, temporary climate anomalies affecting regional carbon fluxes can exacerbate the disparity between different sets of model results.

Despite some degree of consensus about the strength and latitude of a terrestrial carbon sink, its cause and particular spatial distribution are still uncertain. Because so much of it contains temperate forest, the United States likely holds a large fraction of the North American carbon sink. In order to determine the possible strength of this sink, atmospheric models are being supplemented with national forest inventories, land use reconstructions and ecosystem models.

Section 1.04 Locating and Quantifying a Sink in the United States

Forest inventories, performed every several years, have traditionally been used to inform forest managers on the health and growth of a forest. Biomass and volume estimates can be determined based on the diameter at breast height (dbh) of the tree stem (bole) and a series of linear regressions. Carbon flux values are generated by differencing and interpolating these biomass and volume estimates. The results from the forest surveys have been used alone or combined with historical data to track large-scale
changes in biomass in the United States. Such expanded biomass inventories have
determined a yearly net carbon sink in the United States.

In a study that included surveyed forest growth along with erosion, wood
production, agriculture, and commerce, Pacala et al. (2001) estimate a .3 - .58 Gt C/yr
sink in the U.S. Although this figure is larger than estimates of .08 - .35 Gt C/yr from
previous land-based studies (Houghton et al. 1999, Houghton and Hackler 2000, Turner
et al. 1995, Birdsey and Heath 1995), it is consistent with the range of atmosphere-based
estimates over the same time frame (Houghton et al. 1999, Houghton and Hackler 2000,
Keeling 1996).

Historical land-use reconstructions can supplement inventory data by helping to
explain the presence of this apparent U.S. sink and its strength by taking into account
areas that have not been historically forested or have been under years of agriculture and
are reverting to forest. For example, Houghton et al. (1999), attributed a yearly net
uptake of .037 Gt C, or 1.4 Mg C/ha, to recovering U.S. forests caused by shifting land
uses recorded by the U.S. Department of Agriculture (USDA) and Bureau of the Census
(Houghton et al. 1999). This is equal to as much as half of the measured U.S. carbon
sink, if it is .08 Gt/yr (see above). Using forest inventory data to track forest growth in the
United States over time, Caspersen et al. (2000) reinforced this by concluding that 98 ±
4.4% of a recent recorded increase in forest mass in U.S. forests during the 1980s is a
result of increasing forest area in response to changes in land use.

These studies suggest there are two major ways total forest area in the United
States can be increasing and contributing to a carbon sink. First, large tracts of land in
the eastern United States are recovering from decades of agricultural use or logging
(reforestation); second, large areas in the West are increasing in biomass due to decades of fire suppression (afforestation) (Turner et al. 1995, Pacala et al. 2001). In fact, Houghton et al. estimated that as much as 65% of the current US forest area is recovering from agricultural use or extensive logging (1999). As land is reforested or afforested, the total forested area within the United States consequently increases. Growing forests sequester carbon, banking it immediately into the living biomass, and then slowly into litter layers and the soil.

Considering the possibility that the Northern American carbon sink may be largely due to land use change in the United States, reforestation may be considered a viable way to decrease net emissions by managing and encouraging naturally occurring sinks. Forest ecosystems are capable of storing large quantities of carbon in trunks, limbs, roots, leaf litter and organic soil components. While conversion of forests to other types of land can result in net emissions of CO₂, forest regeneration generally eventually results in carbon storage (Birdsey 1992, Korner 2000). This is because forests, storing carbon in vegetation and the soil, contain more carbon than cropland and pasture which have been repetitively denuded, tilled, and grazed. This could be especially evident in areas where fast growth of trees is encouraged (Birdsey 1992b).

How can we know, then, what impact changing land use and industrial practices have on the United States’ carbon sequestration abilities? Essentially, the accuracy with which plant and soil carbon stocks can be estimated is a function of the effort invested, and the accuracy of that effort. Improved biomass figures, using new data techniques, can quickly and easily help generate carbon sequestration estimates for policy making and even GIS-based carbon modeling. I will use East Texas, a forested region with a
long history of land use change, as a case study example for these new techniques. I will then examine the results, and consider the suitability of these methods for other states in the South. More on how this can be done follows in Section 1.05.

Section 1.05 Locating and Quantifying a Sink in East Texas

Changes in forest area, management, age distribution, and NEP\(^{\dagger}\) affect how much carbon may be stored over a region. Forests in the southern United States are constantly shifting in size and character in response to timber prices and other factors. East Texas, for example, contains approximately 4.8 million hectares of forest\(^{\ddagger}\) (USDA 1992). Of that, nearly 200,000 hectares of land reverted to forest between 1986-1992, while over 114,000 ha forest hectares have been diverted to other uses (Rosson 2000). Roughly half of the diverted hectares became agricultural land (Rosson 2000). This pattern reflects trends occurring in other parts of the South, although the overall rate of conversion to agriculture in the South has slowed significantly since the 1970’s (Figure 1) (Wear and Greis 2002).

Timber markets and, correspondingly, land prices, are major factors in determining land use. As Southern urban centers grow, urban sprawl will encroach on forests and offer competitive prices for forest. Unless timber prices or some other factors significantly change or encourage forest establishment or protection, the USDA Forest Service Southern Forest Resource Assessment forecasts that by 2020, as much as 4.9 million hectares, or about 8%, of forest land throughout the South could be lost to

\(^{\dagger}\) NEP, or Net Ecosystem Production, is defined by Ricklefs and Miller (2000) as “the difference between gross primary production and the energetic costs of both the plants and the soil organisms.” Gross primary production is the total energy or nutrients incorporated by a community (Ricklefs and Miller 2000).

\(^{\ddagger}\) In this thesis, the term “forest” means all stocked “forest land.” The USDA Forest Service term “forest land” is defined as an area of at least an acre or greater with a live stocking value of greater than 16.7, or a canopy cover greater than 10%, or an area of at least one acre that was previously forested.
urbanization (Wear and Greis 2002), at a cost of 262 million Mg of carbon stored.\textsuperscript{vii} If timber prices increase, however, while forest area is certain to be lost by some degree of urbanization, forest area elsewhere is also certain to be gained as agricultural lands shift to timber production in order to follow profits (Wear and Greis 2002).

Even though total forest area may in the future remain stable or in some places increase, historical records indicate the South, as a whole, still contains nearly 40\% less forest than in pre-settlement eras (Figure 2) (Smith et al. 2001, Wear and Greis 2002). While much forest has over time been urbanized or otherwise remains lost to carbon sequestration opportunities, a review of survey data or even a flight from Houston to Atlanta will reveal that substantial areas remain in agricultural use. Despite the hints of forest reversion and recovery mentioned previously, there are still, according to Natural Resource Conservation Service Natural Resource Inventory (NRI) data for Texas, at least 1.5 million hectares of un-urbanized, diverted forest land in East Texas.\textsuperscript{viii}

In addition to forest area, forest age affects carbon storage in East Texas. Because much of the South was heavily and repeatedly logged as late as the early 20\textsuperscript{th} century, many stands, in plantations and natural forest, are still quite young, and have yet to reach maximum carbon storage. This is apparent in East Texas (Rosson 2000, Wear and Greis 2002, Marks and Harcombe 1981) and elsewhere in the South (Birdsey 1992a, Sheffield and Dickson 1998).

Many regions of the American South such as East Texas may also be well-suited as carbon sinks since mild temperatures, generous precipitation, and prevalent, fast-growing species lead to an above-average net ecosystem production (NEP) (Johnson et

\textsuperscript{vii} Based on an average carbon storage of 53.5 Mg C/ha (Birdsey and Heath 1995).
\textsuperscript{viii} Excluding those “forest fringe” counties that straddle both the forest and prairie regions of Texas, the NRI indicates at least 1.5 million hectares of agricultural or otherwise forestable land in East Texas.
al. 2001). Considering the high NEP, along with a large land base of young forests and open land, Texas could actively utilize at least two types of opportunities for carbon sequestration (and possibly even carbon credits). First, the many hectares of active plantation forests can be utilized for biomass accumulation. Second, open areas in East Texas may be reforested.

**Plantations**

Of the 4.8 million ha of forested land in East Texas, 0.7 million hectares are in productive pine plantations. The plantation fraction is rapidly increasing; from 1986 to 1992, the amount of industrial plantation area grew by 177,000 hectares while the total amount of forested area (plantation and otherwise) in this region grew by nearly 200,000 hectares (Rosson 2000). In other parts of the South, pine plantation area grew to nearly 12.5 million hectares in 1996 from .8 million hectares in 1952 (Sheffield and Dickson 1998).

Forest Inventory and Analysis (FIA) data collected by the Forest Service (1992), indicates that in 1992, well over 40% of all pine plantation area was fifteen years old or younger (this is graphically presented as Figure 5 in Chapter II). Like the total forest area data, this also corresponds to trends throughout other parts of the South; Sheffield and Dickson (1998) suggest the skewed age distribution is due to the recent reversion of agricultural land due to national changes in the agricultural economy. The age distribution may also be due to short rotation lengths used throughout the highly productive South (Dickson 1998). Reviewing the 1992 survey also indicates that growth and removals over the period of 1986-1992 were not in equilibrium, with more trees
being cut than allowed to grow; from 1986 to 1992, for example, 6.9 million cubic feet of pine were removed from East Texas forests and not replaced (Rosson 2000).

As plantations become a larger part of the East Texas landscape, can they be managed to increase above-ground carbon storage? Since so much of the plantation area is composed of very young trees, what would happen if rotation lengths increased?

**Reforestation**

More and more, East Texas contains land that years ago had been converted from mature forest to various agricultural and timber purposes, and has now lately been transformed into plantations or allowed to revert to forest (Rosson 2000; Dr. Weihuan Xu, personal communication). As mentioned in Section 1.04, previous research attributes the majority of the size and source of the North American carbon sink to the regrowth of forest on farmland and previously-logged forest, particularly in the Eastern US (Fan et al. 1998, Birdsey and Heath 1995, Houghton et al. 1999). This fact raises an interesting question: would Texas be able to contribute to a sink under altered land-use practices? What are the implications for the rest of the southern United States?

**A method for studying reforestation and potential carbon loss**

Federally-mandated surveys can help us determine carbon storage in East Texas. Large-scale carbon estimates based on land use surveys, forest inventory data and generalized ecosystem studies typically include the forests of East Texas as part of the southeast or midsouth US (Birdsey 1992; Ahn et al. 2001, Mickler et al. 2002). These estimates use Forest Inventory and Analysis (FIA) data to estimate biomass per unit area and then multiply by the area to obtain a forest biomass figure. The area of forest types is currently determined with high altitude photographs (Bechtold and Zarnoch 1999).
In establishing carbon budgets, stock change estimates, and biomass potential estimates, non-forested areas must also be taken into account. The amount, locations, and category of these non-forested areas—here referred to as open lands—are usually established using sources such as agricultural census data and the Natural Resources Inventory (NRI) performed by the Natural Resources Conservation Service (NRCS). Such surveys involve large databases with many thousands of data points. Unit-area carbon estimates can derived from survey and ancillary sources, then multiplied by area factors to determine carbon in various land categories. Carbon storage and land cover figures are used not only in government policy, but in climate, economic, and ecological models describing carbon storage or land use change, such as the CBM carbon budget model by Plantinga and Birdsey (1993), or the land rent model by Hardie et al. (2000).

Despite such massive nationwide efforts, determining total carbon storage over a natural or political region is hard for two main reasons. First, it is difficult to determine where in an ecosystem carbon is stored. In a forest, while much carbon is located in aboveground vegetation, even more is stored belowground and throughout an ecosystem in soil and litter. It has been estimated that in East Texas, for example, 43% of total forest carbon is in trees (live and dead, including coarse roots), 49% in the soil (first meter, organic, excluding coarse roots), 5% is on the forest floor, and 3% in the understory (this is higher than the national average of 1%) (Birdsey 1992a). When the coarse roots are included in the soil component, the soil contains closer to 59% of the total ecosystem carbon (Birdsey 1992a). These proportions vary across regions, species, and forest types. Because of the high degree of uncertainty involved in calculating soil
carbon, and because soil carbon is related to aboveground carbon (Birdsey and Heath 1995), this thesis does not directly calculate soil carbon sequestration.

The second complicating factor in estimating carbon storage is that throughout much of the United States, landscapes are very heterogeneous. Accurate area estimates of land types or even forest types can therefore become difficult. As a result, there is typically little confidence in carbon estimates at the regional scale; the FIA, which is the main source of data in this thesis, is not intended to be used at the sub state or sub-unit level (James Rosson, USDA Forest Service, personal communication). Furthermore, surveys like the FIA and NRI create only basic county-level GIS maps; they do not show where various land cover types are located. Because of these two reasons, while carbon stock estimates can be reliably made for very large areas, they cannot be generated or mapped on a local level.

To obtain carbon storage estimates for East Texas, I developed an alternate method of biomass calculation, using classified TM raster data wherein each pixel (30m on each side) will represent a land type and biomass value. Total or predicted biomass over an area is obtained by the sum of a biomass factor for a land type times the area of that land type. More details on this process, and how it might be useful, follow in the Methods section of Chapter II.

This paper will use two “quick and dirty” methods to consider two potential methods of aboveground carbon sequestration in East Texas: 1) longer plantation rotations and 2) reforestation of open, formerly forested lands. The better the potential uptake ability of East Texas is understood, the more clearly we can assess regional carbon sinks in the US and their potential strength.
If the United States, through business or policy, accepts the challenge of future 
CO$_2$ emission and sequestration goals, the south United States, Texas included, may be 
able to play a major role in increasing carbon sequestration potential. This can occur 
through both the management and protection of forestlands as well as the conversion of 
non-forestland to forestland. Yet in spite of its potential, carbon sequestration in East 
Texas as a supplement or alternative to timber production or other land uses has not yet 
been looked at closely. Creating carbon sequestration estimates for the region—and 
simple methods to calculate them—should therefore allow a supplement to current 
regional and national carbon sequestration estimates and model data.

Section 1.06 The Study Area

“East Texas” in this paper will refer to a 43-county region (Figure 3). This area 
has historically been—and still is—heavily forested, with the exception of the western 
and southern borders, which contain large prairies and small oak forests. The 43-county 
region is divided into a northern and southern half (Figure 4). The far western edge of 
the region, with Grimes, Henderson, Leon, Madison, Van Zandt, and Waller counties, as 
well as the far southern edge, with Chambers and Jefferson counties, are here referred to 
as “forest fringe” counties (see Figure 6 of Chapter II).

Though small groups had established small settlements throughout East Texas, 
the settlement of East Texas began in earnest in the 1830’s with groups of subsistence 
farmers (Johnson 2002). By the turn of the 20$^{th}$ century, lumber mills had arrived in East

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ix The forest fringe counties contain more prairie soil, less hospitable to natural forest regeneration. Furthermore, it has been suggested that encouraging forest growth in prairie soils, particularly where precipitation decreases (as occurs in Texas as one moves west away from the forests) can actually result in a net carbon loss, not a sink (Jackson et al. 2002).
Texas, extracting 2.2 billion board feet\textsuperscript{x} of lumber in 1907 alone (Maxwell and Baker 1982). In the past century the area has been increasingly utilized for its timber and oil, and is now, like other parts of the southern US, a rich, forested mosaic of preserves, timber plantations, paper mills, small petroleum installations, and scattered farms and ranches. Like other states in the region, East Texas maintains only a fraction of the forest originally present in the pre-settlement era; it also contains substantially less forest than it did about one hundred years ago (Figure 2) (Wear and Greis 2002). Only a very small portion of the original old-growth forest remains; as early as 1917 only 1.2 million ha of old-growth remained (McWilliams and Lord 1988).

\textsuperscript{x} A board foot is approximately equal to 144 cubic inches. 2.2 billion board feet is therefore approximately 5 million cubic meters of wood.
CHAPTER II. SEQUESTERING CARBON: PLANTATIONS

Introduction

Texas pine plantations are good candidates for carbon sequestration research for three reasons:

1) Pine plantations are an important component of the Southern forest landscape. Changes made on the approximately 15.5 million hectares of Southern pine plantations (Wear and Greis 2002) can have big effects.

2) Plantations are available for “multitasking.” In order to maximize wood and pulp production, plantations are heavily managed to increase the amount of biomass in the merchantable bole (trunk) of the tree. Maximizing total aboveground biomass for carbon sequestration, while also providing merchantable timber for wood products, could be simply understood as multitasking.

3) Plantations are homogeneous. A uniform size, age, species group, and, therefore, carbon content, allows carbon budgets to be more easily and accurately calculated than in a heterogeneous forest with trees of varying size, age, species group, and carbon content.

Ultimately, market conditions affect how much carbon is sequestered in a plantation at any given time. Plantations may be cut on short rotations for low-return pulp products like paper or they may be allowed to increase in size under a longer rotation scheme for profitable saw logs. Most of the plantations in Texas are known to be on 25-30 year rotations (Dr. Weihuan Xu, Texas Forest Service, personal communication). Due to market effects (Rosson 2000) and accelerated land use change rates (Sheffield and Dickson 1998), in 1992, the year of the latest published East Texas
FIA survey, 75% of the 0.7 million hectares of pine plantation in East Texas were less than 20 years old (Figure 5). In consideration of such a large area of young plantations, questions arise. As these young plantation stands grow, increasing in size and biomass, how much carbon will they gain? Because trees grow larger and accumulate more biomass as they age (according to the 1992 FIA survey, some older pine plantation stands in Texas hold over 110 Mg C/ha), would a longer rotation schedule accumulate a meaningful amount of aboveground carbon? The 1992 FIA survey data suggests mixed-age natural pine stands hold an average of 70 Mg/ha. How much additional carbon could East Texas planted plantation forests store if allowed to reach 70 Mg/ha or more?

To answer these questions, I will use at the USDA Forest Inventory and Analysis data for plantations in East Texas on aboveground biomass and age distribution to determine how much additional carbon can be sequestered under a longer rotation scheme. I will use this information to draw conclusions about the potential for new rotation schedules in East Texas, and briefly discuss how this data might be interpreted for forests across the South United States.

While soil and leaf litter also accumulate carbon over the length of a rotation, carbon storage in these forest components is correlated to above-ground biomass, the best understood forest carbon storage component. For that reason, this next chapter will focus solely on above-ground carbon storage in trees.

**Methods**

The USDA Forest Service Inventory and Analysis (FIA) program has long been used to estimate merchantable timber volumes at county, state, and national levels. The same source may also be used to determine carbon storage.
State forest inventories are usually taken every 7-11 years; the last published inventory in Texas occurred in 1992. During an inventory, trained field crews visit plots designated for field sampling and describe them using several different criteria, such as forest type, land-use type, and site quality. Tree-level measurements are taken, including species, diameter at breast height (dbh), total height, and other attributes (Hansen 1992).

FIA samples are designed to represent variations in land and forest equitably and with the minimum error allowed by the inventory. The survey is intended to be reviewed at state and supra-state levels; calculations on the state level will have less error than calculations on the plot and county level (Hansen 1992).

Inventory data are currently publicly available on the plot and tree level from the Southern Forest Resource Assessment Data Center, www.srs.fs.usda.gov/sustain/data/index.htm (USDA Forest Service 2002). The counties sampled for the survey are those shown and labeled in Figure 4.

How FIA land cover and biomass estimates are determined

Forest area is determined with dot grid counts overlaid on aerial photos (Rosson 2000). Ground truthing is used to adjust the forest or non-forest area estimate at permanent plots (Rosson 2000). Area expansion factors, or the number of acres each plot represents, are then derived for all ground plots. This two-phase sampling method is designed such that estimates at the state level are precise to one standard error of the total, or about 1% per million acres of forest land and 5% per billion cubic feet of timber volume (Rosson 2000).

The FIA dataset provides biomass estimates under a table column named “totbio” for each tree record. Biomass is calculated by the Forest Service on a green weight basis
per inventory sample tree (live and dead) in each plot using allometric equations and coefficients derived by the Southeastern Forest Experiment Station in Asheville, North Carolina (Clark et al. 1985, Clark and Saucier 1990, Rosson 2000, Rosson 1992).

The FIA collects data and calculates biomass as follows:

At each forested sample plot, placed approximately 3 miles apart from each other, trees 5” in dbh and larger are selected and measured at each of ten satellite points using a 3.75 basal area factor prism (each prism-selected tree represents 3.75 square feet of basal area per acre) (Rosson 2000). Trees greater than 1” in dbh but smaller than 5” are measured on three 1/275-acre circular satellite plots (Rosson 2000).

Biomass estimates are made for trees greater than 1” in diameter at breast height (dbh). Each estimate includes fresh wood and bark weight, as well as bole and branch weight, but does not include leaves or the biomass of any part of the tree under the 12-inch stump (Rosson 1993). For trees with dbh ≥1” and <5”, the following equation is used:

\[ Y = a'(D^2)^b \]

where \( Y \) = biomass, \( a' \) and \( b \) are equal to a predetermined regression coefficient based on species and region, and \( D \) is the dbh of the tree. For softwood trees ≥5” and <9” in dbh, and for hardwood trees ≥5” and <11” in dbh, this slightly different equation is used:

\[ Y = a'(D^2TH)^b \]

where \( TH \) is the total height of the tree as measured with a clinometer. Finally, for softwood trees ≥9” in dbh and hardwood trees ≥ 11” dbh, this size-adjusted equation is used:

\[ Y = a''(D^2)^b(TH)^c \]
where \( a' \) and \( c \) are additional regression coefficients.

Given the tree biomass information, total biomass over any area may be determined. To do this, I first adjusted to a unit area basis by multiplying the aboveground tree biomass for each sample tree by a tree volume expansion factor, labeled "volfac" in the tree record\(^i\) and then summing over all the trees in the plot. I then multiplied the plot biomass estimates by an area expansion factor, "expvol,"\(^ii\) from the plot record. This number was then summed to determine total represented biomass over East Texas for that set of plots.

Estimates of total plot carbon per age class were divided by total represented plot area per age class to determine carbon storage by age per hectare. Average carbon accretion per year is determined by dividing the carbon accretion per acre by the average age increment between the age groups.

**Calculating carbon storage in pine plantations**

To calculate the aboveground carbon in trees, living and dead, in pine plantations of East Texas in 1992, all plots with the following criteria were included in the calculations that follow:

a) classified as monocultures or mixtures of, loblolly, shortleaf, longleaf, and slash pine,

b) planted (not natural).

---

\(^i\) The volume expansion factor, given for each tree record in the survey, approximates the number of trees per area that particular tree represents (Hansen et al. 1992). Mathematically, it is the inverse of the size of the variable-radius plot in which that particular tree was sampled. The size of the variable-radius plot is a function of the dbh of the tree (Harcombe 1998). This factor provides the per-area contribution of the sample tree to total stand biomass (Hansen et al. 1992, Harcombe 1998).

\(^ii\) The area expansion factor is given for each plot record in the survey, and is the number of acres that the plot represents (Hansen 1992). It is determined with dot grid counts over aerial photographs and adjusted with ground truthing (Rosson 2000).
A total of 312 plots out of 3815 met both criteria. Plots were divided into the following age classes: 0-10, 11-20, 21-30, 31-40, 41-50, and 50+. The 0-10 year age class is represented by the median stand age, or 5; the 11-20 year age class is represented by median age 15, and so forth. The age groups chosen are commonly used in other USDA Forest Service publications (e.g. Rosson 1995). Of the 312 plantation sample plots, 52 were of mixed age class, representing 118,302 hectares of timberland. I did not use these plots to calculate carbon accretion. Only nine sample plots were composed of trees older than the 21-30 age range. Because there were so few data points for the 35-, 45-, and 55-year classes, I established a carbon storage estimate for those classes after the addition of plot data from nearby Louisiana pine plantations.

I converted green biomass estimates to dry biomass estimates using a factor of .49657, generalized from FIA data tables by Rosson (1993) and verified with USDA Forest Service laboratory data (Clark et al. 1990). This method was used to account for the range of tree sizes and species within the pine plantations.

Of the dry weight of a tree, about half is carbon, so here a factor of .5 was used to obtain a carbon estimate from the dry weight estimate following Birdsey (1996) and Winjum et al. (1997).

After per-hectare carbon estimates were determined for each age class, two spreadsheet models were developed. The first spreadsheet illustrated carbon storage capabilities in East Texas under the typical 30-year plantation rotation. The second spreadsheet model was used to determine the gains, if any, in total carbon under a longer rotation scheme. Two rotation lengths were tested, the common 30-year rotation and a
longer 40-year rotation, which is much less common (Figure 5, Weihuan Xu, Texas Forest Service, personal communication).

Management and utilization programs operable in 1992 (e.g., thinning patterns, fertilizing, etc.) were assumed to stay the same (except for rotation length) during the course of the following calculations.

In part due to extensive harvesting in East Texas prior to the 1992 survey (Rosson 2000), very few mature plantation plots were recorded in the FIA dataset. Therefore, to obtain a more robust estimate of carbon storage in older plantations, supplemental data from the nine westernmost, non-riverine parishes in Louisiana were used (Figure 6). These parishes are in the same Major Land Resource Area as the 43 counties in East Texas. Determined by the NRCS, an MRLA is defined by land use, topography, climate, soil type, and potential natural vegetation (Nusser and Goebel 1997). The Forest Service does not provide survey data for Cameron, Jefferson Davis, and Allen parishes.

Results

Average carbon storage values ranged from 26 Mg carbon per hectare in the youngest age group to 71 Mg per hectare at age 45 (Table 1 and Figure 7). Loblolly pine plantations dominated the samples with 278 plots of various ages. Slash pine plantations were the next most common, at 27 sample plots. Aggregated over all ages, East Texas pine plantations hold $2.6 \times 10^7$ Mg of carbon over 718,000 hectares. This translates to an average of 37 Mg C/ha.
Table 1. Carbon storage in East Texas pine plantations in 1992

<table>
<thead>
<tr>
<th>Mid stand age</th>
<th>Mg C/ha</th>
<th>average carbon uptake per year, Mg C/ha</th>
<th>Number of surveyed plots per age class</th>
<th>Area per age class (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>26</td>
<td>3.8</td>
<td>126</td>
<td>294,786</td>
</tr>
<tr>
<td>15</td>
<td>41</td>
<td>1.7</td>
<td>107</td>
<td>244,604</td>
</tr>
<tr>
<td>25</td>
<td>59</td>
<td>1.7</td>
<td>18</td>
<td>37,706</td>
</tr>
<tr>
<td>35</td>
<td>55</td>
<td>-0.50</td>
<td>49 (41)</td>
<td>18,893</td>
</tr>
<tr>
<td>45</td>
<td>71</td>
<td>1.45</td>
<td>(11)</td>
<td>0</td>
</tr>
<tr>
<td>55</td>
<td>62</td>
<td>-1.1</td>
<td>7 (6)</td>
<td>2,278</td>
</tr>
</tbody>
</table>

Pine plantations in the younger age classes acquired biomass at the fastest rates (Table 1). This trend of quick, early growth is consistent with the pine plantation literature (Schultz 1997, Switzer and Nelson 1972). Actual accretion rates were somewhat lower than some previous loblolly pine research has indicated, particularly for the 15-year-old age class (Switzer and Nelson 1972, Pope and Graney 1979). Wells et al. (1975), for instance, found average accretion rates as high as 4.6 Mg C/ha/year for a 16-year-old stand.

The accretion and carbon storage density calculated here, however, should not be considered reflective of even-aged stands of pure loblolly pine in Texas. Figure 7 visually demonstrates that even though the pine plantation stands measured by the FIA are considered even-aged by the survey, in reality they are not. Most plots contained large, older hardwoods and other species, likely because new plantations are likely not to occur on clear-cut sites (Dr. Weihuan Xu, Texas Forest Service, personal communication. These large trees bias the expected carbon storage of the plantations upward in the young age classes, and decrease the apparent carbon accretion from one growth stage to the next. In the same way, as these large trees die or are removed, the total carbon storage in

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iii Numbers in parenthesis represent plots taken from the Louisiana dataset as described in Methods.
the stand decreases, and the apparent carbon accretion decreases (or becomes negative, as is the case between the 25- and 35-year age classes). In the same way, older stands often hold a variety of younger trees that can lower the apparent carbon storage.

Removing these large, older, “contaminant” species from the loblolly plots results in accretion rates closer to what one might expect, particularly for the older age classes (Table 2).

<table>
<thead>
<tr>
<th>Mid Stand age</th>
<th>average carbon uptake per year, Mg C/ha</th>
<th>Number of surveyed plots per age class</th>
<th>Area per age class (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>18.0</td>
<td>2.7</td>
<td>126</td>
</tr>
<tr>
<td>15.0</td>
<td>36.5</td>
<td>2.1</td>
<td>107</td>
</tr>
<tr>
<td>25.0</td>
<td>51.9</td>
<td>1.5</td>
<td>18</td>
</tr>
<tr>
<td>35.0</td>
<td>52.8</td>
<td>0.1</td>
<td>8</td>
</tr>
<tr>
<td>45</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>55.0</td>
<td>56.8</td>
<td>1.1</td>
<td>1</td>
</tr>
</tbody>
</table>

While the inconsistency in tree size shown in Table 2 and Figure 7 will affect expected carbon storage values, the “biased” carbon storage values are consistent with plantation management patterns in East Texas and will be used in the following calculations.

In addition to harvest and planting responses due to market and land prices, the carbon storage in East Texas at any point in time is affected by the age distribution of the plantations. The first model table (Table 3) illustrates carbon storage capabilities in East Texas under the typical 30-year plantation rotation, and given the 1992 area distribution of the six age classes. The plantation area in each age class was projected forward in ten-year intervals to the next age class. At the time of the survey, some plantations were
older than 30 years, and would have been cut immediately according to the spreadsheet model. Therefore a set of 10, 20, and 30-year old age classes, with a carbon storage/ha value intermediate to the next higher and lower age classes, were created as "rollover" classes. For example, in a statewide 30-year rotation scheme, the 55-year old age class would be immediately cut. Ten years later, in 2002, those cut stands would appear as a ten-year old age class. The C storage/ha values used to describe the rollover classes are the average of the two surrounding age classes (Table 3).

In 1992, most plantation area was in young stands; by 2002, many of these stands had probably grown old enough to increase the carbon storage in East Texas, increasing average storage from 37 to 47 Mg per hectare. This is demonstrated by Table 3.

Table 3. Fluctuating carbon storage in East Texas pine plantations

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed 44</td>
<td>118,302 5,290</td>
<td>118,302 5,290</td>
<td>118,302 5,290</td>
<td>118,302 5,290</td>
<td>118,302 5,290</td>
<td>118,302 5,290</td>
<td>118,302 5,290</td>
<td>118,302 5,290</td>
</tr>
<tr>
<td>5 26</td>
<td>294,786 7,637</td>
<td>37,707 977</td>
<td>244,604 10,006</td>
<td>294,786 7,637</td>
<td>37,707 977</td>
<td>244,604 10,006</td>
<td>294,786 7,637</td>
<td>244,604 10,006</td>
</tr>
<tr>
<td>15 40</td>
<td>244,604 10,006</td>
<td>294,786 12,832</td>
<td>294,786 17,365</td>
<td>37,707 1542</td>
<td>244,604 10,006</td>
<td>294,786 17,365</td>
<td>37,707 1542</td>
<td>244,604 10,006</td>
</tr>
<tr>
<td>25 58</td>
<td>37,707 2,221</td>
<td>244,604 14,409</td>
<td>294,786 17,365</td>
<td>37,707</td>
<td>244,604 10,006</td>
<td>294,786 17,365</td>
<td>37,707</td>
<td>244,604 10,006</td>
</tr>
<tr>
<td>35 54</td>
<td>18,893 1,125</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
</tr>
<tr>
<td>45 70</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
</tr>
<tr>
<td>55 61</td>
<td>2,278 150</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
</tr>
<tr>
<td>Rollover Age Class</td>
<td>Current Age Class</td>
<td>Current Age Class</td>
<td>Current Age Class</td>
<td>Current Age Class</td>
<td>Current Age Class</td>
<td>Current Age Class</td>
<td>Current Age Class</td>
<td>Current Age Class</td>
</tr>
<tr>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
</tr>
<tr>
<td>10 33</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
</tr>
<tr>
<td>20 49</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
</tr>
<tr>
<td>30 56</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
</tr>
<tr>
<td>TOTALS</td>
<td>716,570 26,429</td>
<td>716,570 33,442</td>
<td>716,570 31,591</td>
<td>716,570 26,358</td>
<td>716,570 33,442</td>
<td>716,570 31,591</td>
<td>716,570 26,358</td>
<td>716,570 33,442</td>
</tr>
</tbody>
</table>

Note: Data for the 45-year age class was derived from Louisiana plantation data as noted in the Methods section of this chapter. Numbers may not add due to rounding.
As the plantations continue to be harvested under the usual 30-year rotation scheme, however, the total carbon storage in plantations will drop again (Table 3) as the plantation age distribution fluctuates.

If the plantations are managed such that we move to more balanced age distribution over time, carbon storage fluctuations are much reduced, and for a 30-year rotation, total carbon storage would be a stable 30 million Mg C (Table 4), about 14% more than that stored above-ground in the East Texas pine plantations in 1992.

A longer rotation schedule, with a balanced age distribution and assuming total plantation area stays the same, will allow Texas plantations to store 3.2 more Mg/ha than the conventional 30-year rotation schedule (Table 4). This can allow over 2.3 million additional Mg of carbon stored on the East Texas landscape, an amount equivalent to 5.6% of the approximately 41\textsuperscript{iv} million Mg of carbon in CO₂ emitted by East Texas in 1999 (TNRCC 2002; Department of Rural Sociology 2000). Note, however, that this additional storage will require 10 years to achieve, yielding an average benefit of 0.5% of East Texas CO₂ emissions every year. Put differently, however, of the total 7% reduction that would have been required for participation in the Kyoto Protocol, this plantation adjustment would have absorbed approximately 38% of the required decrease

\textsuperscript{iv} Assuming that in 1999, the entire state of Texas released 621.47 million Mg CO₂ from fossil fuels (TNRCC 2002); there were 20,044,141 people in Texas in 1999 (Department of Rural Sociology 2000), 4.6 million of whom lived in or near the East Texas metropolitan areas of Houston, Beaumont-Port Arthur, Longview-Marshall, Texarkana, and Tyler (Department of Rural Sociology 2000); I am assuming that the total carbon emissions attributable to East Texas is equivalent to the fraction of the total state population residing there. In 1990, Texas released 569.61 million Mg of CO₂ from fossil fuels (TNRCC 2002). The Kyoto Protocol would have required a 7% net reduction in emissions from 1990 levels. Calculations are as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permitted fossil fuel emissions under Kyoto</td>
<td>569.61 MMT CO₂ 1990 emissions * 12/44 carbon fraction</td>
</tr>
<tr>
<td></td>
<td>* .24 East Texas population fraction * .93 emission rate = 35 MMT/yr</td>
</tr>
<tr>
<td>1999 fossil fuel emissions</td>
<td>621.47 MMT CO₂ 1999 emissions * 12/44 carbon fraction</td>
</tr>
<tr>
<td></td>
<td>* .24 East Texas population fraction = 41 MMT/yr</td>
</tr>
<tr>
<td>Total required uptake or reductions to meet Kyoto</td>
<td>6 MMT/yr</td>
</tr>
</tbody>
</table>
over East Texas (including Houston) for one year, or 3.8% of the required decrease over the additional 10 years required to sequester the additional carbon.

Table 4. Effects of 30- and 40-year rotations, assuming balanced age distributions.

<table>
<thead>
<tr>
<th>Age</th>
<th>Area in class (ha)</th>
<th>Carbon Storage per class (Mg C)</th>
<th>Age</th>
<th>Area in class (ha)</th>
<th>Carbon Storage per class (Mg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>238,857</td>
<td>6,188,000</td>
<td>5</td>
<td>179,143</td>
<td>4,580,000</td>
</tr>
<tr>
<td>15</td>
<td>238,857</td>
<td>9,771,000</td>
<td>15</td>
<td>179,143</td>
<td>7,231,000</td>
</tr>
<tr>
<td>25</td>
<td>238,857</td>
<td>14,070,000</td>
<td>25</td>
<td>179,143</td>
<td>10,413,000</td>
</tr>
<tr>
<td>35</td>
<td>238,857</td>
<td>179,143</td>
<td>35</td>
<td>179,143</td>
<td>9,689,000</td>
</tr>
</tbody>
</table>

Therefore while longer rotations allow some additional carbon storage, although compared to emissions rates, the storage is small. Yet a review of estimates for average carbon storage per age class (Table 1) show that older pine plantations stands can hold much more carbon (70 Mg/ha) than the average plantation in 1992 (37 Mg C/ha), with some individual stands storing more than 100 Mg C/ha. Mixed-age natural stands in the survey hold, on average, 70 Mg/ha.

Assuming that mature planted pine plantations in East Texas stored, on average, approximately 70 Mg/ha (Table 1), and assuming that the entire 716,000-hectare area of planted pine plantations were allowed to reach maturity, East Texas could store at least 50 million Mg C, or about twice the total carbon stored in 1992, and 50% more than the maximum storage predicted in Table 3. This additional carbon storage (over the total
storage in Table 4), if it occurred over the span of 25 years, would yearly amount to 13% of the 7% Kyoto emissions reduction for East Texas.

Discussion

In the next several decades, given current market prices for agricultural land and timber, Texas is expected to lose as much as 25% of its private forests, while total plantation area is expected to increase (Wear and Greis 2002). Managing these plantations, therefore, can have measurable effects that are useful, if not extremely important, as a mitigation tool, and are potentially valuable in carbon credit systems.

The data source

The carbon storage estimates and speculations made here are based almost entirely on data from the 1992 FIA survey for East Texas. Consequently, it is relevant to consider some of the limitations of these data. First, there are few plantations older than 25 years in East Texas. The lack of older plantation plots limited results for plantation storage older age classes. This is important, because if successful stands are allowed to age whereas less successful stands are cut, those plots located in successful stands may not be representative of other plots in the same age class.

The second limitation is that, as in most biological systems, there is considerable stand-to-stand variation in biomass and hence, carbon storage. Differences in the management of a plantation (Adams and Vidrine 2002, Sword et al. 2002, Barnett et al. 2002, Marino et al. 2002), as well as inherent differences in soil moisture and nutrient availability (Brender 1973, Livingston 1972), can affect the rate at which pines grow, and their size at a given age. Furthermore, some management methods will allow the

\* See footnote iv, Chapter II.
presence of other tree species of various sizes, altering effective accretion rates (e.g., Tables 2 and 3 in the Results section). Genetic stock differences will also affect carbon storage; volume regression equations for the coastal plain and Piedmont regions of the South have resulted in significantly different slopes (McClure et al. 1987). Such differences may encourage an under- or overestimation of carbon storage for certain regions in the South, including East Texas (Brown and Schroeder 1999, Pacala et al. 2001).

Even though plantations are ideally monospecific and even-aged, not all plantations in this dataset are managed rigorously. Many plots contained “contaminant” or “residual” species such as *Liquidambar styraciflua* (sweetgum) or *Celtis laevigata* (sugarberry) which accounted for a large part or all of the measured biomass estimate for that plot. Additionally, although the majority of trees in each plot used here should have been the same age; the variation in dbh among individuals measured in the plots often ranged greater than 20 inches, indicating age variation. In young plantations, the presence of such large trees drives the average carbon storage up. This phenomenon has been shown in Table 1 and Table 2, where young stands containing hardwoods and other species held more carbon than young, pure, stands. In the same way, older plantations may hold a significant amount of biomass in young trees (Figure 7). Plantation carbon storage and accretion estimates for Texas, therefore, must consider the presence of large “contaminant” trees.

*The permanence of a plantation carbon sink*

Climate change and land use change, both discussed at the beginning of this paper, may affect reliability of these estimates for long-term storage. Although
preliminary calculations indicate East Texas might have some potential for sequestering carbon, changes in precipitation, growing season, or temperature will affect the ability of forests here and elsewhere in the south United States to store carbon (Betts 2000, McNulty et al. 1996, Smith and Heath 2001). Most of the plantations in East Texas and elsewhere in the South, for instance, are loblolly pine (Wear and Greis 2002). Climate models linked to forest ecosystem models predict shifts in NPP in the Southern US; these shifts would likely cause a reduction in loblolly pine range (McNulty et al. 1996), affecting the northeastern corner of the state most (Iverson and Prasad 1998).

**Market considerations**

Managing plantations for maximal carbon storage can be economically useful, even if the carbon storage benefit is not large.

One harvest of older trees, because they are larger and more useful for lumber, can be more profitable than two harvests of trees logged for pulp because the older trees are larger and more useful for lumber (Schwartz 1997). Furthermore, carbon credit programs can also help make carbon sequestration a more profitable venture. Prices for such credits, without U.S. participation in the Kyoto protocol, have run between $.16 and $2.55 per Mg C (Rosenzweig et al. 2002) while some economic analyses value carbon at over $10 per Mg C (Niles et al. 2001). Some participants in the Chicago Climate Exchange, however, expect $20/Mg C (Richard Sandor, Chairman and CEO, Chicago Climate Exchange, personal communication). At this price, the forty-year rotation length discussed above, yielding 2.3 million Mg C of additional storage, would be worth $46 million dollars, or .5% of the 2000 Texas Gross State Product (GSP)\(^{vi}\) for agriculture and

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\(^{vi}\) The United States Department of Commerce Bureau of Economic Analysis defines the GSP as the “value added in production by the labor and property located within a state” (US Department of Commerce
forestry (US Department of Commerce Bureau of Economic Analysis 2002a). Allowing plantations to grow to 70 Mg C/ha would generate even more: $1 billion, or approximately 10% of the 2000 GSP for agriculture (US Department of Commerce Bureau of Economic Analysis 2002a).

Other considerations

Non-merchantable biomass may create a carbon offset if utilized for bioenergy (Few 1981). While burning biomass releases CO₂ into the air just as fossil fuels do, there is not net addition of CO₂ into the atmosphere, thus “offsetting” fossil fuel CO₂ emissions. Such offsets are also eligible for trade in a carbon credit system. The extractable bioenergy from plantations in Texas and elsewhere may provide a carbon offset of as much as .54 Mg C for every Mg of biomass used to produce electricity (Tuskan and Walsh 2001).

Some have asserted that shorter rotations and aggressive plantation management, rather than longer rotation lengths, may result in a higher carbon uptake. Johnsen et al. (2001), for example, using the model HARVCARB, suggested that after taking the end-use of the plantation carbon (such as paper and wood products) into account, slightly shorter, and not longer, rotations might result in an overall sequestration of more carbon. After a 100-year run of the model, with stands under aggressive, 20-year rotations, total sequestration was nearly twice as much total carbon (including products in landfills), as a model run with a typical 25-year rotation plan. Yet there are three major problems with such a perspective.

Bureau of Economic Analysis 2002b). For the year 2000, the GSP for the agriculture, forestry, and fish sector was $9.6 billion (US Department of Commerce Bureau of Economic Analysis 2002a).
1) Under a short rotation scheme, large volumes of paper, rather than lumber, will be produced, since the boles of the trees will not have an opportunity to grow sufficiently large to produce much sawtimber. Eventually, most of the carbon in harvested wood or wood products will decay, but paper is short-lived and decomposes quickly, and as much as 90% of the stored carbon may return to the atmosphere very soon after logging (Schroeder et al. 1993). Additionally, the rate at which trees may be turned into paper products is independent of how much wood is produced. Also, higher paper production only makes sense if there is a market for it. Finally, we have little control over the rate of paper movement into landfills.

2) Such calculations do not consider soil carbon. As discussed in the introduction, as much carbon can be stored in the soil as can be stored above ground (Birdsey 1992, Birdsey and Heath 1995). In some places, the soil carbon fraction is even higher (Birdsey 1992). Soil carbon is not allowed to accumulate in aggressively-managed plantations (Cannell 1999, Guo and Gifford 2002).

3) Neither Birdsey (1992, Birdsey and Heath 1995) nor Johnsen et al. (2001) considered the carbon released by equipment during the various phases of plantation management, such as harvesting, site preparations, and fertilizing. Including management-related emissions from fossil fuels in a carbon sequestration calculation is worth considering, since much of the activity on a plantation will involve fossil-fuel burning heavy equipment.
Basic calculations such as those made here in this chapter are the beginning of an attempt to quantify the current and potential carbon storage in East Texas forests. Plantations are one land use class in East Texas in which biomass can be actively increased with changes in land use and management. Compared to regional carbon emissions, however, the gains in carbon storage made by changing rotation length statewide are comparatively small. However, plantations are not the only type of forest that can sequester carbon in the landscape; new and standing forests may do as good a job or better, and with less management (Moulton and Richards 1990). East Texas may have many opportunities for afforestation; this is the subject of Section 2.03.
CHAPTER III. SEQUESTERING CARBON: LAND USE CHANGE

(A Method to Determine the Effects of Land Use Change in East Texas on Above-ground Carbon)

Introduction

Southern forests are changing in both size and character in response to land use shifts. Large sections of the South, for instance, have lost forest area, while in a few places it is being gained (Figure 8; Wear and Greis 2002). This trend is also apparent in East Texas in 1992 the year of the last published FIA survey. In that case, 196,000 hectares had reverted from other uses to timberland since 1986; 114,000 hectares were diverted to non-forest, however, in that same time period (Rosson 2000). The pace of this change threatens to quicken: this past year, approximately half a million hectares have been posted for sale in East Texas (Stewart 2002). These hectares, many of which are plantations and forests, may soon be covered by fast food and subdivisions, and many tons of stored carbon may be lost in the process. But what if forest reversion continued, and forest diversion to other land uses were encouraged via carbon credits? This chapter uses simple methods and readily available data to calculate the current carbon storage in East Texas, and then uses those same methods to form a rough estimate of the level of aboveground carbon storage that might be feasible as a result of continuing forest reversion in East Texas.

In the 43 counties that make up East Texas according to the FIA survey, a little less than half of the total land area is forested (Figure 9). When the FIA survey counties are considered in the context of a Natural Resource Conservation Service Major Land Resource Area map, several are found to straddle both forest and prairie regions (Figure 10). In fact, approximately 19% of their total FIA survey area is prairie or only sparsely
forested. With the “forest-fringe” counties removed, only slightly more than half (rather than less than half) of the East Texas region is forested (Figure 11). Much of the original forest has been diverted to other uses, such as pastureland.

Like much of the rest of the South (Figure 12), the next most common land use category in East Texas is pastureland, with approximately 28% of the total area within the Coastal Plain and Flatwoods MRLA. Like pastureland, the rangeland and cropland categories (another 1%) are also potentially forestable. How much could carbon storage in East Texas increase if these 1.5 million hectares of open land are allowed to revert to forest?

To answer such questions, accurate information about land cover types and their spatial distribution, land use change rates, and forest inventory size is required for estimating the size and distribution of carbon stocks in the major terrestrial ecosystem types in the US. Years of agricultural and resource surveys have provided several different carbon stock estimates. Current regional and national carbon estimates for forests are primarily built on FIA data, which estimate carbon storage from tree diameters measured by field sampling (e.g., Birdsey and Lewis 2002). More information about the FIA and NRI surveys is included in the Methods section of this chapter.

Both the FIA and NRI employ multi-tier sampling strategies involving both remote sensing and ground measurements. These inventories, scheduled at multi-year intervals, provide baseline information about land cover, management intensity, productivity, and disturbance. This information can in turn be used to estimate carbon stocks and changes over 5-10 year periods. A relatively high sampling intensity allows
nationwide or state-level descriptions of some of the causes of observed carbon stock changes, such as vegetation growth, mortality, or harvesting.

The FIA division of the US Forest Service was organized (under a different name) in 1930 to provide estimates on growing stock and the status of the nation’s timber supply (USDA Forest Service 1972). The NRI, instituted in 1982 and conducted every five years hence (Harlow 1994), provides information on general trends in soil and water use. As will be explained in the Methods section, neither the FIA or the NRI are as accurate at sub-state levels as on state and national levels (Miller and Hartsell 1992, Kelly et al. 1992, Nusser and Goebel 1997, Nusser 1999). The highly heterogeneous nature of the forest landscapes in the South U.S., including those of East Texas, can further complicate carbon storage estimation. Furthermore, practical limitations to these spreadsheet-based inventories allow gaps in spatial information\(^1\) and currently limit opportunities for spatial and geographical analysis on the county or sub-state scale. Maps are limited to county-level representations based on aggregated county-level data, such as total forest area (see Figure 8 for an example).

Remote sensing data, on the other hand, promise a pixel-based, map-like representation of the Earth’s surface that is spatially continuous and highly consistent, as well as available at a range of spatial and temporal scales. By graphically demonstrating potential and current carbon storage, localized estimates might facilitate participation in carbon incentive and trading programs operable within the Chicago Climate Exchange or other programs mentioned in Chapter I. Further, this method may be utilized throughout

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\(^1\) For example, wooded areas smaller than one acre are excluded from both the FIA (Rosson 2000) and NRI (Nusser and Goebel 1997).
the similarly-forested Southern United States to graphically evaluate the potential for additional carbon sequestration at the regional and county scale.

To determine the carbon storage potential of East Texas, I have used a simple GIS method to create an above-ground forest carbon inventory by marrying freely available, classified 30-m National Land Cover Data (NLCD) satellite images to a simple look-up table of carbon-per-hectare values derived from FIA survey data intended for analysis at the state level. With this method, I also hope to provide an accessible and efficient process to understand carbon stock change on a graphical level, useful to both science and policy. I will demonstrate this method with two estimates:

1) an estimate for carbon storage in 1992 (the last year of available data);

2) a projection for carbon storage determined by substituting non-forested areas detected by the NLCD with forest.

While broad, regional calculations for East Texas may be valuable, county-level carbon estimates may be even more useful, particularly in regional policy and modeling applications. To determine if the NLCD classified satellite data is as robust a statewide land use/land cover estimation method as the well-established NRI and FIA, the area estimates of several broad land-use categories were first compared where possible. Then, because various sources of error can be masked in large state-level or multi-county approximations, and mask the reliability of the product, estimates were also compared at the county level.

As in the previous plantation study, I will focus here solely on above-ground carbon determinable through direct tree measurements and allometric relationships. Soil carbon, leaf litter carbon, and minor understory shrubs will all be excluded. Though a
significant component to forest systems, belowground carbon is very poorly understood (e.g., Birdsey 1992a), and would be the subject of another thesis. Fortunately, soil carbon content may often be approximated with aboveground carbon estimates; this will be considered briefly in the Discussion.

**Methods**

The three different surveys used here, because they are intended for different purposes and collected by different agencies, are all unique in design and interpretation. Therefore, before they are used, each of the three surveys is described here.

**How NRI land cover data is derived**

The National Resources Inventory (NRI) is a nationwide survey using stratified area samples. Land use and vegetation land cover data are collected at the sample site level, while urban and water cover data are collected at the Primary Sampling Unit (PSU) level. A PSU is typically approximately 65 hectares (.5 mi by .5 mi). Depending on the heterogeneity of a region, about two PSUs are studied per 12 square miles of land area during the data collection process (Nusser and Goebel 1997). The goal in determining the number of PSUs needed for the 1992 NRI, the survey year used here, was to have a coefficient of variation\(^{ii}\) less than 10% surface area estimates for any area constituting at least 10% of the surface area in a pre-defined multi-county region, the MRLA (defined in Chapter II) (Nusser and Goebel 1997). The two forested MRLAs of East Texas (see Figure 13) are the Western Coastal Plain, also located throughout parts of Arkansas, Louisiana, and Oklahoma (about 14 million hectares in total area), and the Western Gulf Coast Flatwoods, also located in Louisiana (totaling about 1.7 million hectares) (USDA

\(^{ii}\) A coefficient of variation, typically described as a percentage, is for a normal distribution the standard deviation of a variable standardized by its mean. When the coefficient of variation is small, the data scatter compared to the mean is small (Freund and Simon 1997).
Natural Resource Conservation Service 1981). Though reliable on an MRLA level, the NRI is not intended to be used on the county level, where variance increases and error grows to beyond accepted thresholds.

Data for the 1992 NRI were collected at more than 800,000 sample sites nationwide (Nusser and Goebel 1997). This very large sample size permits the collected information to be legitimately used to analyze issues at many geographic levels: national, regional, state, and multi-county, but not county or sub-state (Nusser and Goebel 1997). Some categories like water, rural roads, and Conservation Reserve Program are not directly measured; instead, they are taken from other sources such as census or USDA program files. The other land-use/cover categories, such as forest area, are statistically determined from sample sites, and must be an acre or larger to count; small forested tracts, for instance, will likely not be counted toward the forest land cover category (Nusser and Goebel 1997). Furthermore, some federal land is counted in its own category “Federal Land Cover with Use Not Recorded,” and will not be counted toward other categories.

The NRI records statistics for thirteen general land cover/land use categories (Table 1). Land-use/cover are tabulated and published on a per-county basis (Michael Bockhold, NRCS, personal communication).
Table 1. NRI general land cover types.

<table>
<thead>
<tr>
<th>NRI Land Cover Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultivated Cropland</td>
</tr>
<tr>
<td>Non-cultivated Cropland</td>
</tr>
<tr>
<td>Pastureland</td>
</tr>
<tr>
<td>Rangeland</td>
</tr>
<tr>
<td>Forestland</td>
</tr>
<tr>
<td>Minor Land Cover/Uses</td>
</tr>
<tr>
<td>Urban Small and Large Built-Up</td>
</tr>
<tr>
<td>Rural Transport: Roads and Railroads</td>
</tr>
<tr>
<td>Water: Small Streams and Ponds</td>
</tr>
<tr>
<td>Water: Census Streams and Lakes</td>
</tr>
<tr>
<td>Federal Land Cover with Use Not Recorded</td>
</tr>
<tr>
<td>Conservation Reserve Program</td>
</tr>
<tr>
<td>Other</td>
</tr>
</tbody>
</table>

While the latest nationwide NRI results are available over the web from the Natural Resources Conservation Service (e.g., http://www.nrcs.usda.gov/technical/NRI/), not every state publishes its own state-level NRI, which must be requested from the state NRCS office. NRI data for Texas is available as a text e-mail by request from the Texas NRCS in Temple, Texas.

_How FIA land cover and biomass estimates are derived_

The FIA survey, as explained in Chapter II, has for many years been used to estimate national trends in timber volume and growth. The last available year of the Texas survey is 1992; the first plot for this survey was measured in November 1991, and the last in August 1992 (Rosson 2000). In Texas, over 2,000 forested plots and more than 70,000 trees were surveyed.

Like the biomass calculations described in the Methods section of Chapter II, forest type determinations are not made in the field. Instead, stocking computations based on sample trees in a plot are used to determine forest type by determining the
stocking\textsuperscript{iii} proportions of deciduous or evergreen species groupings. If softwoods do not constitute a majority of the stocking, but still comprise more than 25% of the plot, a mixed forest type is assigned (May 1990).

\textbf{How carbon storage is calculated with FIA Data}

I generated carbon storage estimates for each forest type by first obtaining, from the FIA data, estimates of carbon storage per hectare for each forest type. Because they were significantly different, all forested plots were divided by their FIA units, Northeast or Southeast (Figure 4). The entire process may be explained in three steps:

1) A biomass estimate was calculated by the USDA Forest Service for each sample tree in a plot, based on species and dbh. The estimates are included with the downloaded FIA dataset.

2) Using the above data, I calculated carbon storage per hectare per plot as described in the methods of Chapter II. I converted each fresh biomass estimate to a dry biomass estimate (a factor of .49657 for evergreen plots, a factor of .53713 for deciduous plots, and a factor of .51685 for mixed plots) (Rosson 2000) which I then converted to carbon (using a factor of .5) (Birdsey 1996, Winjum et al. 1997).

3) I classified each plot into one of three types (evergreen, deciduous, mixed), and then calculated average carbon storage per hectare per forest type. Total carbon storage was derived by multiplying carbon storage per hectare per forest type times the number of hectares of that forest type.

\textsuperscript{iii} Stocking, determined by the basal area of sample trees in a plot, is a measure of the extent to which a site is occupied by trees according to that site's potential (Hansen and Hahn 1992).
**How NLCD land cover data is derived**

There are 21 land cover classes in the NLCD system. This classification is based on a modified Anderson Level II (Anderson 1976, USGS 2001). In this system are four forest classes (Deciduous, Evergreen, Mixed, and Woody Wetlands) and five classes of open, agricultural land (Grasslands, Pasture/Hay, Row Crops, Small Grains, Fallow).

Table 2. NLCD land cover classes.

<table>
<thead>
<tr>
<th>NLCD Land Cover Classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Water</td>
</tr>
<tr>
<td>Perennial Ice/Snow</td>
</tr>
<tr>
<td>Low-Intensity Residential</td>
</tr>
<tr>
<td>High-Intensity Residential</td>
</tr>
<tr>
<td>Commercial/Industrial/Transportation</td>
</tr>
<tr>
<td>Bare Rock/Sand/Clay</td>
</tr>
<tr>
<td>Quarries/Strip Mines/Gravel Pits</td>
</tr>
<tr>
<td>Transitional</td>
</tr>
<tr>
<td>Deciduous Forest</td>
</tr>
<tr>
<td>Evergreen Forest</td>
</tr>
<tr>
<td>Mixed Forest</td>
</tr>
<tr>
<td>Shrubland</td>
</tr>
<tr>
<td>Orchards/Vineyards/Other</td>
</tr>
<tr>
<td>Grasslands/Herbaceous</td>
</tr>
<tr>
<td>Pasture/Hay</td>
</tr>
<tr>
<td>Row Crops</td>
</tr>
<tr>
<td>Small Grains</td>
</tr>
<tr>
<td>Fallow</td>
</tr>
<tr>
<td>Urban/Recreational Grasses</td>
</tr>
<tr>
<td>Woody Wetlands</td>
</tr>
<tr>
<td>Emergent Herbaceous Wetlands</td>
</tr>
</tbody>
</table>

The primary source of data for the NLCD is leaves-off (winter) Landsat thematic mapper (TM) data acquired in and around 1992, collected by the Multiresolution Characteristics Consortium (MRLC) and classified by the U.S. Geological Survey (USGS) as part of a cooperative agreement between the USGS and U.S. Environmental Protection Agency (USEPA). Pre-processing procedures are explained in detail by the MRLC (http://edc.usgs.gov/glis/hyper/guide/mrlc#mrlc4). Images were classified and processed according to Vogelmann et al. (2001).
The Landsat TM satellite instrument recorded the spectral reflectance of the earth’s surface at a 30m by 30m pixel resolution. During the classification process, the raw satellite data, simply a vector of reflectance values for each pixel, was partitioned into 100 spectral classes through an unsupervised classification process. Each spectral class of vectors was associated with a land use category using aerial photographs as reference data. The classification was then refined once more with decision trees and broad visual inspections. Decision-making rules and models resolved confused spectral classes (those classes that represent two or more land use categories) with the help of ancillary data, such as leaves-on (summer) TM images, 3 arc-second Digital Terrain Elevation Data, National Wetlands Inventory data, soils data, and high-altitude photography images. Confused clusters that could not be modeled out were visually identified and manually reclassified on-screen with the ancillary data as a guide. The resulting land-cover images were stored as raster format data, map-registered to the Albers Conical Equal Area projection.

On a state level, NLCD data has thus far shown to be about 60% accurate (Yang et al. 2001). When similar classes, such as the three forest classes, are grouped together, the accuracy increases to 80% (Yang et al. 2001). The accuracy assessment for Texas is still pending (Stephen Howard, USGS, personal communication). While the resolution of the NLCD is 30m, use of the MRLC as a county-level data instrument is not encouraged (Stephen Howard, USGS, personal communication).

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iv That is to say, the classification software separated the range of spectral signals into statistically different sets.
Data acquisition and preparation

I acquired FIA county-level forest area data as described in Chapter II. NRI land cover data for Texas is available as a text e-mail by request from the Texas Natural Resource Conservation Service Technical Support Department in Temple, Texas. The NLCD is available by state or portions of states via ftp from the USGS Eros Data Center at http://edcwww.cr.usgs.gov/pub/data/landcover/states/. The FIA dataset was managed in Microsoft Access, the NRI dataset in Microsoft Excel, and the NLCD dataset managed in both ERDAS IMAGINE (v. 8.5) and Microsoft Excel.

NLCD files of Texas were mosaicked\(^\text{v}\) and partitioned into the 43 counties of East Texas. To see if the NLCD was as robust a regional land cover classification method as the well-established NRI and FIA surveys, I made two different area comparisons:

1) Area estimates of four broad categories comparable in definition were compared over East Texas using the NRI. These categories included Water, Urban, Forest, and Pasture/Hay.

2) Area estimates for three broad forest categories comparable in definition were compared over East Texas. To investigate county-level correspondence between the FIA and NLCD, the three forest categories were compared for each of the 43 East Texas counties, as well. These categories included Deciduous Forest, Evergreen Forest, and Mixed Forest.

The NLCD and FIA, while both generating deciduous, mixed, and evergreen forest categories, do not categorize forest types in the same way. There are two issues regarding forest type classification that must first be addressed before comparing the two datasets. First, the coverage threshold for the NLCD is 75%; therefore, if a forest area is

\(^\text{v}\) The NLCD was downloaded in sections. Before being used, the sections were joined together, or “mosaicked.”
determined to be approximately 75% pine, it is considered evergreen, but if it is
approximately 50% evergreen, it is classified as mixed (USGS 2000a, USGS 2000b).
The FIA, however, classifies forests based on the stocking of dominant species (May
1990, Rosson 2000). To group the FIA forest plots into one of the three NLCD 75%
threshold groups of evergreen, mixed, or deciduous, every plot in the FIA dataset for
Texas was reclassified based on the sum of basal area of the evergreen or deciduous
species in the plots. Because basal area is strongly correlated to crown coverage (Smith
et al. 1991, Minor 1951, Persson 2002), I considered this to be the best method to
simulate the classification process performed for the NLCD.\textsuperscript{vi}

The NLCD dataset contains one more forest category, “Woody Wetlands.” The
woody wetlands class is defined as “areas where forest or shrubland vegetation accounts
for 25-100 percent of the cover and the soil or substrate is periodically saturated with or
covered with water” (USGS 2000A, USGS 2000b). Because the evergreen species
resident in this part of the country (i.e., loblolly, shortleaf, and longleaf pine, and Eastern
redcedar), are not likely to be found on wet, swampy soils (USDA Forest Service 1990),
we can safely add woody wetland tracts to deciduous forest area.

Once “apple to apple” adjustments of land cover between the datasets were
established, I compared state-level (NRI vs. NLCD, FIA vs. NLCD) and county-level
(FIA vs. NLCD) land cover classes. Equipped with an understanding of how the NLCD
land cover estimates compared with NRI and FIA land cover estimates (shown in

\textsuperscript{vi} In four species groups in Tennessee, regression analyses have shows that the relationship between dbh
and crown diameter is fairly strong, with R\textsuperscript{2} values ranging from .644 to .935 (Gerig and May 1995). In a
study modeling crown radius in California conifers (Gill et al. 2000) also indicate that dbh is a good
predictor of crown radius. In a study of seven species of bottomland hardwood species (Francis 1986), the
dbh/crown relationship was apparent, but all seven species could not be described by a single regression
equation.
Results), I then progressed to using simple accounting methods to generate a carbon storage estimate for East Texas. I estimated potential carbon storage by considering only the areas within the forest MRLAs (Figure 10), since these MRLAs, by definition, would be more likely to naturally support forest.

Except where specified, management and cutting methods used in 1992 (e.g., thinning patterns, fertilizing, logging, etc.) were assumed to stay the same during the course of the following calculations.

**Results**

Four categories common to the NLCD and NRI, water, urban, forest, and non-cultivated pasture/rangeland, were compared across the 43 counties that that make up East Texas. Two of the four categories agreed very well, and two did not. The NLCD showed 78% less urban area than the NRI, and 22% more forest (which had a 95% confidence interval for the forest area category of ± 655,487 ha).

<table>
<thead>
<tr>
<th>Table 3. Comparison of land area estimates for four major land cover types common to the NLCD and NRI.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Area (ha)</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>NLCD</td>
</tr>
<tr>
<td>NRI</td>
</tr>
<tr>
<td>Difference</td>
</tr>
<tr>
<td>Percent Difference (NLCD-NRI)/(1/2(NLCD+NRI))</td>
</tr>
</tbody>
</table>

The NLCD and NRI actually may be slightly closer than is indicated here. One of the NRI land cover/use categories is “Federal Land Cover Not Recorded;” which covers 387,138 ha of land in the 43-county area studied in this thesis. Much of the federal land in East Texas is in the National Forests of Texas or the Big Thicket National Preserve; both of these contain large areas of forest. Omitting the “Federal Land Cover” category
could therefore account for as much as 39% of the discrepancy in forest type calculation between the NRI and NLCD.

One reason that the urban NLCD estimate differs so drastically from the statistical NRI estimate is that NLCD is based on satellite data that interprets vegetation signals literally, regardless or where or how that vegetation is situated. The NLCD dataset, then, will interpret some parks and residential areas as a forest or grassland and not an urban cover type. This type of classification decision is apparent upon close examination of an NLCD image of the Rice University area (Figure 14), where forest and pasture pixels are identified within the broader urban landscape. This is not a fault with the NLCD data, but rather demonstrates how heterogeneous regions may be perceived in two different ways by two different survey methods. By more specifically describing the components within a landscape, the NLCD methods can reveal more about carbon storage and land cover than the current NRI techniques.

Both the FIA and NLCD divide the forest category into subclasses. To compare the FIA and NLCD forest type area estimates, each FIA plot was reclassified according to the NLCD 75% threshold using basal area (see Methods), then compared (Table 4). Additionally, to investigate bias in the NLCD (Table 5), I regressed the FIA on the NLCD and performed a simple t-test on the slope of the regression. For this t-test, \( t = \frac{(slope-1)}{m_e} \), where \( m_e \) is the standard error of the slope (Sokal and Rohlf 1969).

Table 4. Comparison of state-level land area estimates for four major forest types common to the NLCD and FIA.

<table>
<thead>
<tr>
<th></th>
<th>Deciduous (ha)</th>
<th>Evergreen (ha)</th>
<th>Mixed (ha)</th>
<th>Total (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLCD</td>
<td>2,198,040</td>
<td>1,036,943</td>
<td>1,823,714</td>
<td>5,058,697</td>
</tr>
<tr>
<td>FIA</td>
<td>1,759,086</td>
<td>1,109,905</td>
<td>1,856,371</td>
<td>4,725,366</td>
</tr>
<tr>
<td>Difference</td>
<td>438,954</td>
<td>-72,962</td>
<td>-32,657</td>
<td>165,682</td>
</tr>
<tr>
<td>Percent Difference (NLCD-FIA)/((\frac{1}{2}(NLCD + FIA)))</td>
<td>22%</td>
<td>-7%</td>
<td>-2%</td>
<td>4%</td>
</tr>
</tbody>
</table>
Overall, the NLCD tends to overestimate total forest area compared to the FIA, which has an approximate 95% confidence interval of $\pm 27785$ ha.\textsuperscript{vii} While the NLCD yields similar results to the FIA for total forest area estimates for East Texas, forest type area estimates over individual counties did not always compare as closely (Figure 15). The correspondence between the FIA and NLCD is good, although the NLCD does slightly overestimate forest area compared to the FIA. Much of this difference is located in the deciduous forest class, where the NLCD finds more area than the FIA (apparent in Table 4 and Figure 15b). Bias in the deciduous and total forest area estimates is also apparent (Table 5.)

Table 5. Regression statistics for comparisons of NLCD and FIA area estimate error estimates. For the regressions, the intercept was forced to zero.

<table>
<thead>
<tr>
<th></th>
<th>Deciduous Forest Area</th>
<th>Evergreen Forest Area</th>
<th>Mixed Forest Area</th>
<th>Total Forest Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope \textsuperscript{viii}</td>
<td>.7871</td>
<td>1.0508</td>
<td>.9593</td>
<td>.9434</td>
</tr>
<tr>
<td>$m_e$ \textsuperscript{viii}</td>
<td>.0433</td>
<td>.0463</td>
<td>.0467</td>
<td>.0107</td>
</tr>
<tr>
<td>Df</td>
<td>41</td>
<td>41</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td>t</td>
<td>-4.915</td>
<td>1.097</td>
<td>-.8714</td>
<td>-5.2810</td>
</tr>
<tr>
<td>Significance</td>
<td>p&lt;.001**</td>
<td>.10&gt;p&gt;.05</td>
<td>p &gt;.10</td>
<td>p&lt;.001**</td>
</tr>
</tbody>
</table>

\textsuperscript{**} Denotes a significant difference, indicating bias in the area estimates.

To determine carbon storage using the NLCD and FIA data, carbon storage estimates were made for each of the three forest types using biomass figures and expansion factors from the FIA (Table 6). Plot-to-plot variation in carbon storage is high despite large sample sizes. Individual plots ranged in carbon content from over 200 Mg C/ha to as little as 1 Mg C/ha.

\textsuperscript{vii} This confidence interval is based on FIA sampling error estimates provided by FIA reports (Miller and Hartsell 1992). Sampling errors for state totals are based on one standard deviation from the mean, indicating a 66% chance that the true results would be within the confidence interval (Rosson 2000)

\textsuperscript{viii} The symbol $m_e$ represents the standard error of the slope (Sokal and Rohlf 1969)
Table 6. Carbon storage estimates per hectare for each of three forest types over Northeast and Southeast Texas. Because they are based on current management and removal rates, these figures represent 1992, and not potential, carbon storage.

<table>
<thead>
<tr>
<th>Forest Type</th>
<th>SE Tx Mg C/ha</th>
<th>NE Tx Mg C/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg</td>
<td>SD</td>
</tr>
<tr>
<td>Evergreen</td>
<td>49.2</td>
<td>29.9</td>
</tr>
<tr>
<td>Deciduous</td>
<td>53.5</td>
<td>32.2</td>
</tr>
<tr>
<td>Mixed</td>
<td>63.6</td>
<td>31.7</td>
</tr>
</tbody>
</table>

These figures, not far from the established national average determined by Birdsey and Heath (1995), were multiplied over the areas of a given forest type estimated by the NLCD to obtain carbon storage per county. The trend line between the FIA and NLCD-method county carbon storage estimates remain similar to the area trend lines, but the amount of variance explained ($R^2$) is lower (Figure 16), and the spread about the regression curve is larger. In Upshur county, for example, where the NLCD and FIA estimates of total forest area agree quite well, the NLCD underestimates mixed forest area as compared to the FIA, while it overestimates deciduous forest area. In Liberty, however, the NLCD overestimates the mixed forest type area compared to the FIA, while underestimating the area of deciduous forest.

At the state level, the NLCD method agrees relatively well with the FIA, with the NLCD method estimating about 289 million Mg C in East Texas, and the FIA survey estimating about 254 million Mg C. The NLCD method estimate is very close the 95% confidence interval for the FIA estimate, 267±12.8 million Mg C.\textsuperscript{ix} Like the area estimates, however, the bias is still apparent (Table 7). While both of these figures are lower than the estimate produced by Birdsey (2002) for the TNRCC (now TCEQ), recall

\textsuperscript{ix} This confidence interval is based on sampling error published by the FIA; here, the sampling error for dry biomass was found in Rosson (2000).
that this figure is an estimate for East Texas, whereas Birdsey’s estimate (317 million Mg) is for the entire state.

Table 7. Regression statistics for comparisons of NLCD and FIA carbon storage error estimates. For the regressions, the intercept was forced to zero.

<table>
<thead>
<tr>
<th></th>
<th>Deciduous Forest Area</th>
<th>Evergreen Forest Area</th>
<th>Mixed Forest Area</th>
<th>Total Forest Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>.7192</td>
<td>1.0224</td>
<td>.8885</td>
<td>.8956</td>
</tr>
<tr>
<td>( m_e )</td>
<td>.0421</td>
<td>.0596</td>
<td>.0586</td>
<td>.0212</td>
</tr>
<tr>
<td>Df</td>
<td>41</td>
<td>41</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td>t</td>
<td>-6.6647</td>
<td>.3757</td>
<td>1.9029</td>
<td>-4.923</td>
</tr>
<tr>
<td>Significance</td>
<td>P&lt;.001**</td>
<td>P&gt;-.10</td>
<td>P&gt;.10&gt;P&gt;.05</td>
<td>P&lt;.001**</td>
</tr>
</tbody>
</table>

** Denotes a significant difference, indicating bias in the area estimates.

Yet while the NLCD may not agree with the NRI and FIA perfectly, the agreement seems close enough to justify its use. Tables 5 and 7 indicate the evergreen and mixed carbon storage estimates are close. Differences between the NLCD and FIA in forest area estimation may be partially explained by the detection of urban forests and other very small forest tracts; these differences in area became differences in carbon storage.

According to the NRI, the Western Gulf Coastal Plain and Western Gulf Coast Flatwoods MRLAs constitute about 8.9 million hectares in the 43 FIA counties of East Texas. Within these two forest resource areas, the area of forestable land amounts to at least 1.5 million hectares (these lands are currently pasture, croplands, etc.). Considering the minimum and maximum average carbon storage per hectare value in Table 6 (49.2 and 63.6 Mg C/ha, respectively ), a massive reforestation project replacing those open lands with the current mix of managed and unmanaged forests could store between 76 and 98 million Mg C aboveground forest carbon. This is much more substantial a carbon storage improvement than plantation rotation adjustments might provide (3.2-20 million Mg C, Chapter II). At a possible carbon credit exchange rate of $20/ton (Dr. Richard
Sandor, Chairman and CEO, Chicago Climate Exchange, personal communication), this reforestation project would be worth nearly $2 billion, or, if paid all at once, 20% of the 2000 Texas Gross State Product for agriculture and forestry (U.S. Department of Commerce Bureau of Economic Analysis 2002b). In terms of the Kyoto Protocol, a reforestation project of this scale could put East Texas in Kyoto "attainment" for about 14 years.\textsuperscript{x} Note, however, that it would take decades for a newly-planted forest to achieve the average carbon storage values noted in Table 6. Optimistically assuming 98 million Mg C in aboveground biomass could be stored on reforested lands in forty years (i.e., approximately 2.45 million Mg/C/yr in additional storage), and noting that meeting Kyoto standards would require a 6 million Mg C/yr emissions reduction or sequestration increase (see footnote, this page), a massive reforestation effort could account for 41% of the desired sink.

But where is this forestable property in Texas? Since the TM satellite instrument on which the NLCD classification is based perceives a landscape continuously at a 30m resolution, rather than by statistical survey, and because the NLCD yields per-pixel location and classification information, rather than per-county information, the NLCD is a useful tool for which study land use and carbon storage. By providing a high-resolution, georectified image, one can pinpoint forestable areas, as illustrated in Figure 17, and encourage further county-level, rather than broad state- or national-level, carbon storage exploration for understanding carbon storage and evaluating potential carbon credit programs. For example, an energy investment company interested in creating a carbon offset and trading the credits from such an offset will find that among the dense

\textsuperscript{x} See footnote iv, Chapter II.
forestland of Newton county are as much as 36,114 ha of open, non-forested land. The open land in Newton county alone could sequester at least 1.8 million Mg C.

Discussion
In this chapter, the federal surveys FIA and NRI were used to help determine the reliability of NLCD area estimation abilities. Potential misclassification errors in the NLCD, as well as classification differences between the datasets, occasionally led to very different area estimates, particularly on the county level. Because the Texas NLCD dataset has not yet received an accuracy assessment, one must consider potential error in the NLCD, and differences that will arise when comparing the satellite data to the survey datasets. The FIA data was used in conjunction with the NLCD to demonstrate how the satellite data may be used to calculate and illustrate carbon storage. The very general use of the FIA data, however, may contribute to inaccuracies on a fine scale. An individual can use the NLCD to study carbon storage and land use change on a county, state, or regional scale, taking a leap from traditional county-level tabular survey estimates into graphical insight. Nevertheless, the limitations of this method are worth considering.

Potential error in the NLCD
A frequent concern about land cover maps such as the NLCD is that they are often judged to be insufficient for operational applications. In the case of the NLCD, formal accuracy assessments performed thus far used aerial photos as reference data (Yang et al. 2000, Zhu et al. 2000). The classification of aerial photographs, however, is based on the subjective interpretations of the classifier; in fact, that data itself is just as likely to contain error due to both misclassification and misinterpretation. Furthermore, temporal differences between the satellite and aerial photography data may suggest
problems with the NLCD where they actually do not exist. It has been suggested that the only way to be really sure may be with a thorough ground-truth process (Foody 2001). This would be done with some difficulty now as it is a decade (or more) since the satellite images for the NLCD were collected. Here, NRI and FIA data from the same year, 1992, were informally used to assess accuracy for this thesis.

It is more difficult to assess NLCD area estimate reliability using widely accepted agency data, such as the NRI and FIA, at the county level because estimates below the state level will have larger sampling errors (Kelly et al. 1992, Miller and Hartsell 1992, Nusser and Goebel 1997). Total timberland area estimates from the FIA on a county level, for example, tend to carry a sampling error on the order of one to three percent, and sometimes as much as 15.8% (Miller and Hartsell 1992). As estimates are subdivided into forest types, these sampling errors will be even larger. County-level accuracy for the NLCD in Texas has not been assessed, although the latest MRLC accuracy assessment for a region along the East Coast determined that the NLCD provides a 60% state-level accuracy (Zhu et al. 2000, Yang et al. 2001). Similar classes, such as forest types or the grassland-like agricultural classes were mislabeled the most (Yang et al. 2001). These labeling differences, however, should not affect carbon storage estimates here appreciably, particularly on the state level (note the relative similarity in several of the carbon storage figures in Table 6).

Fits on the area and carbon storage regressions (Figures 17 and 18) suggest that the NLCD method used here is often nearly as good as the FIA at county- and state-level area and carbon estimates. But because of the higher error, the county-level carbon storage estimates from the NLCD method, like the FIA, should be taken as only an
approximation to reality. County-level biomass estimates from the FIA carry a sampling error commonly between 10-20%, but can be as much as 88% (Rosson 1993).

It is unlikely that the NLCD and FIA state- and county-level totals are different from each other just on the basis of sampling error. There will be differences related to methods of estimating area and methods of estimating biomass. Issues with the two methods follow.

*Important issues regarding area estimation*

As shown in the Results, the greatest county-level discrepancies between the FIA and NLCD occur in estimates of the forest cover types. This kind of discrepancy could have been caused by the following three reasons:

1) differences in timing between the survey and satellite pass, if land-cover change occurred between the satellite flyover dates and the survey dates,

2) differences in the perception of detectable stocking levels by the FIA and NLCD, and

3) the per-pixel classification method of the NLCD data, may also cause area estimate discrepancies.

These important issues will now be discussed individually here.

1) *Differences in timing of data collection*
The FIA data was collected between November 1991 and 1992 (Rosson 2000). Leaf-off NLCD images were selected from 1987-1991, while leaf-on images ranged from 1986-1992 (USGS 2000a, USGS 2000b). During the course of these few years, clearcuts could have been made, or young forests established. Some leaf-off images, used to help differentiate evergreen and deciduous trees, were taken as late as mid-March; in this subtropical climate, some species would be in bloom by then, affecting evergreen/deciduous classifications.

2) Differences in detecting stocking levels
   As would be expected in a real-world system, the forests of East Texas fall along an evergreen-to-deciduous continuum, trending from one class to another spectrally and in the field. The NLCD and modified FIA definitions of the three forest classes used here utilize stocking thresholds of 75% to define forest type, but these thresholds are only approximated spectrally. The NLCD was classified by analyzing several mosaics at a time, with a small number of aerial photos used as guidance; with that in mind, the 75% threshold is not a hard figure, and there is most likely variation to either side of the threshold (Dr. Stephen Howard, USGS, personal communication). Therefore slight differences in the perception of stocking level may factor into discrepancies in area between the NLCD and FIA. Though likely to have only a moderate effect at the county level, differently labeling forests will affect carbon storage estimates to some degree, since the three forest types, deciduous, evergreen, and mixed forests differ significantly in carbon content (Table 6).

   The FIA practice of using basal area of sample trees in a plot to determine stocking, and, hence, forest type might affect the classification of regenerating stands. Currently, since only trees with dbh>1” typically count toward stocking levels, saplings
have very little basal area and seedlings have none (May 1990). Basal area might well be
the variable most closely related to timber volume, but it is inadequate as a stand
descriptor in small-diameter stands populated by a few big trees which dominate basal
area and thus are used to determine forest type. Given that the forests of East Texas have
been heavily utilized, with removals exceeding growth from 1986-1992 (Rosson 2000),
and recalling that many of the even-aged pine stands in East Texas are very young
(Figure 5), a significant number of young forests may have been differently classified by
the FIA and NLCD.

3) *Per-pixel classification*

Classifying the earth’s surface on two slightly different scales will cause
dissimilarities between NLCD and other data, particularly in heterogeneous landscapes.
The NLCD is per-pixel classification that observes the earth’s surface 30 m at a time
(Vogelmann 1998, Vogelmann et al. 2001). The FIA, on the other hand, uses a per-plot
forest classification process, taking the stocking of the sample trees of the entire plot
(approximately 1 acre in area) into account (May 1990). Such a plot is about five times
the area of an NLCD pixel. A few large trees may spectrally define a pixel for the NLCD
as a certain forest type, placing, for example, a deciduous forest type pixel in a forest
defined as evergreen by the FIA (Figure 18). In a related problem, some counties in the
study area have no measured areas of a forest type that is in fact detected by the NLCD in
those counties. The NRI also perceives forest area in tracts much larger than 30m pixels.
Such situations raise concern that some forest type variation is not caught by the usual
statistical methods, but is observed from the NLCD’s continuous, detailed perspective.
This will be yet another factor to consider when observing some of the state and county-
level discrepancies in forest type area estimates.
While useful for producing more detailed results than that provided by the NRI or FIA, the satellite instrument's literal, rather than statistical, interpretation of the forested landscape in this way may at times work to a disadvantage. While not the result of a true error, the NLCD's 30m resolution view of the landscape may lead to some misleading results. For example, applying carbon storage values for forests to small, "forested" residential pixels (Figure 12) will lead to an overestimation of the carbon storage calculated by the NLCD method; it is unlikely that a residential neighborhood "forest" pixel stores as much carbon as an actual forest pixel; a recent study by Nowak and Crane (2002) determined urban "forests" store 25.1 Mg C/ha, compared with the approximately 53.5 Mg C/ha national forest average (Birdsey and Heath 1995).

The distinction between carbon storage in residential areas and true forests remind us that forests, even if they are in the same category, can store very different amounts of carbon. Using broad carbon storage estimates, therefore, may become a problem when using the NLCD carbon storage method.

Calculated carbon storage from FIA biomass estimates

Because the FIA is the national and most complete standard by which forest types, forest biomass, and other figures may be extracted, it is the appropriate source for carbon storage estimates and future predictions. Yet the use of a small number of general allometric equations and broad area, density, and carbon-content factors—generalized further by the broad regional averaging used here—mask site and treatment affects to volume, biomass, or carbon content (Miller and Hartsell 1992, Jenkins et al. 2001). Additionally, it has been suggested (Brown and Schroeder 1999) that some forests hold more carbon than is estimated by the FIA.
The act of roughly averaging carbon storage data, even if specific to a forest type, does not take into account differences between various plots or regions that will differ in growing conditions, and, therefore, carbon content. A recently-recovering forest, for example, will hold less carbon than one that has never been logged, and a loblolly plantation on a dry, sandy rise will hold less carbon than a plantation on a wetter site. Supporting this, previous work by Harcombe (1998) has shown that aboveground carbon content in East Texas can vary 50% over on either side of the mean. This high variability is also evident in Table 6. Such variability has also been seen in forest work conducted in the Appalachians, Australia (Tajchman et al. 1996) and in carbon sequestration research performed in Mexico (de Jong 2001). Plot-to-plot variability is likely one reason why the carbon storage estimates for some counties differed so widely between the very NLCD method used here and more specific FIA methods.

Such high variability is well-recognized in the FIA dataset. As stated earlier in this section, FIA analysts note that county-level biomass estimates from the FIA carry a sampling error commonly between 10-20%, although the error can be as much as 88% (Rosson 1993).

Interestingly, forests may store more aboveground carbon than we think. There is, for instance, some uncertainty about the allometric equations used by the FIA to convert diameter to biomass and carbon content. Previous studies (Brown and Schroeder 1999), have produced alternative estimates of carbon content in eastern deciduous forests, concluding, for example, that eastern forest biomass is 35% higher than reported in FIA perhaps because different species’ carbon allocation or growth patterns will vary over large range of sites, or because sample populations from which allometric equations are
derived may be different from the populations to which the equations are applied (Brown and Schroeder 1999, Pacala et al. 2001).

**The NLCDxFIA method**

In spite of the limitations considered above, the advantage of using NLCD and FIA data as they have been used in this chapter is not necessarily in its accuracy or precision, but in its comprehensiveness. No other national dataset—satellite or survey—is available to describe land cover so comprehensively, and at such resolution. Little information exists in the NRI about forestland resident in parks, preserves, or other land-use classifications, while the FIA is currently limited only to well-stocked forestlands. Subsequent land cover classifications generated by the MRLC (such as the MRLC 2000) promise to be increasingly accurate, and methods such as that described above should be in place to fully utilize these products. Furthermore, the NLCD provides high resolution, georectified data, manipulatable in GIS context. Layering additional GIS data, such as soil survey (e.g., SSURGO) or elevation models (e.g., digital elevation models), might help improve the accuracy of carbon storage calculations, or aid the inventory of soil carbon.

Furthermore, regardless of any differences, the correspondence between the FIA and NLCD is much better than reported in a recent study by Mickler, Earnhardt, and Moore (2002), who wrote that the differences between the FIA and NLCD state-level area estimations varied by -75%, 55%, 45%, and 31% for the deciduous, evergreen, and mixed forest classes. Most of this difference likely lies in the fact that these authors compared the forest areas calculated by the NLCD for the entire state of Texas against the forest areas calculated for the only 43 FIA counties of East Texas (Mickler et al.
2002). Additionally, they may not have reclassified FIA data to fit the NLCD 75% thresholds, as was done here.
CHAPTER IV. A SCIENTIFIC AND POLITICAL CONTEXT

This thesis has shown that land use change in the forests of East Texas, just as those throughout the South, can create a carbon sink. It has been shown in this thesis that the exact strength of that sink is uncertain. Poorly-understood processes, like soil carbon flux, will also affect the strength of carbon sinks in East Texas and the South. Nevertheless, the mitigative powers of a forest sink resulting from land use change can measurably offset fossil fuel emissions.

Section 4.01 Aspects of Land-use Change

Timber market and growth models such as the Subregional Timber Supply (SRTS) model have predicted continuing increases in pine plantation area (Prestemon and Abt 2002) while total forest area stabilizes or decreases (Wear and Greis 2002, Birdsey and Heath 1995). This shift will have two major consequences in terms of carbon storage. First, natural forest systems tend to retain and store more soil carbon than plantation systems (Knoepp and Swank 1997, Weaver et al. 1987). As native forest area is replaced by plantation area, the soil carbon stored in natural forests will be lost. Secondly, more above-ground carbon is stored in natural stands than in average plantation stands. According to the information in Chapter II of this thesis, pine plantations stored 41.9 Mg C/ha over their lifetimes when on a 30-year rotation. The 1992 FIA data indicate natural, unplanted stands in Texas store, on average 60.3 Mg C/ha (some stands held over 150 Mg C/ha). If Texas experiences the increase in plantation area predicted by Prestemon and Abt (2002), by 2040 Texas will hold over 1.5 million hectares of pine plantations (about twice the current plantation area), potentially generating a loss of 20 million Mg C over that part of the state (Table 6). In terms of
$20/Mg carbon credits, this is worth about $400 million, or 5% of the 2000 agricultural GSP for Texas. This same loss would also set back Kyoto attainment goals, where they in affect, by 7% per year.

Table 6. Projected plantation area in 2040 and potential effects on carbon storage. The area distribution of forest types is assumed to be the same in 2040 as in 1992. Total forest area is assumed to stay the same. Numbers may not add due to rounding.

<table>
<thead>
<tr>
<th></th>
<th>Area (thousands ha)</th>
<th>Carbon (thousands Mg)</th>
<th>Area (thousands ha)</th>
<th>Carbon (thousands Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plantation</td>
<td>717</td>
<td>25,797</td>
<td>1,537</td>
<td>55,360</td>
</tr>
<tr>
<td>Natural Forest</td>
<td>3,805</td>
<td>229,636</td>
<td>2,984</td>
<td>179,966</td>
</tr>
<tr>
<td>All Types</td>
<td>4,522</td>
<td>255,433</td>
<td>4,522</td>
<td>235,327</td>
</tr>
</tbody>
</table>

Forest management and land use change also affects the soil component of the forest carbon system, and that is the subject of the next section.

**Section 4.02 Soil carbon**

In the forests of the United States, soils store, on average, 59% of total forest carbon (Birdsey 1992a). Yet as significant a component as soil carbon might be in a forest ecosystem, estimates have been difficult to establish (e.g., Currie et al. 2003, Heath et al. 2003b). Forest attributes such as volume and biomass help determine leaf litter loading, and, hence, carbon flux into the soil. Belowground organic matter inputs—from fine and coarse root biomass—add carbon to soil, and Trettin and Jurgensen (2003) suggest that in wetland forests, mycorrhizal fungi biomass may also be important as a carbon input to soil, since those fungi tend to be prevalent in such habitats. Abiotic factors such as temperature and flooding affect decomposition rates and carbon flux into and out of the soil; warm temperatures accelerate decomposition (Currie et al. 2003). Flooding slows decomposition, but occasional flooding can provide an ecosystem with enough moisture to actually accelerate decomposition (Trettin and Jurgensen 2003,
Currie et al. 2003). Because they tend to experience both flood-induced periods of anoxia and accelerated decomposition, forested wetland soils are poorly understood and insufficiently modeled (Trettin and Jurgensen 2003, Changsheng Li, University of New Hampshire, personal communication). This fact is significant since there are 26 million hectares of wetland forests in the United States (Trettin and Jurgensen 2003). These forests might hold a very large, but heretofore unrecognized, carbon sink capacity.

Land use history also affects soil carbon storage. A forest that is regularly clearcut and prepared with heavy equipment is likely to lose much more carbon than one that is not (Currie et al. 2003). During the first 14 years of reforestation after tilling, for example, the average content of soil in planted pine plantation stands has been found to be 16 Mg/ha less than that in never-tilled longleaf soils (27 Mg/ha) (Markewitz et al. 2002). Yet while a forest established over an oldfield that experienced years or decades of plowing may contain less carbon, that carbon will be gradually gained as the forest matures (Currie et al. 2003). In the reforestation projects considered in this chapter, therefore, a great amount of soil carbon may be stored in addition to aboveground carbon, making the apparent sink strength for a reforestation project even larger.

Section 4.03 Carbon sequestration in East Texas Forests

Aboveground carbon storage in East Texas can occur in pine plantations, but greater aboveground carbon storage may be found in reforestation and forest preservation processes in natural forests. Forests sequestering carbon also provide opportunities for carbon credits and habitat.

Houghton et al. (1999) notes that changes in land use after 1945 caused the accumulation of $2 \pm 2$ Gt of carbon, largely as a result fire suppression and forest growth
on abandoned farmlands. As shown here, continuing to return agricultural land to forest could yield an additional 98 million Mg of aboveground carbon storage in East Texas. In the South as a whole, assuming the national carbon storage average of 53.5 Mg C/ha (Birdsey and Heath 1995), and the presence of over 10 million ha of open agricultural land in the South, at least 541 million tons C could be sequestered aboveground. This storage could be even greater, since the productive forests of the South could potentially be managed to store much more than 53.5 Mg C/yr. In 1992, for example, the average East Texas natural forest carbon storage was 60.3 Mg C/ha. Furthermore, prudent forest management and time will permit soil carbon to build up, effectively doubling (or more) the carbon storage noted here (Birdsey 1992a, Birdsey and Lewis 2002).

One of the best CO2 mitigation methods may not only involve seeking open lands to reforest, but also seeking forest to preserve. Preserving forests will have two benefits. First, it reduces the amount of CO2 released from land-use change: assuming the national aboveground carbon storage average of 53.5 Mg aboveground C/ha (Birdsey and Heath 1995), the South could release 262 million Mg C by 2020 to the atmosphere because of urbanization.\textsuperscript{i} Put in Kyoto terms (a 7% reduction in CO2 emissions below 1990 levels), preventing this loss of forest to urbanization alone would provide nearly a year’s worth of compliance for the entire country.\textsuperscript{ii} Secondly, many Southern forests continue to accumulate aboveground carbon and soil carbon as they recover from prior harvesting. Existing forests, therefore, are likely sinks. The national accretion rate for recovering forests (approximately 65% of total forest area) has been estimated at 1.4 Mg C/ha/yr (Houghton et al. 1999). Accretion rates in East Texas and throughout the South could be

\textsuperscript{i} As the South continues to experience urban growth, forest area will continue to be lost, by as much as 7%, or 4.9 million ha, by 2020 (Wear and Greis 2002).
\textsuperscript{ii} Assuming 1999 fossil fuel emissions of 1.5 Gt C (Marland et al. 2002).
even higher; the NEP there, as in the rest of the South, is high, and the forests are relatively young (Rosson 2000, Marks and Harcombe 1981, Wear and Greis 2002, Sheffield and Dickson 1998).

By encouraging forest reversion and protection, carbon credit programs offer both mitigation and collateral environmental benefits. Markets like the CCX (Chicago Climate Exchange) are beginning to serve as mechanisms for the Bush Administration’s voluntary climate change program. Participation in the CCX, a pilot program until 2007, includes a voluntary commitment to reduce greenhouse gas emissions by 4% over the next four years, 1% per year starting in 2003 and ending in 2006. The reductions may occur through conservation efforts, reforestation, and carbon credit purchasing through the exchange (Anon 2003). Preserving, expanding, and sustainably managing forests to maximize carbon storage could also help watersheds and increase biodiversity.

Unfortunately, sequestration is jeopardized by climate change, itself. Elevated temperatures, species shifts, and climate changes are certain to affect forests’ ability to store carbon. Elevated CO₂ and nitrogen deposition have been predicted to increase forest biomass—and therefore, leaf litter—while land-use change is certain to cause great losses or gradual gains in soil carbon as the soil is plowed or allowed to lay fallow and recover. Species shifts, besides affecting aboveground carbon storage in trees (Iverson and Prasad 1998, LaDeau and Clark 2001), can affect leaf litter quality and the availability of key forest floor decomposers which affect carbon and nutrient flux into the soil (Currie et al. 2003). Climate change might dry some areas and deluge others, changing decomposition rates and species distributions (Currie et al. 2003). Consequently, a comprehensive approach to climate change will require fundamental
changes in current energy technology to achieve a reduced reliance on carbon-based fuels. Nevertheless, carbon sinks have the potential to offset emissions, and so sequestration warrants consideration as an interim strategy for slowing climate change.
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Figure 1. Annual forest area change in the South
From 1970 to 1990, the average annual change in forest area for the southern United States, except Kentucky. Data taken from USDA Forest Service Southern Forest Resource Assessment, 2002.
Figure 2. Historical forest area in the South
Total area of forested land by state and year in the American South. Note time increments are not equally spaced. Data taken from a compilation completed by Wear and Greis (2002). The area estimate for Texas is significantly higher than the Forest Service 1992 FIA forest area estimate of 4.8 million hectares. This difference is due to the difference in measured area; the FIA only measures the area in 43 counties of Texas, whereas the report used by Wear and Greis (2002) for the Texas data included the entire state (Smith et al. 2001).
Figure 3. East Texas
The East Texas study area and its relationship to the rest of the state.
Figure 4. Texas FIA survey counties
The 43 counties of East Texas, and the two FIA regions: Southeast and Northeast.
Figure 5. East Texas plantation age distribution

Plantation age distribution in East Texas according to the latest FIA survey (1992).

Plantation Age Distribution

Per 1992 FIA Survey

Hectares in Age Class

not recorded  5  15  25  35  45  55

Age Class (years)
Figure 6. Plantation study region
Study region for Texas plantation study, including those parishes in Louisiana referenced for additional plantation data for the 35-, 45-, and 55-year age classes. The Louisiana parishes of Allen, Cameron, and Jefferson Davis were not provide additional data.
Figure 7. Carbon storage for East Texas FIA plantation plots, 1992
Note the wide spread on both sides of the mean due to the presence of “contaminant” individuals. The presence of young, large plantations on the graph is most likely a result of measurements on new plantations that we not clear-cut before planting. By age 6, the success of the plantation would have been determinable, and the large trees on the site would have been cut (Dr. Weihuan Xu, Texas Forest Service, personal communication).
Figure 8. Land use change in the South
From 1982 to 1992, changes in percent of (A) urban and (B) forest land uses per county (Wear and Greis 2002).

Figure 9. Land cover/use in East Texas

Land uses in East Texas according to the 1992 NRI by the Natural Resources Conservation Service, including the "forest-fringe" counties of Orange, Jefferson, Chambers, Liberty, Harris, Waller, Grimes, Madison, Houston, Leon, Anderson, Henderson, Van Zandt, Franklin, and Red River.
Figure 10. Some FIA forest counties contain prairie regions
Several counties monitored by the FIA naturally contain large areas of prairie (Texas Blackland Prairie, Texas Claypan Area, Gulf Coast Prairies and Gulf Coast Saline Prairies).

MRLA, state, and county layers derived from National Resources Inventory (NRI) GIS coverages available at www.nrcs.usda.gov/technical/land/about/maps/coverages.html, last accessed 18 March 2003.
Figure 11. Land cover/use in East Texas

Land uses in East Texas according to the 1992 NRI by the Natural Resources Conservation Service, excluding the “forest-fringe” counties of Orange, Jefferson, Chambers, Liberty, Harris, Waller, Grimes, Madison, Houston, Leon, Anderson, Henderson, Van Zandt, Franklin, and Red River.
Figure 12. Broad land cover/use in the United States
Much of the southern landscape of the United States is occupied by forest, pasture, and cropland. Much of the pasture and cropland can support carbon-storing forests.
Figure 13. Western Coastal Plan and Western Gulf Coast Flatwoods distribution.
The two forested MRLAs of East Texas are the Western Coastal Plain (about 14 million ha in total area) and the Western Gulf Coast Flatwoods (about 1.7 million ha in total area).
Figure 14. Rice University according to the NLCD

NLCD image of Rice University area with road and water overlays, taken from the USGS Seamless Data Server. Note that many areas around campus are classified as “mixed forest” and “pasture/hay.”

Figure 15. Forest area: FIA vs. NLCD
How the FIA and NLCD compare in estimating a) total forest area, b) deciduous forest area, c) mixed forest area, and d) evergreen forest area in East Texas. Regressions forced through the origin.

\[ y = 0.9434x \]
\[ R^2 = 0.9759 \]
Deciduous Area County Estimates:
NLCD vs. FIA

\[ y = 0.7871x \]
\[ R^2 = 0.6066 \]
Evergreen Area County Estimates:
NLCD vs. FIA

\[ y = 1.0608x \]

\[ R^2 = 0.841 \]
Mixed Area County Estimates:
NLCD vs. FIA

\[ y = 0.9593x \]

\[ R^2 = 0.7241 \]
Figure 16. Carbon storage: FIA vs. NLCD

FIA carbon storage estimates per county vs. carbon storage estimates using the NLCD accounting method in a) total forest aboveground carbon storage, b) deciduous aboveground carbon storage, c) evergreen carbon storage, d) mixed carbon storage. Regressions are forced through the origin.

18.a)
Deciduous Aboveground Carbon County Estimates:
NLCD Method vs. FIA

\[ y = 0.7192x \]
\[ R^2 = 0.5811 \]
Evergreen Aboveground Carbon County Estimates:
NLCD Method vs. FIA

$y = 1.0224x$
$R^2 = 0.7332$
Mixed Aboveground Carbon County Estimates: NLCD Method vs. FIA

\[ y = 0.8885x \]
\[ R^2 = 0.6273 \]
Figure 17. Open lands in the East Texas forest landscape

An example of non-forested open agricultural areas (Pasture/Hay) in the otherwise heavily-forested northern sections of Tyler, Jasper, and Newton counties near B.A. Steinhagen Lake. Other land cover types in the region that are not visible here include Urban/recreational grasses, Grasslands/herbaceous, Bare rock/sand/clay, and others. Those tracts labeled “transitional” are likely recent clearcuts (Stephen Howard, USGS, personal communication).
Figure 18. NLCD forest heterogeneity
A predominantly evergreen patch of forest just south of Sam Rayburn Reservoir in Angelina County, Texas is interrupted by pixels of other forest and land-cover types. The smallest-sized squares are each 30-m pixels.

Map of a section of Angelina County taken from the NLCD dataset; area shown is centered at approximately 31.14°N -94.31°W, just south of Sam Rayburn Reservoir. Map generated using ArcView 3.2.