ABSTRACT

LIU, SHAN. Estimating the Potential Impact of Carbon Markets on North Carolina Forests. (Under the direction of Dr.Abt).

Several studies have examined the theoretical aspects of determining the optimal carbon rotation. This paper explores the tradeoff between timber and net carbon sequestration in managing representative forest management types in North Carolina. Under conservative assumptions regarding the social benefits of carbon storage, optimal rotation periods are extended depending on the forest type, carbon price, interest rate, and emission penalty under consideration. Analysis shows when carbon price is low the extension of the joint timber-carbon rotation are similar among DOE, CCX, and VCS protocols; when carbon price is high, the joint rotation extends longer under DOE protocol than the other two protocols, especially in the lowland hardwood forest type. Results suggest that such joint strategies could be financially attractive. Sensitivity analysis is used to examine the effects of changes in financial parameters on landowner returns and optimal management. Under most assumptions, our findings indicate that including carbon sequestration in forest management increases returns but leads to only marginal changes in rotation length.

Estimating the Potential Impact of Carbon Markets On North Carolina Forests

by
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DEDICATION

This thesis is dedicated to my dearest parents，Weiju Zhang and Wenzhang Liu. My appreciation to them is far beyond words. I would like to put some Chinese here so that they can read them.

我最最亲爱的爸妈妈，我要把我的硕士毕业论文献给您们以表达我对您们深深的感激之情。谢谢您们一直在我的身边支持我帮助我！

BIOGRAPHY

Shan Liu was born and grown in Dalian, a popular seaside city in the northeast of China. She enrolled in Beijing Forestry University when she was 19 years old and got her Bachelor degree in Science which was Major in Forestry in July 2008. After that she came to North Carolina State University in Raleigh, NC, US to pursue her graduate studies. She obtained her Master of Science degree in Forestry, with a minor of Statistics that ended in December 2009.

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Finally, I am deeply grateful to my parents, my aunt and uncle who have been giving me unconditional love and constant support all my life, my fiancé Liang Yu who has been always be there for me, my dear friends Liwei Lin, Xiaoyu Zhao, Minzhen Zhang and many others. I would never have finished without their physical, emotional, and spiritual support.

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Chapter 1

Introduction

Global warming has become a widespread environmental concern. Human activities have changed and are continuing to change the concentrations of GHG’s in the atmosphere notably carbon dioxide (IPCC, 2007). The EPA has recently started the regulatory process to propose declaring that carbon dioxide and five other greenhouse gases as pollutants in April 2009, in response to a federal court ruling. A formal endangerment finding would obligate the agency to regulate GHGs under the Clean Air Act[1]. Even through the United States is not a Kyoto signee, carbon cap and trade legislation is currently being considered in Congress.

As a result, a number of different of carbon accounting registry and program rules have been proposed to track and provide carbon offsets. Pricing carbon uses market forces to both slow down the speed of climate change and to help society adapt to a carbon neutral

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[1] VanNess Feldmen Weekly Climate Change Policy Update, August 24, 2009

economy (Stern 2008; Metcalf 2009). The major focus for this effort is to reduce our GHGs emissions, especially carbon dioxide (Tucker 1995).

Forests are the largest natural absorbers of CO_2 which humans can manage by reducing deforestation, by increasing reforestation, and by adapting silviculture to enhance carbon dioxide sequestration (Dixon 1994; Malhi *et.al* 2002) . However, the IPCC estimates that even if such a program were maximized by 2050 only 12 to 15 percent of the emissions (from the burning of fossil fuels) to that date could be taken up; thereafter, the forest would have to be carefully managed and replaced when harvested. In the U.S. South, forests cover most of the landscape, support an important industry, and also have a significant role as a carbon sink.

The role of forestry in carbon accounting is pivotal. There is the potential for reforestation and appropriate harvesting regimes to sequester additional carbon in forests. This could create additional revenue for forest owners, thus providing an incentive to encourage careful management of the forest resource. Figure 1.1 describes the potential global impact of forest management.

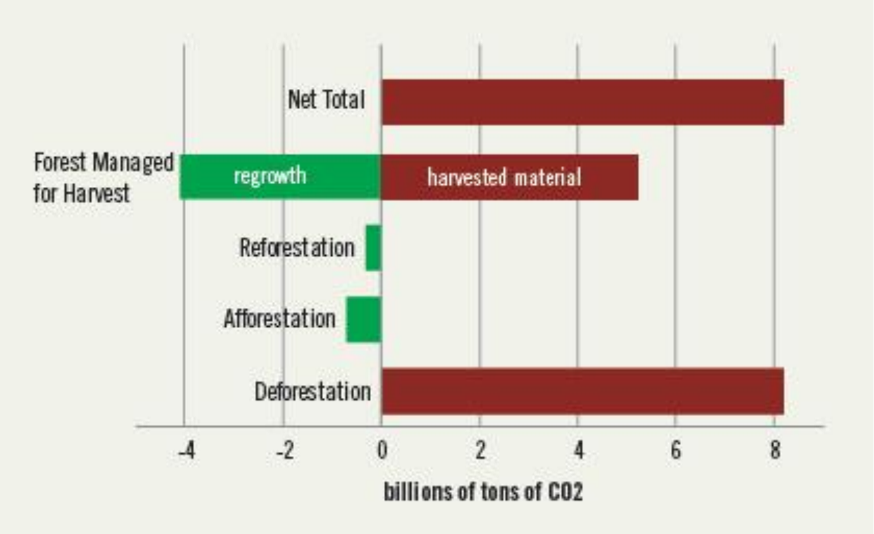

Figure 1.1 Annual emissions and absorptions of CO_2 from land-use change in forestry. Source: EarthTrends, 2008; using data from Baumert *et.al.*, 2005. Available at www.wri.org.

Carbon offsets are created by reducing emissions or increases in sequestration of GHGs produced by one entity to compensate for emissions produced by another entity (Galik *et al*., 2008), and it has been taken up by the nongovernmental sector and the private sector to enable individuals and businesses to reduce their carbon footprint. Since the late 1990s, a number of companies have emerged to serve this niche market by funding and managing projects in renewable energy, energy efficiency, and forest restoration.

Since carbon offset markets have begun to develop, forest landowners have an economic incentive to consider carbon sequestration in their silvicultural decisions. However, a variety of national and regional GHG initiatives including forest offsets have emerged with complicated rules and policies to estimate carbon (Kollmuss, 2008).

The global dynamic and regulation of CO_2 emission into the atmosphere by fossil fuel combustion and land-use change are inadequately understood (Dixon *et.al*, 1994). Carbon accounting in forestry requires careful estimation of increments in the various carbon pools over time. If the trees are harvested then life cycle analysis of the resulting products would be necessary to track carbon emissions over time. In this analysis we define a carbon emission factor that we can use to simulate the effects of different carbon emission accounting protocols. We define an "emission factor" as the proportion of the accumulated carbon income that must be paid back at harvest. The net amount of carbon sequestered or emitted is calculated for every year and then consolidated into a present ton-equivalent metric similarly to the approach used in the analysis of Richards and Stokes (2004).

The purpose of this paper is to explore the potential affect of carbon offsets on forest management in North Carolina. There are three objectives:

1. Use USFS Forest Inventory Analysis (FIA) North Carolina plot data to estimate empirical carbon yield curves for the major forest types.
2. Use these estimates along with assumptions about prices (timber and carbon) , interest rates, and emission factors to measure the potential impact on forest rotations.
3. Evaluate the impact of proposed carbon offset protocols on rotation.

Chapter 2

Literature Review

Human activities such as transportation or electricity generation or altering land and vegetation release GHGs into the atmosphere. Noticeably, 80% of the total greenhouse gas emissions of the U.S. are related specifically to carbon dioxide exchange (Health 2005). Environmental concerns in general, and issues regarding climate change in particular, are moving from the realm of corporate Environment, Health, and Safety personnel, into that of corporate financial strategy. Carbon sequestration is becoming an important land management objective (Health, 2005). A variety of drivers influence carbon offset markets, such as regional, national and international regulations, which require producers and consumers to emit fewer GHGs, or to pay a price.

The Kyoto Protocol grew out of the United Nations Framework Climate Change Convention (UNFCCC) , adopted at the Rio Earth Summit in 1992 and first Conference of the Parties (COP) hold in Berlin in 1995 until 1997 the participating countries agreed to the Kyoto Protocol. Under the Kyoto Protocol, caps are accepted by the industrialized countries. The decision was made to exclude emissions from tropical deforestation. Many believed that the challenges and uncertainties inherent to quantify forest sector emissions would weaken the overall strength of the climate regime, and developing countries worried that economic development would be threatened by reducing deforestation (Davis, 2008). Accounting challeneges in the Kyoto Protocol and climate legislation regarding the tradeoffs between renewable energy and carbon sequestration are currently being debated (Searchinger *et.al*, 2009).

The Intergovernmental Panel on Climate Change (IPCC) predicts that forest will continue to be converted to agriculture in tropical countries causing large carbon emissions over the next few decades (IPCC, 2007). Between 2000 and 2005, roughly 13 million hectares of forest disappeared each year, with largest losses occurring in the biologically rich tropical forests of the developing world (FAO, 2005). However, the threat of climate change has created a new imperative—and renewed hope—to protect the values and service rendered by tropical forests. Yet the forestry sector was largely excluded from Kyoto Protocol’s first commitment period. The Intergovernmental Panel on Climate Change (2007) estimates that deforestation contributes 15-20 percent of global greenhouse gas emissions. With negotiations underway for a post-Kyoto agreement set to start after 2012, reduced emissions from deforestation in developing countries, popularly known as REDD, has emerged as a key issue (Davis, 2008).

Several carbon offset markets have recently emerged. There are five distinct offset accounting schemes:

- U.S. Department of Energy (DOE) 1605(b)
- Chicago Climate Exchange (CCX)
- Voluntary Carbon Standard (VCS)
- Georgia Forestry Commission (GFC) Carbon Sequestration Registry Project Protocol
- Climate Action Reserve (CAR) Forest Project Protocol

Each protocol has its own set of strengths and weakness, many authors evaluated the protocols by type, baseline defintion, additionality, pools included and reverse-uncertainty-leakage (Galik et al., 2008). Protocols 1605(b) and GFC fail to address issues such as leakage and risk, but provide information to assist landowners in carbon accounting. The other protocols provide more robust carbon accounting schemes, with most directly consideration of leakage, reversal and uncertainty. Mandatory buffer set-asides to address reversal risk are included or contemplated under CCX and VCS, as are deductions for leakage (VCS), and uncertainty (CCX, CCAR) (Galik et al., 2008).

Numerous studies have been conducted to assess the potential methodologies for estimating carbon sequestration in forests. Smith *et al.* presented the basic approach of the methods and estimated carbon stock based on FORCARB and FIA data from forest inventory. Forest inventory techniques are based on sample designs with a sound scientific basis. The method estimates net carbon flux in forests at large scales. Since the assessments were generally applied to areas extending form tens to hundreds of thousands of hectares, the precision of these estimates in carbon pools varies depending on location. Health and Birdsey (1993), Plantinga and Birdsey (1993) and Heath *et al.* (2001) presents forest carbon budgets for the United States using FORCARB. The well-known FORCARB forest carbon model (Health and Birdsey, 1993; Plantinga and Birdsey, 1993) accounts for carbon in U.S. forests and forest products and has been used to examined uncertainty in U,S, forest carbon budgets (Heath and Smith ,2000). FORCARB produces separate estimates for all forest carbon pools such as live trees, down dead wood and soil organic carbon and so on, which is also used in this analysis.

The Carbon Online Estimator (COLE) is a useful carbon estimator tool available on line, which uses data from USDA Forest Inventory and Analysis (FIA) plots to establish numerous tables about carbon pools of forest in the format used in (Smith et al.,

2006) .Carbon Online Estimator (COLE) used USDA Forest Service Forest Inventory and Analysis (FIA) and FORCARB data and it has been used to examine forest carbon characteristics of regional area in the United States. The methods in our analysis to establish carbon pool model are similar to those in COLE.

Research is also being done on the carbon costs and prices. Richards and Sotkes (2004) suggest that it may be possible to store up to 2 PgC per year for \$10-\$150 per tone C. One reason is that costs may vary considerably across regions. Further, while regional studies often benefit from having detailed spatial data, they potentially ignore an important issue necessary for calculating net carbon benefits: leakage. Leakage occurs when efforts to sequester carbon in one place may cause forest owners to release carbon in another place. Ignoring leakage can cause studies to underestimate the total costs of carbon sequestration (Murray et al., 2004; Sohngen and Brown, 2004). Global substitution is also important because forestry can shift harvesting from one region to another and from one level of management intensity to another.

Another issue discussed in Richards and Stokes (2004) is that some studies have failed to make the distinction between setting aside carbon for a year and setting aside carbon permanently. Sohngen and Mendelsohn (2003) claimed one-third of the carbon that should be stored this century should be set aside by 2050. Lengthening a rotation increases carbon storage for a limited period of time. Setting aside old growth in a conservation area permanently stores carbon if that area would have been harvested otherwise harvested. Bin and Sohngen examines the potential role of forest set-asides in three global carbon sequestration policies. Results show that reserving forests from timber harvests and land-use conversion may provide benefits but also lead to significant leakage.

As an alternative, a number of authors have applied dynamic forestry models to estimate carbon sequestration costs. Adams *et al*. (1999) examine potential sequestration in the United States using a dynamic model of the forestry and agricultural sectors, and McCarl and Schneider (2001) update the analysis by including additional options like agricultural soil carbon sequestration and biomass energy production. Sohngen and Mendelsohn (2003) use a dynamic optimization model of timber markets to assess global carbon sequestration potential across a range of prices. Because the model is dynamic, it can capture important adjustments in the forest stocks (and consequently carbon stocks).

Determining the level of carbon stocks in forest ecosystem has become a concern of governments, businesses, and many organizations. Many studies showed that regulating the rotation length of forests is an effective way to manage the carbon budget of forests and incentives for carbon sequestration could lead to longer rotation period (Adams et al., 1999; Murray, 2000; EPA, 2005; Sohngen, 2008). These studies examine the relationship between carbon and timber rotation length. These studies were based on representative species or aggregated forests (Liski et al., 2001; EPA, 2005). Representative species are only useful to provide limited information for policy makers and forestry community to manage specific forest offset project rules. Large-scale modeling study can provide information on the potential sequestration across landscape but are less useful for specific projects (Sohngen, 2008).

Chapter 3

Study Area and Data

3.1 Study Area

The study area includes the four US Forest Service (USFS) Forest Inventory and Analysis (FIA) survey units in North Carolina as shown in Figure 3.1(for this analysis the northern and southern coastal plain were analyzed separately). North Carolina’s forests are among the state’s most valuable natural resources, not only in terms of their beauty, their important role in environmental health and wildlife habitat, but also in terms of their contribution to the state’s economy. With 17.6 million acres of timberland, North Carolina ranks fourth in the nation in the total forest acreage. Fifty-eight percent of the state is covered by forests and hardwoods, and the forest products industry contributes $3.8 billion in annual revenue to the economy. Because North Carolina’s private landowners own 90% of these forests, they play a critical role in the timber market.

Figure 3.1.1 North Carolina State and regions map
Sources: Available at www.ncforestry.org

In this analysis we considered only private ownership because federal forest management is determined by policy. As shown in Table 3.1.1, there are about 15.57 million acres of private timberland in North Carolina, of which 74.54% is non corporate and 25.46% is corporate.

Table 3.1.1 Forestland acres by private ownership in North Carolina

Private	Acres	Percentage
Corporate	3,962,538.94	25.46%
Non corporate	11,603,969.20	74.54%
Total	15,566,508.14[2]	100.00%

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[2] The total acres in Table 3.1.1 and Table 3.1.2 do not match because there are data points have information about ownership or forest management type, if certain information is missing, the software will automatically ignore it then do the calculations.

From forest management type, upland hardwood is the largest area, about 6.6 million acres, or 42.47%, followed by planted pine, natural pine, mixed pine, and lowland hardwood.

Table 3.1.2 Forestland acres by forest management type in North Carolina

Forest mgt. type	Acres	Percentage
Planted Pine	2,926,486.90	18.84%
Natural Pine	2,520,308.95	16.23%
Mixed Pine	1,810,847.21	11.66%
Upland HdWd	6,596,132.91	42.47%
Lowland HdWd	1,678,149.50	10.80%
Total	15,531,925.47[3]	100.00%

3.2 Data

3.2.1 Forest Yield-related Data

The source of the raw forest data are from the Forest Inventory and Analysis (FIA) database. This database has a uniform data structure for forestry inventories and contains extensive data on forest and site attributes such as stand age, stocking, species, diameter, and so on. FIA data are collected periodically on permanent plots across the South. The survey

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[3] The total acres in Table 3.1.1 and Table 3.1.2 do not match because there are data points have information about ownership or forest management type, if certain information is missing, the software will automatically ignore it then do the calculations.

plots are located randomly. Using standard forest measurement techniques, the height, diameter and quality of each tree is recorded.

Figure 3.2.1.1 Four FIA regionally units and locations of program offices

Sources: The Forest Inventory and Analysis Database: Database Description and Users Manual Version 3.0 for Phase 2

There are a number of geographically work units but four regionally distributed units (see Figure 3.2.1.1). The four FIA work units are named as Pacific Northwest Research

Station (PNWRS), Northern Research Station (NRS), Rocky Mountain Research Station (RMRS), and Southern Research Station (SRS). We used SRS data for North Carolina Forests.

Generally, there are nine data tables in the FIA database. We used four for this analysis: the Condition Table, the Tree Table, the Plot Table and the Plot Condition Table. The 2006 raw FIA data are used for North Carolina and then imported into SAS and R. Since there are data points share the same the plot and plot condition, so we aggregated them together as one plot data pint (See Table 3.2.2.1). Since upland hardwood is the most common forest management type, there is the largest amount of upland hardwood data points in database.

Table 3.2.1.1 FIA plots data in North Carolina.

Forest mgt. type	plots × conditions	plots
Planted Pine	522	416
Natural Pine	527	492
Mixed Pine	367	346
Upland HdWd	1311	1196
Lowland HdWd	329	302

The first step in the analysis is calculating mean volume of yield from the growing stock volume of timber in forest stands. We got the mean volume using function:

$$\mathbf{Mvol = VOLCFNET * TPACURR} \qquad \mathbf{(1)}$$

where Mvol= mean volume of a aggregated plot, VOLCFNET= net cubic-foot volume per tree, and TPACURR= the number of trees per acre. The VOLCFNET and TPACURR variables are in the FIA data base.

The mean volume (pine and hardwood) graphs of plots by forest management type are shown from Figure 3.2.1.2 to Figure 3.2.1.6.. These plots show the high variability in volume per acre and the distribution across age classes. Planted pine plots tended to be younger with higher volume.

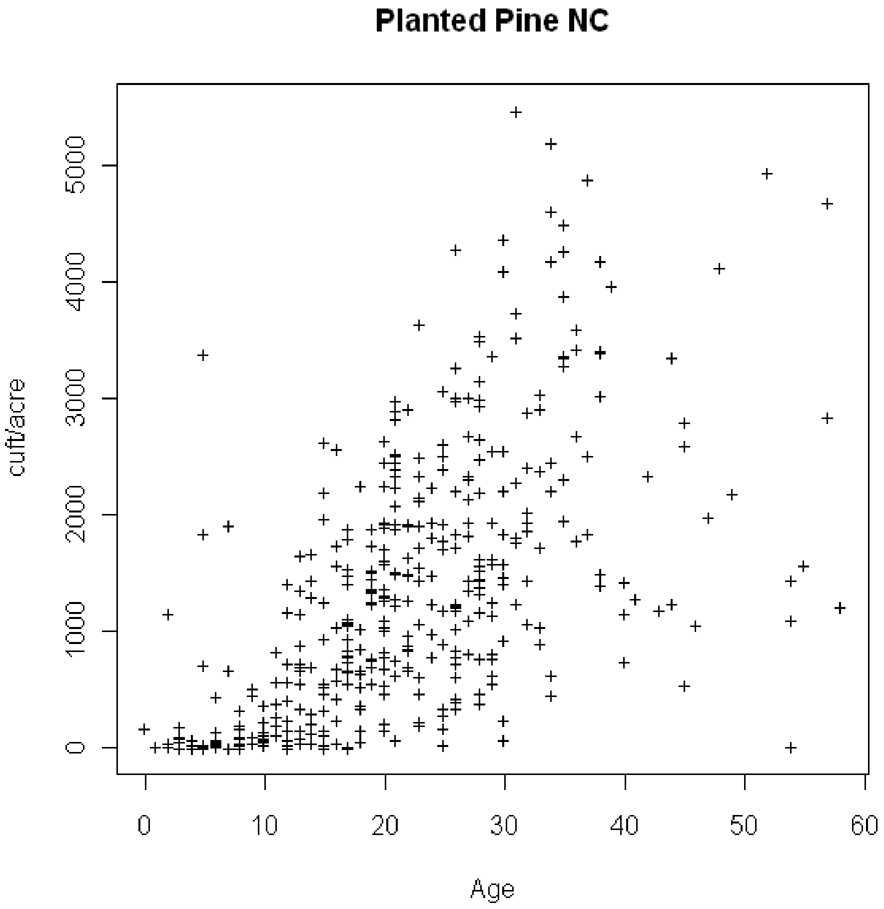

Figure 3.2.1.2 Mean volume of planted pine plots in North Carolina

We had 492 plot data points in natural pine, with ages up to more than 100 years, and with mean volume up to 7000cuft/acre.

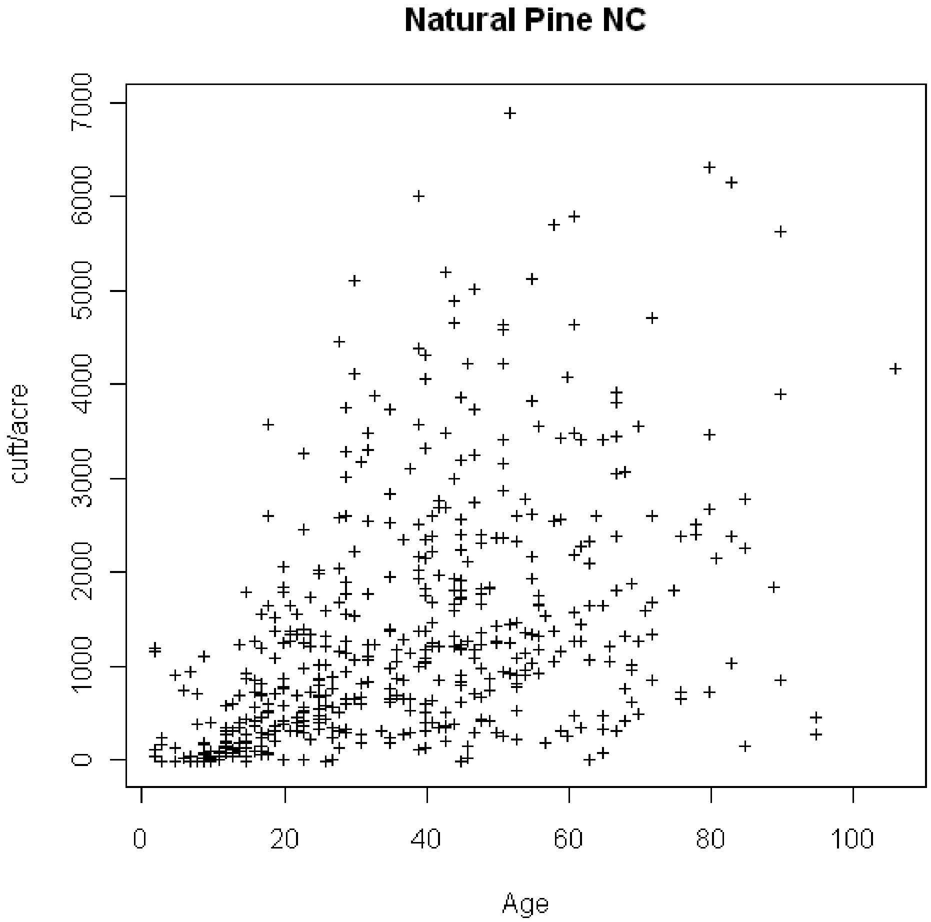

Figure 3.2.1.3 Mean volume of natural pine plots in North Carolina

There are 346 aggregated data points of mixed pine. Volumes are lower than planted pine and natural pine, most are under 3000 cuft/acre, with an average of 1500 cuft/acre.

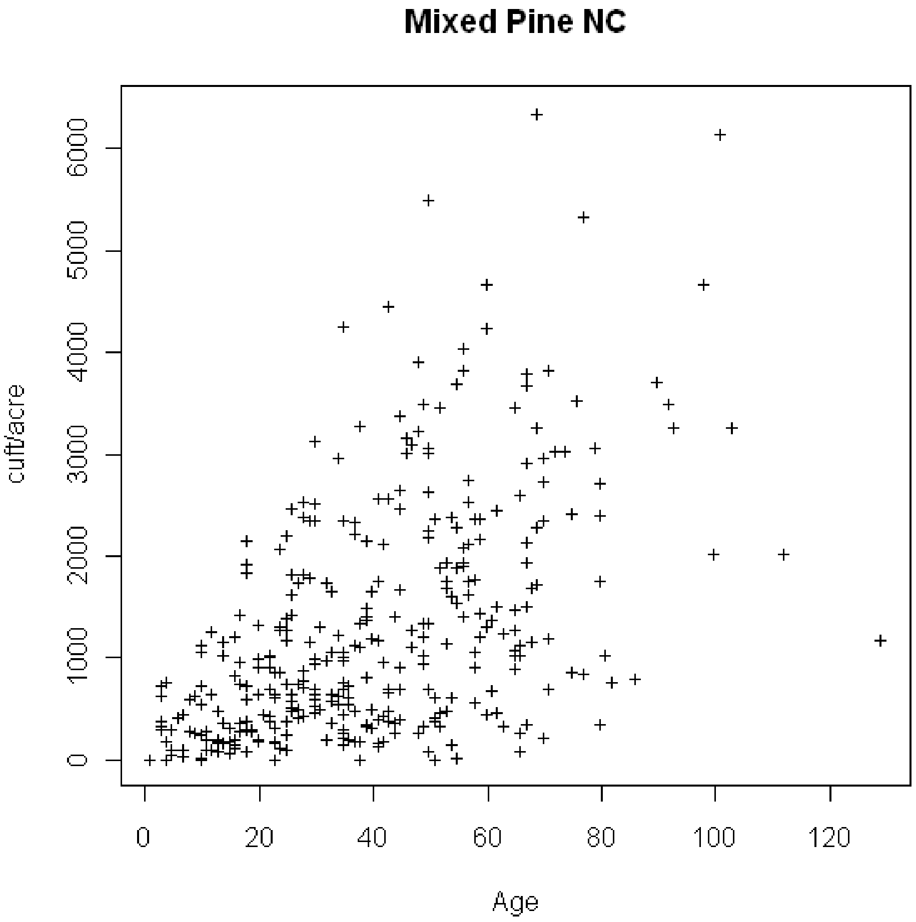

Figure 3.2.1.4 Mean volume of mixed pine plots in North Carolina

There are 1196 aggregated plots in upland hardwood, which is the largest amount of data points among the five forest management types.

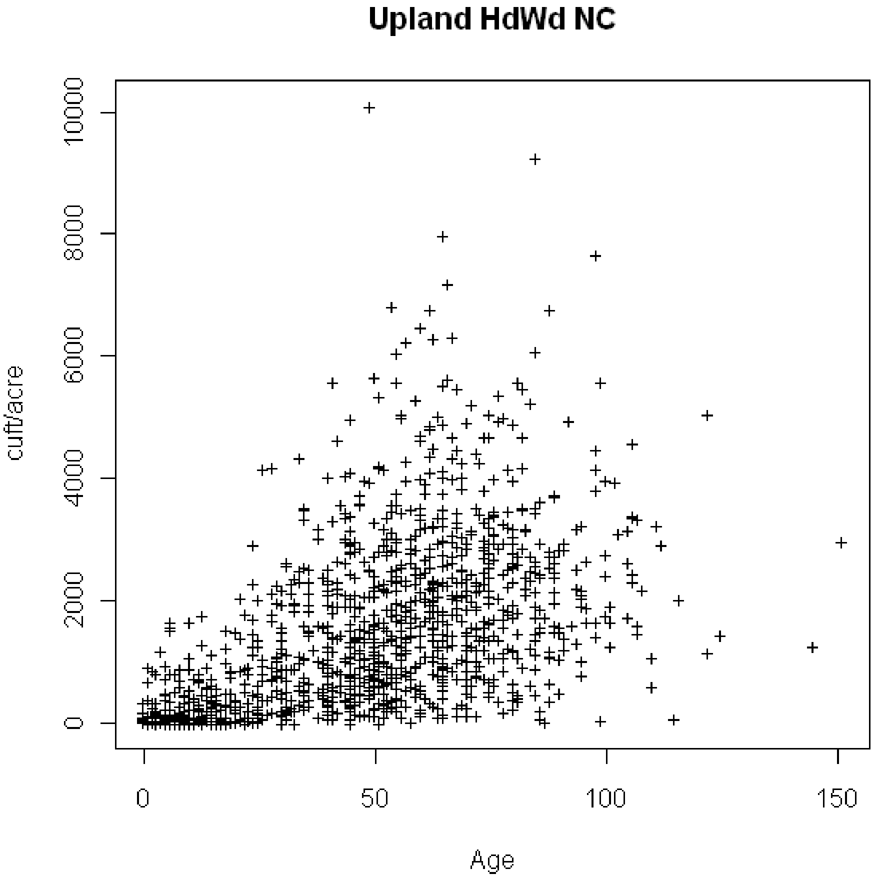

Figure 3.2.1.5 Mean volume of upland hardwood plots in North Carolina

They are only 302 plots in lowland hardwood, the least of the 5 management types. The mean volume is around 3000 cuft/acre.

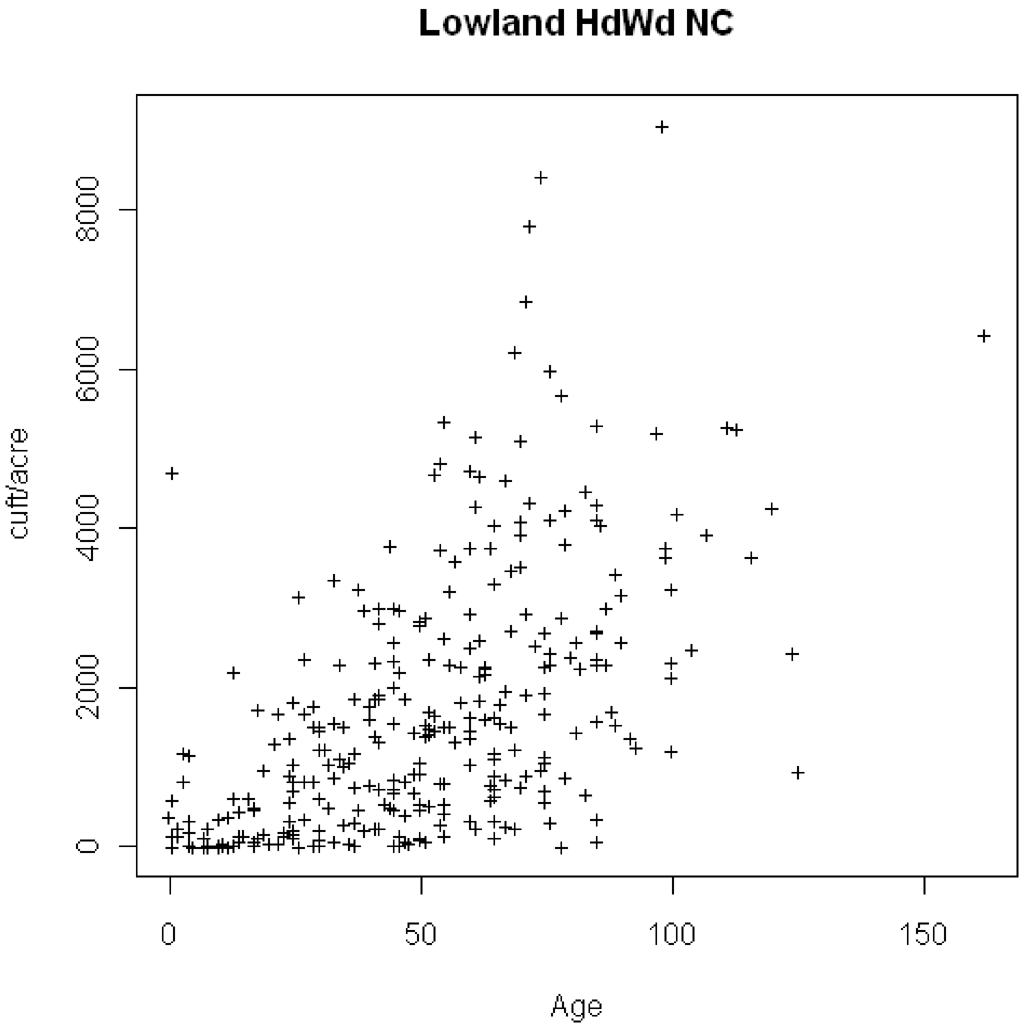

Figure 3.2.1.6 Mean volume of lowland hardwood plots in North Carolina

We analyzed the plots data in R software to estimate mean volume for every forest management type through a 100 year lifespan.

3.2.2 FORCARB Carbon Data

FORCARB is a set of tables of forest carbon stocks and carbon in harvested wood to provide basic information on average carbon change per area developed by the U.S. Forest Service (Smith *et.al*, 2006). The tables represent the average regional carbon values for that type of forest with average of mean volume. The tables in FORCARB are categorized by region, forest type, previous land use, and, in some cases, productivity class and management intensity.

In FORCARB carbon database, forest carbon is set as six representative pools: live tree, standing deadwood, down deadwood, understory, forest floor and soil, but we do not include soil carbon in this analysis because we assumed it doesn’t change with rotation. Definitions for each pool estimated in this analysis are listed in Table 3.2.2.1.

Table 3.2.2.1 Classification of carbon in forest ecosystems and in harvested wood

Carbon Pool	Definition
Live tree	Live trees with diameter at breast height (d.b.h.) of at least 2.5 cm(1 inch), including carbon mass of coarse roots (greater than 0.2 to 0.5 cm, published distinctions between fine and coarse roots are not always clear), stems, branches, and foliage.
Standing dead trees	Standing dead trees with d.b.h. of at least 2.5 cm, including carbon mass of coarse roots, stems, and branches.
Understory vegetation	Live vegetation that includes the roots, stems, branches, and foliage of seedlings (trees less than 2.5 cm d.b.h.), shrubs, and bushes.
Down dead wood	Woody material that includes logging residue and other coarse dead wood on the ground and larger than 7.5 cm in diameter, and stumps and coarse roots of stumps.
Forest floor	Organic material on the floor of the forest that includes fine woody debris up to 7.5 cm in diameter, tree litter, humus, and fine roots in the organic forest floor layer above mineral soil.

Sources: Smith *et al*., 2006.

Carbon data is from Appendix A of Smith *et al*., (2006). Volume data from Appendix A of Smith *et al*., (2006) were given by decade, but we estimate continuous age functions for our analysis. The estimated carbon functions are shown in the following figures.

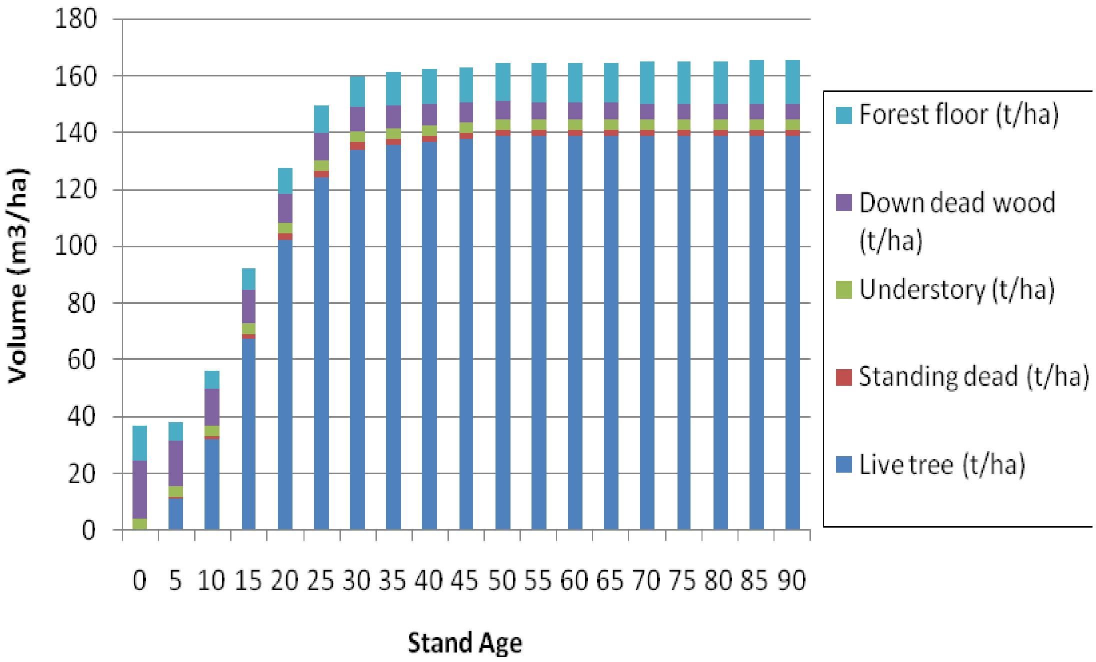

Figure 3.2.2.1 Regional estimates of carbon stocks on forest land for loblolly-shortleaf pine with high productivity and intensive management from FORCARB carbon data in Southeast.

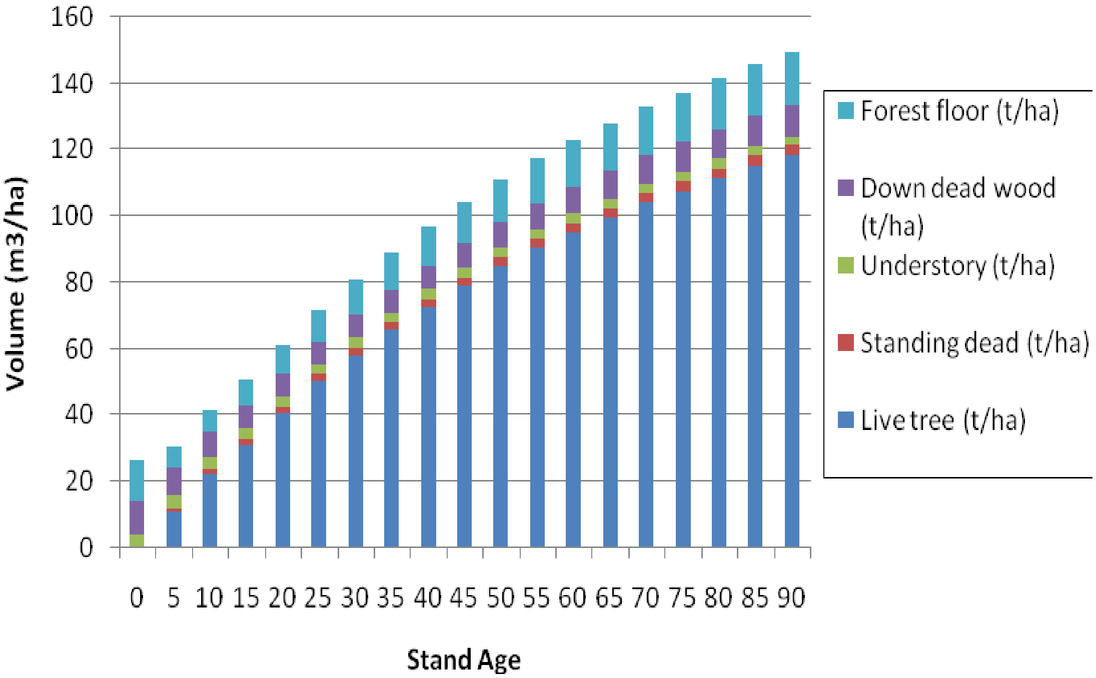

Figure 3.2.2.2 Regional estimates of carbon stocks on forest land for loblolly-shortleaf pine from FORCARB carbon data in Southeast.

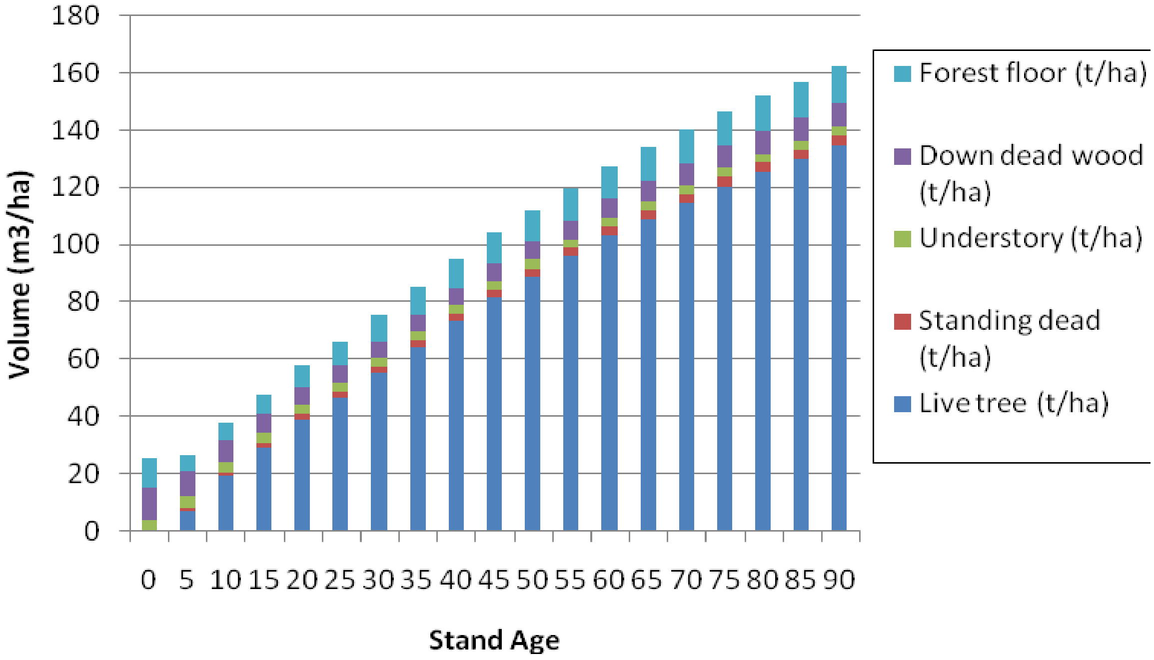

Figure 3.2.2.3 Regional estimates of carbon stocks on forest land for oak-pine from FORCARB carbon data in Southeast.

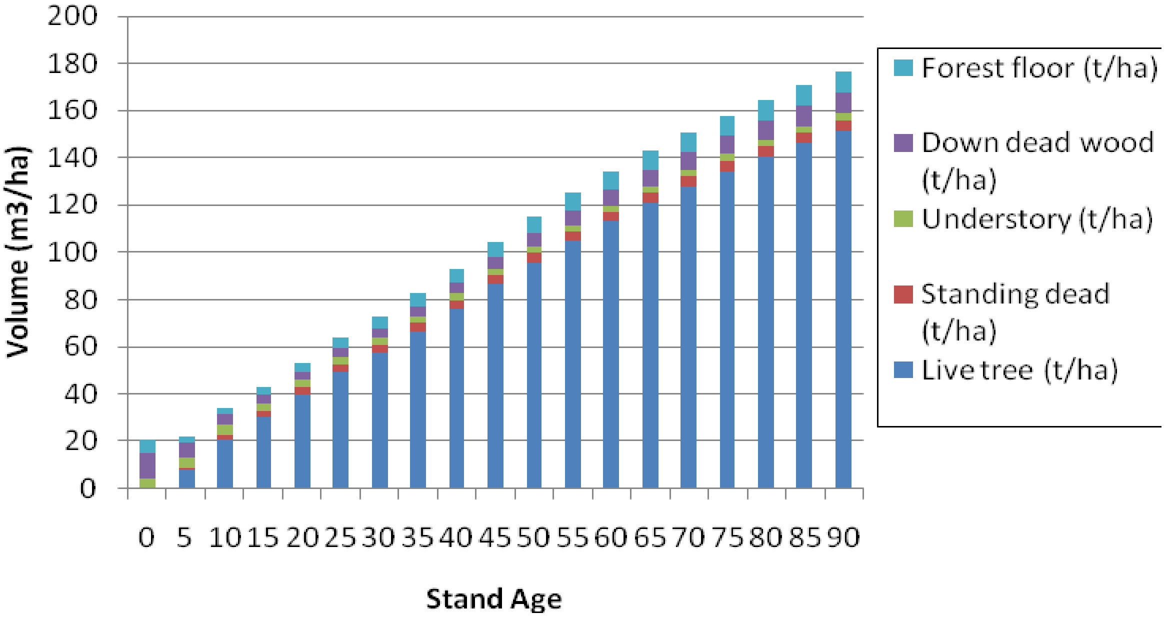

Figure 3.2.2.4 Regional estimates of carbon stocks on forest land for oak-hickory from FORCARB carbon data in Southeast.

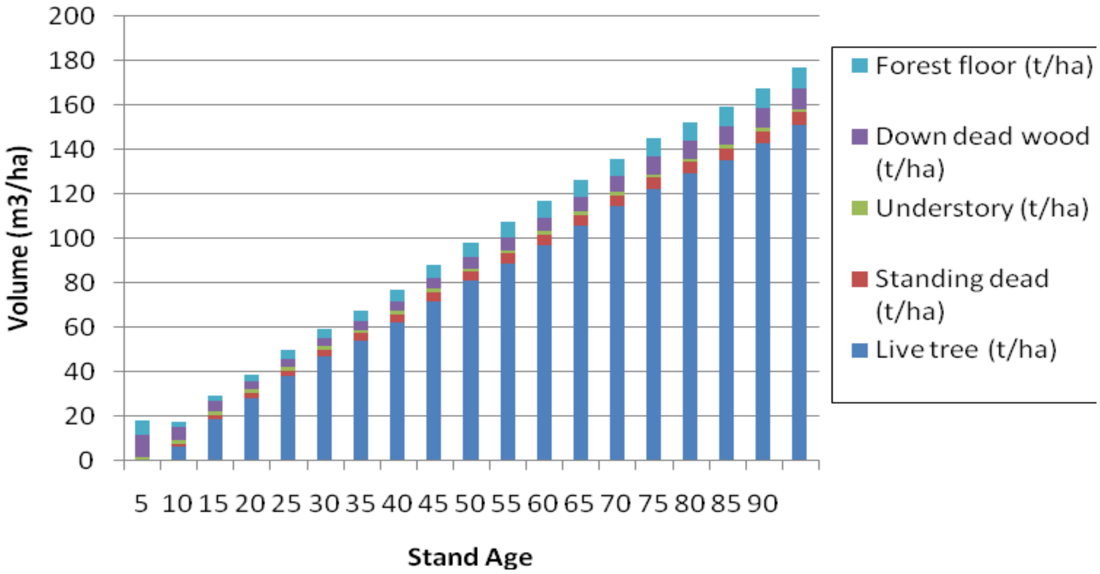

Figure 3.2.2.5 Regional estimates of carbon stocks on forest land for oak-gum-cypress from FORCARB carbon data in Southeast.

We linked FORCARB carbon tables to major forest management types for further analysis in this paper (see Table 3.2.2.2) and estimated functions based on ecological relationships.

Table 3.2.2.2 FORCARB carbon table linked to major forest management types

Forest mgt. type	FORCARB forest type
Planted Pine	Loblolly-shortleaf pine with high productivity and intensive management
Natural Pine	Loblolly-shortleaf pine
Mixed Pine	Oak-pine
Upland HdWd	Oak-hickory
Lowland HdWd	Oak-gum-cypress

3.2.3 Price and Cost

The timber price data are from the quarterly surveys of Forest2Market of east-south region .The stumpage price is the price paid to the forest manager for standing timber. Forest2Market provides standard forms to a broad sector of the timber industry, both companies and individuals, who are actively engaged in the daily operation of selling and buying timber on the stumpage and delivering to yards and mills. From these reports, the simple average is obtained for each Forest2Market micro market region. Quarterly stumpage prices from Forest2Market are used for the three products across the U.S. South (see below).

-Pulpwood (PW) at a d.b.h. of 4 to 10 inches;

-Chip-n-saw (CNS) at a d.b.h of 10 through 14 inches;

-Sawtimber (ST) with a d.b.h greater than 14 inches.

Table 3.3.2.1 lists the original price from Forest2Market July/Aug issue, and Table 3.3.2.2 shows the link from product classes to ages. Table 3.3.2.3 shows the percentages of hardwood and softwood by unit in each forest management type, while Table 3.3.2.4 lists weighted prices according from the percentages from Table 3.3.2.23. These are discrete prices. Then we obtain the prices we used in the analysis of the extended Faustmann model by weighting them by acres of forest management type in regional units.

Because as an individual tree grows it moves between size classes in discrete steps, these discrete prices may be appropriate to use for an individual tree. However a stand of trees will have a distribution of diameters for any given age. So as the stand ages, some proportion of the trees will enter the large size class and it may take several years for all of the trees to move to a higher value product. Thus we set prices according to ages in this analysis, we apply pulpwood price for timber under age 10, chip n saw price for timber between age 10 to 20, and sawtimber price for timber above age 20.

Table 3.3.2.1 Pine and hardwood price from Forest2Market

Unit	Pine			Hardwood	
	Pulpwood	10" Chip N Saw	14" Sawtimber	Pulpwood	Sawtimber
1	$6.49	$12.45	$24.47	$3.93	$22.94
2	$5.98	$11.26	$24.02	$4.95	$21.09
3	$5.90	$14.97	$23.03	$3.62	$16.69
4	$5.68	$10.12	$18.21	$2.87	$19.01

Sources: Market Guide for timber owners in east-south region of Forest2Market July/Aug 2009

Table 3.3.2.2 Link from timber product size of Forest2Market to age

Timber	Pine			Hardwood	
	Pulpwood	10” Chip N Saw	14” Sawtimber	Pulpwood	Sawtimber
Age	0~10	10~20	>20	0~20	>20

Table 3.3.2.3 Percentages of pine and hardwood by unit by forest management type

Unit1		
Foret Mgt.	Pine%	Hardwood%
Planted Pine	0.9531076	0.04689236
Natural Pine	0.8629736	0.13702643
Mixed Pine	0.5010354	0.49896456
Upland hardwood	0.0978069	0.90219309
Lowland hardwood	0.0411815	0.9588185
Unit2		
Foret Mgt.	Pine%	Hardwood%
Planted Pine	0.9318601	0.06813994
Natural Pine	0.8397038	0.16029617
Mixed Pine	0.4991813	0.50081865
Upland hardwood	0.1066628	0.8933372
Lowland hardwood	0.0147446	0.98525544
Unit3		
Foret Mgt.	Pine%	Hardwood%
Planted Pine	0.9016291	0.09837089
Natural Pine	0.8224796	0.17752044
Mixed Pine	0.4308048	0.56919516
Upland hardwood	0.0557221	0.94427786
Lowland hardwood	0.0011552	0.99884476
Unit4		
Foret Mgt.	Pine%	Hardwood%
Planted Pine	0.7536503	0.24634972
Natural Pine	0.4413502	0.55864977
Mixed Pine	0.1966484	0.80335156
Upland hardwood	0.0130838	0.98691622
Lowland hardwood	0	1

Table 3.3.2.4 Weighted prices of pine and hardwood by unit by forest management type

Unit1	Price		
	0~10	10~20	>20
Planted Pine	$6.37	$12.05	$24.40
Natural Pine	$6.14	$11.28	$24.26
Mixed Pine	$5.21	$8.20	$23.71
Upland hardwood	$4.18	$4.76	$23.09
Lowland hardwood	$4.04	$4.28	$23.00
Unit2	Price		
	0~10	10~20	>20
Planted Pine	$5.91	$10.83	$23.82
Natural Pine	$5.81	$10.25	$23.55
Mixed Pine	$5.46	$8.10	$22.55
Upland hardwood	$5.06	$5.62	$21.40
Lowland hardwood	$4.97	$5.04	$21.13
Unit3	Price		
	0~10	10~20	>20
Planted Pine	$5.68	$13.85	$22.41
Natural Pine	$5.50	$12.96	$21.90
Mixed Pine	$4.60	$8.51	$19.42
Upland hardwood	$3.75	$4.25	$17.04
Lowland hardwood	$3.62	$3.63	$16.70
Unit4	Price		
	0~10	10~20	>20
Planted Pine	$4.99	$8.33	$18.41
Natural Pine	$4.11	$6.07	$18.66
Mixed Pine	$3.42	$4.30	$18.85
Upland hardwood	$2.91	$2.96	$19.00
Lowland hardwood	$2.87	$2.87	$19.01

Table 3.3.2.5 Percentages of acres of pine and hardwood by forest management type by unit

Planted Pine	Acres	Acres%
1	1,199,865.51	0.410002011
2	1,110,509.98	0.379468633
3	578,635.52	0.197723599
4	37,475.88	0.012805757
Total	2,926,486.89	1
Natural Pine		
1	1,000,493.38	0.396972514
2	526,347.04	0.208842269
3	761,302.04	0.302066951
4	232,166.49	0.092118266
Total	2,520,308.95	1
Mixed Pine		
1	562,578.42	0.310671392
2	320,196.40	0.176821324
3	625,454.22	0.345393151
4	302,618.16	0.167114133
Total	1,810,847.20	1
Upland Hdwd		
1	907,631.65	0.13760057
2	570,795.84	0.086534921
3	2,779,995.58	0.421458394
4	2,337,709.84	0.354406115
Total	6,596,132.91	1
Lowland Hdwd		
1	798,720.99	0.475953418
2	684,467.70	0.407870515
3	187,804.20	0.111911483
4	7,156.61	0.004264584
Total	1,678,149.50	1

Table 3.3.2.6 Weighted prices of pine and hardwood by Forest Management type

Forest management type	Price		
	0~10	10~20	>20
Planted Pine	$6.04	$11.90	$23.71
Natural Pine	$5.19	$9.17	$20.76
Mixed Pine	$4.75	$7.64	$21.21
Upland hardwood	$3.62	$3.99	$18.95
Lowland hardwood	$4.36	$4.51	$21.52

Planting costs are only applied in the forest management type of planted pine. Per-hectare costs of establishing pine on burned or unburned land is based on the current practice of pine plantations and we set $500/ha in this study. Though pine plantations might be thinned, we modeled income only from final harvest.

Chapter 4

Methods

This study examines the timber yield, carbon pools, and potential for carbon sequestration in North Carolina. We use a bio-economic modeling approach integrating yield models, carbon models with economic model. This analysis is spatially explicit, but the methods can be applied to any region.

Using regional yields, a range of discount rates and different assumptions about the penalty paid at harvest. We assume that landowners are credited for the storage annually and debited at the time of harvest. For the purposes of this analysis, we assume that the prices of carbon and timber are constant over time.

We use NPV to analyze the optimal timber rotation, the optimal carbon rotation and optimal joint rotation. To see how carbon price, discounted rate and emission rate effect optimal rotation ages, we will have sensitive analysis with carbon price at $5/t, $10/t, $20/t, and \$55/t; discounted rate at 0.04, 0.06 and 0.08; emission rate at 40%, 60% and 80% which represents the proportion of carbon income that must be paid at harvest.

4.1 Forest Growth and Yield Estimation

Forest management decisions require information on the growth of trees over time. Traditional empirical growth and yield models focus on site and silvicultural interactions to represent volume as a function of age and site characteristics. At the beginning, we estimated yield using quadratic or cubic curves. The variability in the data, however, led to equation with unrealistic rotation implications. To impose the standard logistic growth form we use the von Bertalanffy growth function. This function is used in the Carbon Online Estimator (COLE). The von Bertalanffy growth function (VBGF) introduced by von Bertalanffy in 1938 and has several variants (Bertalanffy, 1938; Bertalanffy, 1960). In this analysis, forest growth yield has the form of

$$y= \alpha (1- e^{- \beta *Age})^{3} \qquad (2)$$

The coefficient “α” gives the asymptote and the coefficient “β” controls the rate of approach to the asymptote, or the growth rate. A separate equation was estimated for each management type shown in Table 3.2.2.2.

The Chapman-Richard function, which is one variant of Von Bertalanffy formula, is commonly used to describe the growth curve, its form is:

$$V(t)= r (1-e^{c-kt})^{m} \qquad (3)$$

Where r represents the maximum volume, c is the initial volume, k is the constant rate, and m describes the shape of the growth curve. In our analysis, c equals to zero because at age zero volume is zero. So I apply this function into R, Figure 5.1.1 shows the comparisons between the Chapman-Richard function and Von Bertalanffy function.

4.2 Optimal Timber Rotation -Faustmann Model

Faustmann's formula gives the present value of the income stream for forest rotation. It was derived by the German forester Martin Faustmann in1849. We derive Faustmann's result in two steps. First calculating the net present value for the first rotation, and then treating this present value as an infinite series of repeating payments.

For the first rotation, NPV is :

$$\text{NPV}= (P \bullet Vt \text{ -Cost}) \bullet (1+r)^{t} \tag{4}$$

Where P = price of timber, Vt = volume of timber at time t, and r = discount rate.

Assuming that the price of sawtimber is Ps, the price of chin n saw is Pcns, the price of pulpwood is Pp, and the interest rate is r, the emission rate is q, the net present value with carbon payments is:

$$\text{NPV(Timber)}=\begin{cases} Pp \bullet \mathbf{Vt}^{t} \bullet (1+\mathbf{r})^{-\mathbf{t}} - \mathbf{CostP} & \textbf{when t} < \mathbf{10} \\ Pcns \bullet \mathbf{Vt}^{t} \bullet (1+\mathbf{r})^{-\mathbf{t}} - \mathbf{CostP} & \textbf{when } \mathbf{10} \geq \mathbf{t} \geq \mathbf{20} \\ Ps \bullet \mathbf{Vt}^{t} \bullet (1+\mathbf{r})^{-\mathbf{t}} - \mathbf{CostP} & \textbf{whent} > \mathbf{20} \end{cases} \tag{5}$$

Where: Vt^t=growing stock volume (m^3/ha) at age t, Vc^t=accumulated tons of Carbon at age t, CostP=planting costs, r=interest rate (6%). We use NPV to determine the optimal time to harvest in one rotation in forestry. If the land is staying in forestry, then there is an additional cost of postponing income from this harvest, but also income from all future harvests. Faustmann (1995) derived the formula for ascertaining the NPV of a forest in perpetuity, which can be represented by the equation 5. SEV (Timber) is the Faustmann rotation.

For an infinite series of identical rotations the Faustmann or soil expectation value (SEV) is:

$$\text{SEV (Timber)} = \text{NPV (Timber)} + \text{NPV (Timber)} \bullet [\{(1+r)]^{t} - 1\}^{-1} \quad (6)$$

4.3 Carbon Pool Estimation.

Growing stock volume or yield is converted to carbon pools using parameters from FORCARB tables. Five carbon pool models are established based on the relationships in ecosystem level (See Table 4.3.1), as estimated from the underlying FIA sampling data. FIA adopted the approach from Birdsey (1996) using forest carbon stocks and carbon in harvested wood to provide basic information on average carbon change per area. FORCARB is a national empirical simulation and carbon-accounting model. Estimates of carbon in live and standing dead trees are based on the methods of Jenkins et.al (2003) and Smith et.al (2003). Carbon in tree biomass is accruing even if sampling trees remain below the threshold for classification of growing-stock volume but above the classification size where trees are considered part of the understory.

The volume data point form Appendix A of Smith *et al.*, (2006) were given by every ten years, since we are estimating on annual basis, we establish continuous functions based on volume or age.

Table 4.3.1 Models for carbon pools

Live tree	f(Volume)
Standing dead trees	f(Volume)
Understory vegetation	f(Livetreec)[4]
Down dead wood	f(Livetreec)[4]
Forest floor	f(Age)

4.4 Optimal Carbon Rotation – Hartman Model

The Carbon sequestered in forest has different lifetimes (Ramlal *et.al*, 2009). Carbon is gradually sequestered over the plantation life and is usually released as a result of harvests or natural disturbances. Carbon emissions from decay and harvest are accounted on an annual basis by using the emission rate q. In our analysis, the net amount of carbon sequestered or emitted is calculated for every year and then consolidated into a present ton-equivalent

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[4] Estimate live tree carbon pool from timber volume then use the live tree carbon pool data to estimate understory vegetation and down dead wood carbon pool.

metric, for the i-th pool of carbon, similarly to the approach used in the analysis of Richards and Stokes (2004).

We assume a constant real unit price Pc, for each metric ton of carbon sequestered and use the range of values \$5, \$10, \$20 and \$55 per metric ton of carbon. The present value of the stream of carbon sequestration benefits or revenues, SEV(Carbon), is calculated as:

$$\text{SEV (Carbon)} = \text{NPV (Carbon)} + \text{NPV (Carbon)} \bullet \llbracket\{(1+r)\rrbracket^{t} - 1\}^{-1} \tag{7}$$ [5]

The model uses Hartman's (1976) approach to calculate the net present value of the annual flow of carbon sequestration benefits over an infinite series of rotations. This is a modified standard forest Faustmann optimal harvest model by including the flow of benefits. Carbon can be viewed as a flow benefit because sequestrations occur each year over the lifetime of the rotation.

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[5] We are not include the cost of carbon sequestration, like transition fee or consultant fee, so present value equals to net present value, because the cost is assumed to be 0.

Chapter 5

Results

5.1 Empirical Timber Yield Curve

Estimating the Von Bertalanffy equation requires non-linear regression. We use R software procedure and goodness of fit statistics. We put aggregated plots data described in Chapter 4 into R software to estimate mean volume for every forest management type through a 100 year lifespan. The graphs of each forest management type are shown as following, the coefficients obtained from growth and yield model are listed in Table 5.1.1.

As shown in the graphs, for mixed pine and lowland hardwood yields using the Chapman-Richard function were linear. But in Von Bertalanffy function, the parameter can be fixed to estimate the standard logistic shape. For all other management types, the two function forms provide similar results.

Table 5.1.1 Summary of coefficients of Von Bertalanffy yield model curves

Forest Mgt. Type	a[6]	b[7]	Achieved convergence tolerance[8]	Std.Error	n
Planted Pine	2835***	0.07429***	2.34E-06	889	416
Natural Pine	2179***	0.06501***	1.19E-06	1153	492
Mixed Pine	2330***	0.04767***	5.17E-06	1013	346
Upland HdWd	2573***	0.04379***	2.15E-07	1209	1196
Downland HdWd	3896***	0.02847***	8.36E-06	1385	302

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[6] Unit of coeffcient ‘a’ is cuft/acre. In FIA data, the unit of stocking is cubic feet and that of plot is acre.

[7] Unit of coefficient ‘b’ is 1, because it represents growth rate in the model.

[8] Significant codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1.

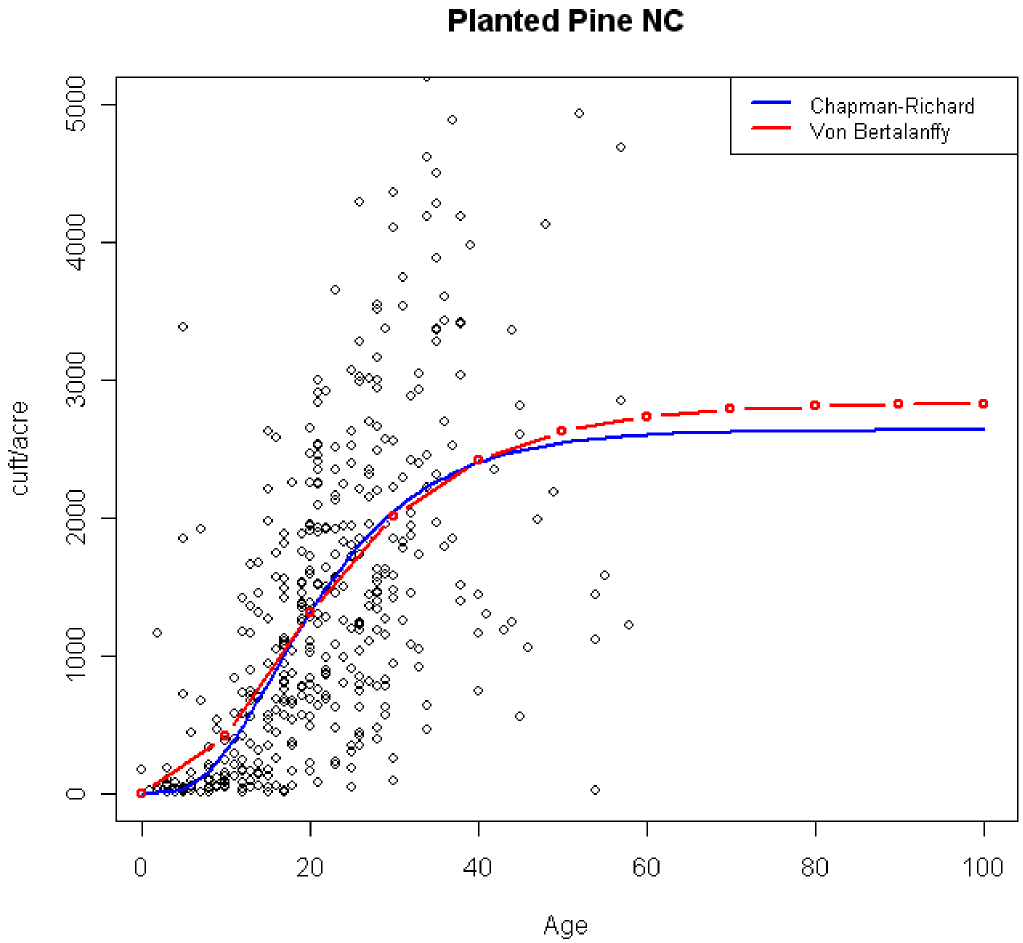

Figure 5.1.1 Yield models using plot data of planted pine in North Carolina

Most plated pine plots are less than 60 years old (see Figure5.1.1). The asymptote of Von Bertalanffy model (red line) is 2835cuft/acre, or 198.29 m^3/ha, which is highest growth rate about 0.07 among all five management types.

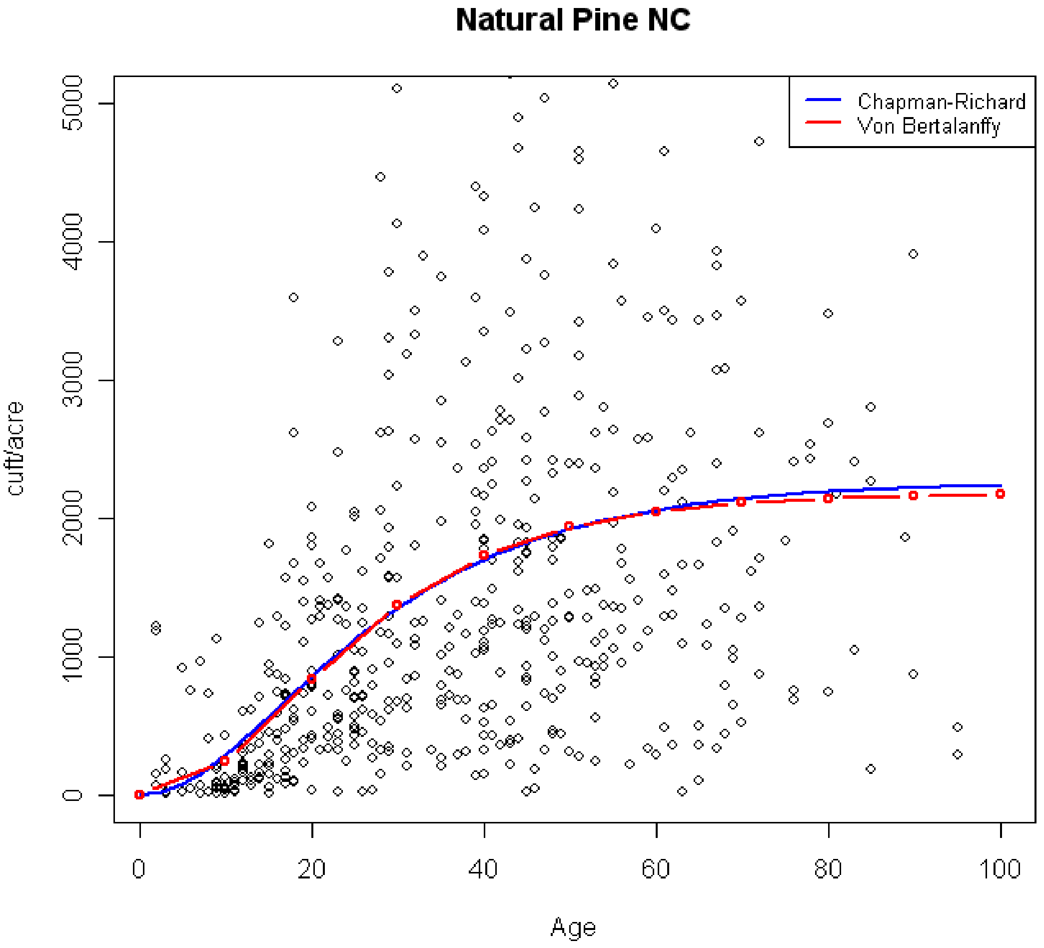

Figure 5.1.2 Yield models using plot data of natural pine in North Carolina

There is more variation in age and volume for natural pine. This reflects variations in natural stands and ownership objective. The data shows natural pines reach a maximum mean volume later than planted pines, and lower, only 2179cuft/acre with a slightly decrease growth rate 0.065.

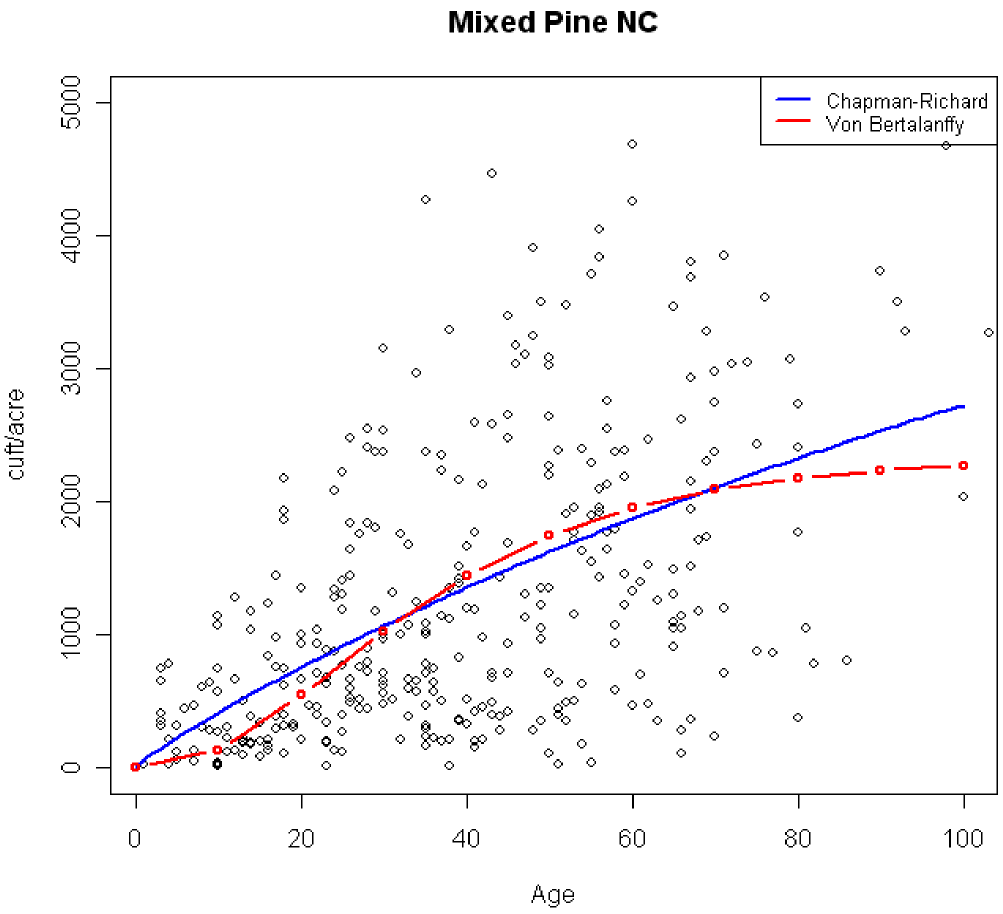

Figure 5.1.3 Yield models using plot data of mixed pine in North Carolina

There are fewer plots of mixed pine-hardwood than the pine types. The asymptote mean volume calculated using Von Bertalanffy formula in R is 2330cuft/acre, which is higher than natural pine, with 0.048 as growth rate.

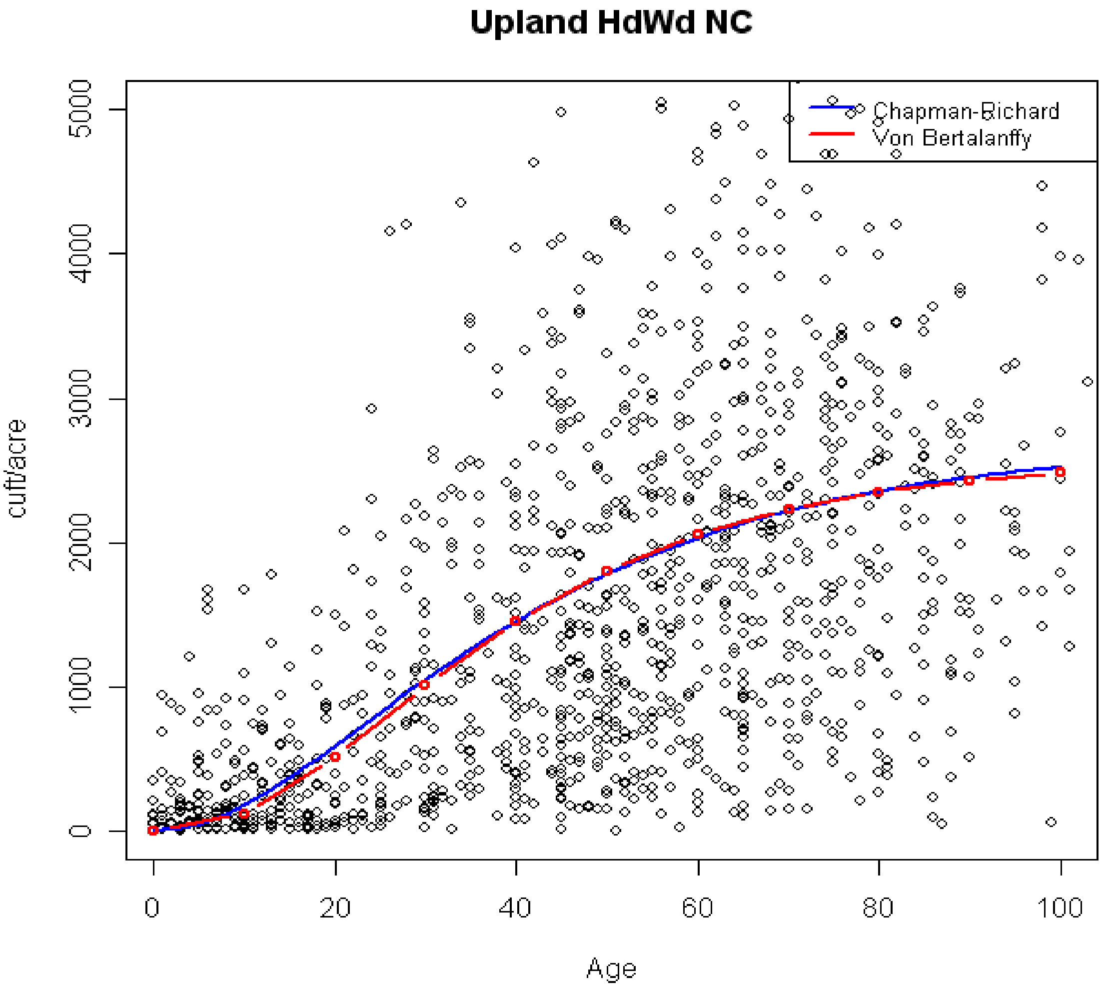

Figure 5.1.4 Yield models using plot data of upland hardwood in North Carolina

Upland hardwood is the most common forest management type in North Carolina.. The asymptote in upland hardwood is 2573cuft/acre, with 0.044 growth rate.

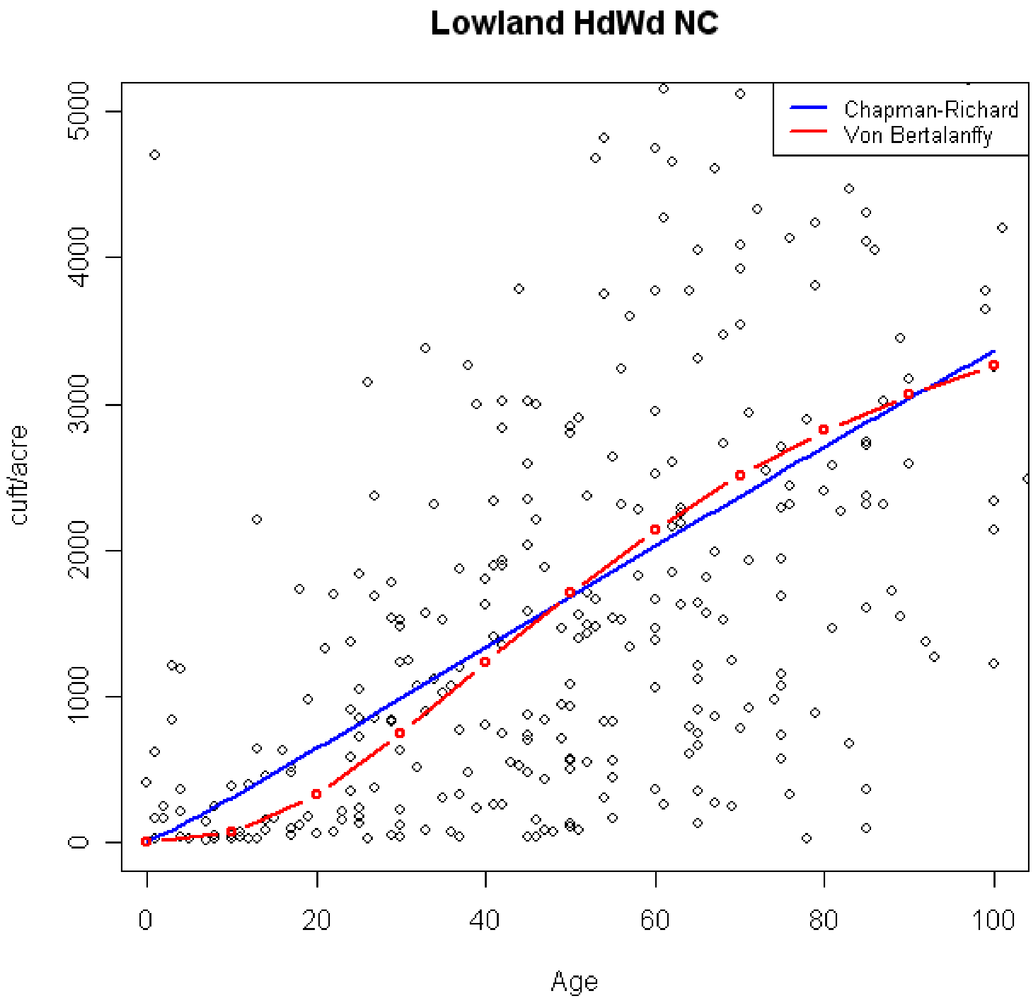

Figure 5.1.5 Yield models using plot data of Lowland hardwood in North Carolina

The asymptote from lowland hardwood model is the highest, 3896cuft/acre. We have many old plots of lowland hardwood with high mean volume, even higher than planted pine.

However, b coefficient shows growth rate is the lowest only 0.028. Figure 5.1.6 shows the difference in yield curves for the five forest management types.

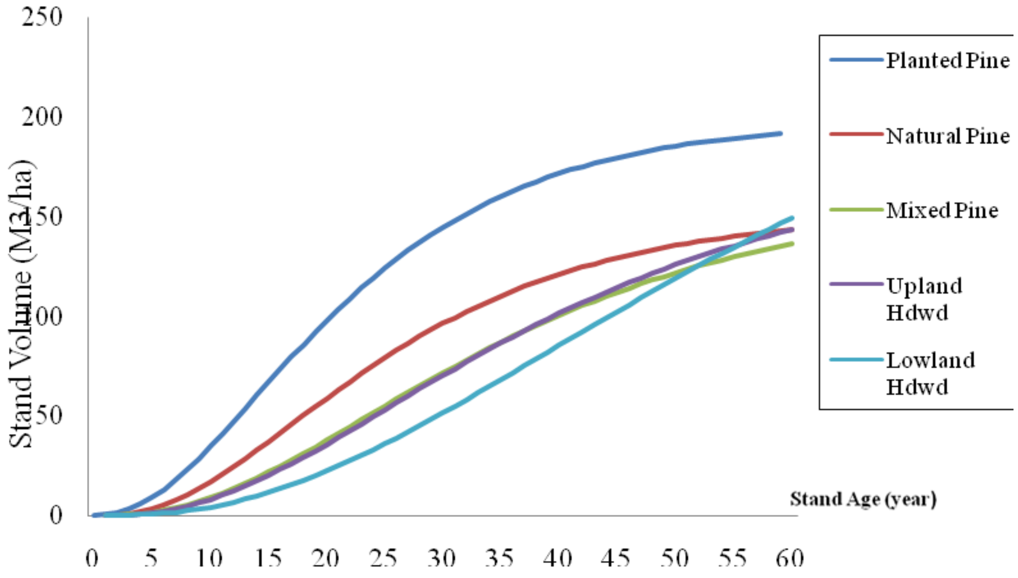

Figure 5.1.6 Yield curves of Von Bertalanffy model for five forest management types in North Carolina State

For the economic analysis we use a discount rate of 0.04 when calculating the net present value. To simplify the analysis, we apply weighted pulpwood price for timber under age 10, weighted chip n saw price for timber between age 10 to 20, and weighted sawtimber price for timber above age 20. Using these yield curves from model, we then estimated the Faustmann rotations. Since we get different parameters for Von Bertalanffy formula for the yield curve and different price of timber for different management types, the rotation lengths are different by every forest management type

Hartman showed that when there are non market revenues with older timber, it may be economically efficient to extend rotation ages (Hartman, 1976). For this analysis, we pay for increments and emissions of carbon in forests in the harvest year rather than paying for carbon stored in market products.

Table 5.1.2 Comparison of estimated optimal timber rotation ages of Faustmann and maximum mean annual increment[9]

Forest mgt. type	Faustmann rotation	Maximum Mean Annual Increment
Planted Pine	22	25,26[9]
Natural Pine	21	29
Mixed Pine	25	40
Upland HdWd	28	43
Lowland HdWd	35	60

Using the forest yield curves as mentioned above, the model can estimate the Faustmann rotation which is to harvest at the highest SEV of the land and maximum mean annual increment which is to harvest at the mean annual growth maximum of the land. Obviously, Faustmann rotation is shorter, which is reasonable, because it also accounts for the opportunity cost of delaying harvest.

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[9] Using timber prices listed above in this analysis, 4% interest rate and 40% emission rate

5.2 Empirical Carbon Yield Curve

The estimate we have here is using the parameters from FORCARB carbon table apply to our timber yield curve. We do not estimate soil carbon in this analysis, because stocks are assumed not change when rotations change (Johnson, 1992).

The coefficient sets shown in Table 5.2.1 are based on the following function:

$$Y = \text{intercept} + a1*X + a2*X^2 + a3*X^3 \tag{7}$$

Where X represents either volume or age when computing different carbon pools. Specifically, Volume of timber, “livetreec” means live tree carbon, and “age” means the age of the timber or the stand age of the plot.

The red numbers in Table 5.2.1 points out the coefficients which are not statistically significant at 5% significance level.

Table 5.2.1 Coefficients obtained from FORCARB tables.

Planted Pine	intercept	a1	a2	a3	X	R^2
livetreec	6.06885	0.5285	-8.00E-04	9.78E-07	(V)	0.9982
deadc	0.39326	0.0216	-9.00E-05	1.28E-07	(V)	0.9619
understoryc	4.12277	-0.0158	2.00E-04	-7.97E-07	(livetreec)	0.9517
downdeadc	20.1896	-0.399	0.006	-2.55E-05	(livetreec)	0.9741
forestfc	9.06767	-0.1162	0.006	-4.68E-05	(age)	0.8529
Natural Pine	intercept	a1	a2	a3	X	
livetreec	7.59587	0.6362	-0.002	3.08E-06	(V)	0.9959
deadc	0.50662	0.0295	-1.00E-04	2.39E-07	(V)	0.9659
understoryc	4.25563	-0.036	3.00E-04	-1.16E-06	(livetreec)	0.9899
downdeadc	9.87186	-0.148	0.002	-5.46E-06	(livetreec)	0.9985
forestfc	9.06767	-0.1162	0.006	-4.68E-05	(age)	0.8529
Mixed Pine	intercept	a1	a2	a3	X	
livetreec	5.99183	0.8099	-0.002	4.37E-06	(V)	0.998
deadc	0.48399	0.0373	-2.00E-04	3.77E-07	(V)	0.9766
understoryc	4.22233	-0.0321	3.00E-04	-1.11E-06	(livetreec)	0.9872
downdeadc	10.8778	-0.2028	0.002	-7.20E-06	(livetreec)	0.9859
forestfc	7.83759	-0.0749	0.004	-3.32E-05	(age)	0.8294
Upland HdWd	intercept	a1	a2	a3	X	
livetreec	6.84742	1.0322	-0.004	7.10E-06	(V)	0.9979
deadc	0.87549	0.0591	-4.00E-04	7.59E-07	(V)	0.9417
understoryc	4.30932	-0.0318	2.00E-04	-5.94E-07	(livetreec)	0.9900
downdeadc	9.60356	-0.2699	0.004	-1.17E-05	(livetreec)	0.9476
forestfc	4.08565	-0.0861	0.004	-3.07E-05	(age)	0.8941
Lowland Hdwd	intercept	a1	a2	a3	X	
livetreec	6.84794	0.9662	-0.003	5.60E-06	(V)	0.9975
deadc	0.84064	0.0596	-3.00E-04	5.92E-07	(V)	0.9651
understoryc	1.8628	-0.0054	2.00E-05	2.25E-08	(livetreec)	0.9314
downdeadc	8.74611	-0.2454	0.003	-1.14E-05	(livetreec)	0.9361
forestfc	4.08565	-0.0861	0.004	-3.07E-05	(age)	0.8941

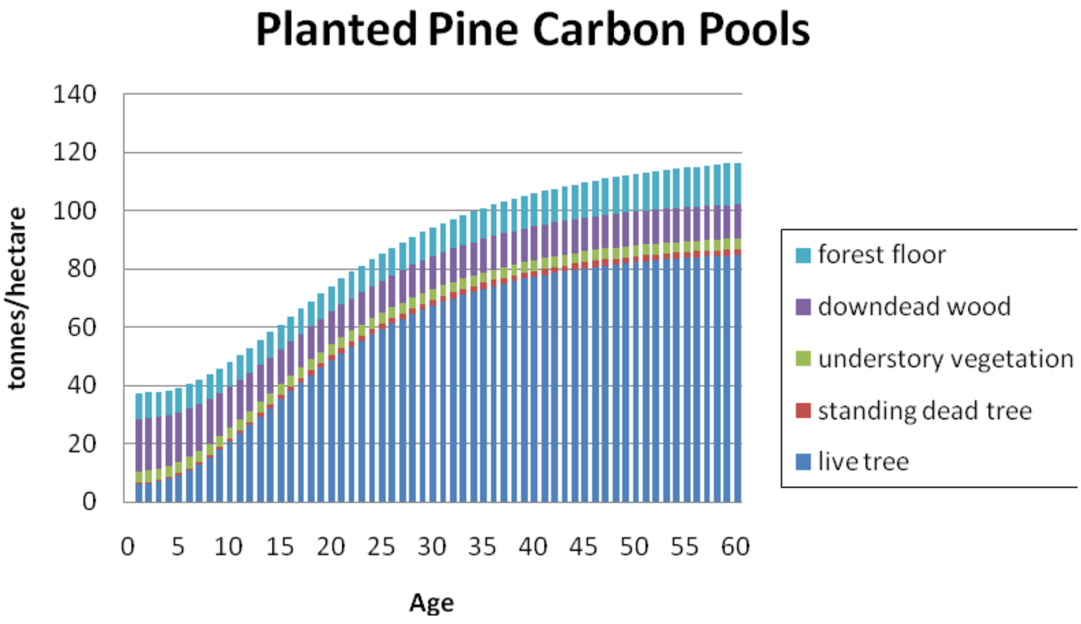

Figure 5.2.1 Carbon pools estimates of planted pine in North Carolina

These figures show carbon stocks over 60 years. Live tree carbon is the major carbon pool which is merchantable in all the protocols. As shown in Figure 5.2.1, the carbon curves share the same shape as timber yield curves, but continually increase because carbon is cumulative. The rate of increase slows down around 30 years old. Deadwood carbon is the least we accumulate during the rotation compares to the other pools, followed by understory vegetation carbon.

Live tree carbons yield in natural pine approaches near 70 tonnes/ha, about 10% less than planted pine. Deadwood carbons amount and understory vegetation carbons stay stable similar to planted pine.

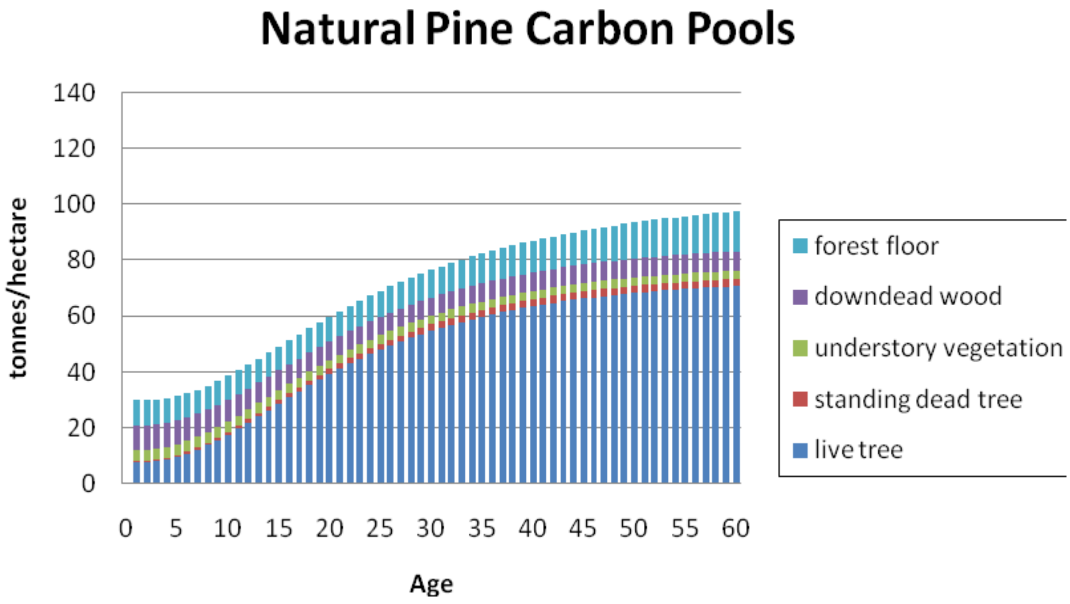

Figure 5.2.2 Carbon pools estimates of natural pine in North Carolina

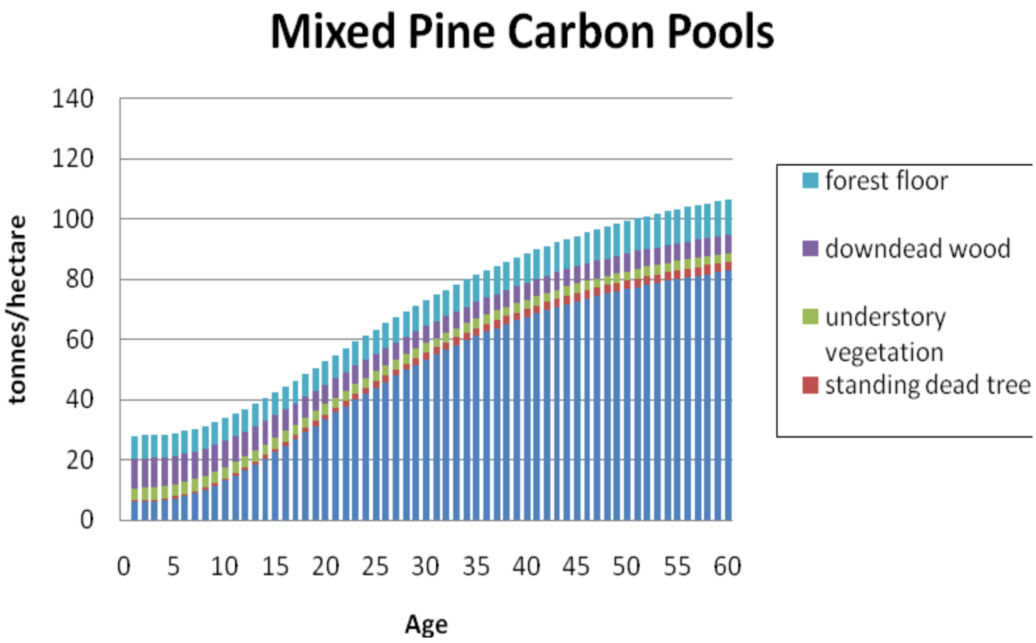

Figure 5.2.3 Carbon pools estimates of mixed pine in North Carolina

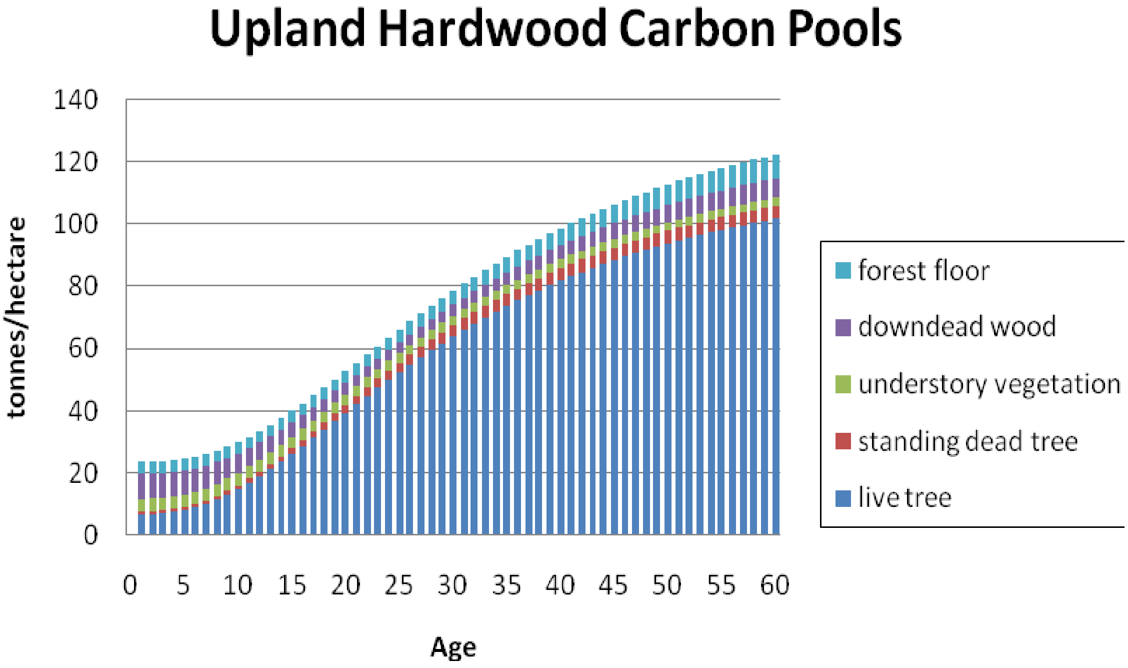

Figure 5.2.4 Carbon pools estimates of upland hardwood in North Carolina

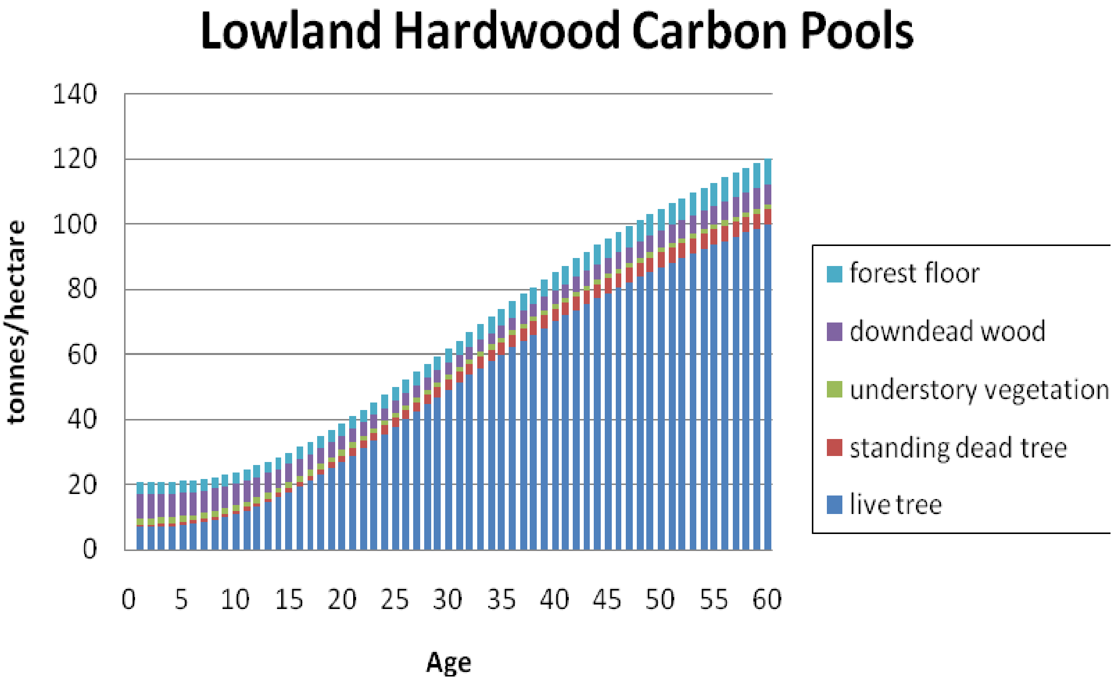

Figure 5.2.5 Carbon pools estimates of lowland hardwood in North Carolina

In mixed pine, lives tree carbon yields increase to 82 tons/hectare, which is the highest among pine management types. FORCARB carbon tables show higher carbon in this management type.

In hardwoods, lives tree carbon yield increase up to more than 100 tones/hectare at year 60. Understory vegetation carbon is very low in lowland hardwood. Downdead wood carbon and forest floor carbon in both hardwood types are similar.

5.3 Rotation Comparisons of Carbon Protocols

We compare creditable carbon from the DOE, and CCX and VCS carbon protocols. The significant variation in the amount of creditable carbon generated under each methodology stem from differences in the scope and component of carbon accounting (see Table 5.1).

Table 5.3.1 Carbon pools accounted for DOE, CCX and VCS protocols

Protocol	Live tree	Standing dead trees	Understory	Down deadwood	Forest floor
DOE	Y	Y	Y	Y	Y
CCX	Y	-	Y	-	-
VCS	Y	O	O	O	O

Y- Accounted O-Optionally accounted

Table 5.3.2 Comparison of joint rotation under DOE, CCX and VCS protocols by forest management type at carbon price: \$5/t and \$55/t[10]

	Forest Mgt. Type		DOE	CCX	VCS
Carbon:\$5/t	Planted Pine	Timber rotation	21		
		Joint rotation	22	21	21
	Natural Pine	Timber rotation	20		
		Joint rotation	21	20	20
	Mixed Pine	Timber rotation	25		
		Joint rotation	25	25	25
	Upland HdWd	Timber rotation	26		
		Joint rotation	28	28	28
	Lowland HdWd	Timber rotation	33		
		Joint rotation	35	35	35
Carbon:\$55/t	Forest Mgt. Type		DOE	CCX	VCS
	Planted Pine	Timber rotation	21		
		Joint rotation	23	22	22
	Natural Pine	Timber rotation	20		
		Joint rotation	23	22	22
	Mixed Pine	Timber rotation	25		
		Joint rotation	29	28	29
	Upland HdWd	Timber rotation	26		
		Joint rotation	38	37	37
	Lowland HdWd	Timber rotation	33		
		Joint rotation	43	42	42

Galik et al. (2008) focus on analyzing the detailed differences among these carbon protocols, so here we just represent the rotation length across carbon protocols.

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[10] Using timber prices listed above in this analysis, 4% interest rate and 40% emission factor

We can see from Table 5.3.2, under protocol DOE, when carbon price is $5/ton, joint optimal rotation is only one year longer than timber rotation, except lowland hardwood management type, which is two years longer; when carbon price rises to $55/ton, joint optimal rotation is 2-10 years longer. Under CCX and VCS protocols, joint rotations are the same to DOE protocols when carbon price is $5/ton, only planted pine and natural pine are one year shorter then under DOE; joint optimal rotations of all forest management type are shorter than under DOE protocols under $55/ton carbon price, but only one year, which is not significant.

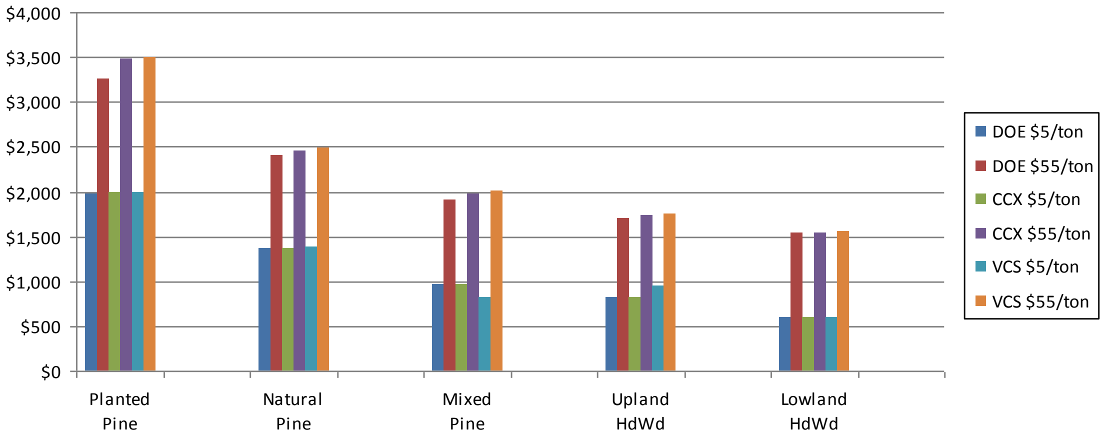

Figure 5.3.1 SEVs of optimal joint rotation under DOE, CCX and VCS protocols by forest management type at carbon price: $5/t and $55/t

Since the revenue is also a key for landowners to decide the harvest, Figure 5.1 shows the comparisons of SEVs under three protocols and two carbon prices. When carbon price is \$5/ton, the values show no major difference under different protocols. Planted pine indicates the highest SEV or more than \$2000/ha, and lowland hardwood is the least which is only about \$600/ha. Mixed pine and upland hardwood are slightly different. When carbon price arise to \$55/ton, SEVs of CCX and VCS protocols are higher than DOE in all five forest management types, specially, in planted pine, but in lowland hardwood has only about \$5 difference. In addition, the SEVs of upland hardwood are higher than those of mixed pine, which is a significant change when carbon is \$5/ton.

5.4 Sensitivity Analysis of Carbon Sequestration

Sensitivity analysis can be used to systematically and comprehensively test the effect of change in model parameters. The results presented in this analysis indicate that extending rotations can be an economically efficient carbon sequestration option. Specifically, the analysis reveals that the impact of the factors on rotation extension. However, our results also imply that extending rotations has less potential, at least in the short period, than has been estimated for other regions of the USA by aggregated models (EPA, 2005; MORE). At low carbon prices, it is unlikely to extend rotation age.

At a given carbon price, the total amount of carbon that can be sequestered in each forest management type is the sum of carbon sequestered in all carbon pools on each aggregated plot at that price.

Table 5.4.1 Optimal rotation length under different carbon prices for five forest management types

<table>
<tr><th rowspan="2">Forest management type</th><th colspan="4">Carbon price ($/ton)</th></tr>
<tr><th>5</th><th>10</th><th>20</th><th>55</th></tr>
<tr><td>Planted pine</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Timber optimal rotation length</td><td colspan="4">21</td></tr>
<tr><td>Carbon optimal rotation length</td><td colspan="4">28</td></tr>
<tr><td>Joint optimal rotation length</td><td>22</td><td>22</td><td>22</td><td>23</td></tr>
<tr><td>Natural Pine</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Timber optimal rotation length</td><td colspan="4">20</td></tr>
<tr><td>Carbon optimal rotation length</td><td colspan="4">29</td></tr>
<tr><td>Joint optimal rotation length</td><td>21</td><td>21</td><td>21</td><td>23</td></tr>
<tr><td>Mixed Pine</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Timber optimal rotation length</td><td colspan="4">25</td></tr>
<tr><td>Carbon optimal rotation length</td><td colspan="4">40</td></tr>
<tr><td>Joint optimal rotation length</td><td>25</td><td>26</td><td>27</td><td>28</td></tr>
<tr><td>Upland Hardwood</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Timber optimal rotation length</td><td colspan="4">26</td></tr>
<tr><td>Carbon optimal rotation length</td><td colspan="4">41</td></tr>
<tr><td>Joint optimal rotation length</td><td>28</td><td>29</td><td>31</td><td>39</td></tr>
<tr><td>Lowland Hardwood</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Timber optimal rotation length</td><td colspan="4">33</td></tr>
<tr><td>Carbon optimal rotation length</td><td colspan="4">60</td></tr>
<tr><td>Joint optimal rotation length</td><td>35</td><td>37</td><td>38</td><td>43</td></tr>
</table>

Higher carbon price make the joint optimal rotation longer because carbon revenue is cumulative. But this influence does affect carbon optimal rotations significantly. Hardwoods show more impact from higher carbon price. Softwoods show only 2 to 3 years longer rotation from $5/ton to $55/ton (See Table 5.4.1).

Table 5.4.2 Change in SEV from extending the rotation to age 60 under carbon price (unit: $/ton/ha)

Forest management type	Carbon price ($/ton)			
	5	10	20	55
Planted Pine	-1194.78	-1078.11	-844.76	-28.06
Natural Pine	-780.51	-683.09	-488.24	193.73
Mixed Pine	-392.39	-294.93	-100.01	582.19
Upland HdWd	-273.54	-153.91	85.34	922.74
Lowland HdWd	-61.48	39.43	241.25	947.59

Most protocols require longer timber rotations, and would prohibit harvest at the optimal rotations calculated here. To estimate the cost of holding timber beyond the optimal timber rotation, Table xxx shows the loss in timber SEV net of the gain in carbon SEV for a 60 year rotation. For example, for planted pine with a $5 carbon price, the optimal timber rotation is at age 21 with an SEV of $1848. At age 60 the timber SEV is $536. Postponing harvest to age 60 implies a loss of $1311 per acre. At $5 per ton, the carbon SEV at age 60 is $116.67. The net loss shown in Table 5.4.2 is $-1194.78. With carbon price increasing, the loss in SEV decreases significantly, but in planted pine management type, it still shows negative.

Table 5.4.3 Optimal rotation length under different emission rates for five forest management types

Forest management type	Emission rate		
	0	0.4	0.8
Planted pine			
Timber optimal rotation length		21	
Carbon optimal rotation length	27	28	28
Joint optimal rotation length	22	22	21
Natural Pine			
Timber optimal rotation length		20	
Carbon optimal rotation length	29	29	29
Joint optimal rotation length	21	21	20
Mixed Pine			
Timber optimal rotation length		25	
Carbon optimal rotation length	40	40	40
Joint optimal rotation length	26	25	25
Upland Hardwood			
Timber optimal rotation length		26	
Carbon optimal rotation length	41	41	42
Joint optimal rotation length	28	28	27
Lowland Hardwood			
Timber optimal rotation length		33	
Carbon optimal rotation length	60	60	60
Joint optimal rotation length	36	35	34

As defined above, a “0” in emission factor implies no penalty at harvest, and a “1” implies all carbon emit before the harvest year so that all carbon income must returned at harvest (less accumulated interest). Intermediate values proxy for various harvest penalties.

When emission rate increase from 0 to 0.4, carbon optimal rotations do not change except for planted pine, while the joint optimal rotation is extended one to three years. When emission rate increase from 0.4 to 0.8, carbon optimal rotations is shorten for one, but mixed pine still the same plan, while the joint optimal rotation is closer to timber optimal rotation.

Table 5.4.4 Change in SEV from extending the rotation to age 60 under emission rate (unit: $/ton/ha)

Forest management type	Emission rate		
	0	0.4	0.8
Planted Pine	-1121.85	-1194.78	-1267.7
Natural Pine	-719.617	-780.51	-841.41
Mixed Pine	-331.468	-392.39	-453.3
Upland HdWd	-198.763	-273.54	-348.32
Lowland HdWd	1.609239	-61.48	-124.56

When there is no penalty at harvest, in other words, all carbon is treatable, the change in SEV is great and negative, but only lowland hardwood shows positive SEV gain. When penalty get higher, the loss is greater among every forest management types.

Table 5.4.5 Optimal rotation length under different interest rates for five forest management types

Forest management type	Interest rate		
	0.04	0.06	0.08
Planted pine			
Timber optimal rotation length	21	20	20
Carbon optimal rotation length	28	29	30
Joint optimal rotation length	22	20	20
Natural Pine			
Timber optimal rotation length	20	20	20
Carbon optimal rotation length	29	30	32
Joint optimal rotation length	21	20	20
Mixed Pine			
Timber optimal rotation length	25	21	20
Carbon optimal rotation length	40	42	45
Joint optimal rotation length	25	22	20
Upland Hardwood			
Timber optimal rotation length	26	22	20
Carbon optimal rotation length	41	44	47
Joint optimal rotation length	28	24	21
Lowland Hardwood			
Timber optimal rotation length	33	27	23
Carbon optimal rotation length	60	60	60
Joint optimal rotation length	35	29	25

When the discount rate is high, revenue pushes forests to be harvested early for more income, because we set timber price as age below 10, 10 to 20, and above 20, there is a large increase at age 20; that is another reason when rate is 0.08, rotation length of all forest management types is 20 or near 20 (only lowland hardwood). When carbon and timber price are set with no increase, when emissions rate increases, the impacts of timber show great influence on joint optimal rotations and push it near the optimal timber rotation. Carbon value less timber loss.

Table 5.4.6 Change in SEV from extending the rotation to age 60 under interest rate (unit: $/ton/ha)

Forest management type	Interest rate		
	0.04	0.06	0.08
Planted Pine	-1194.78	-754.33	-489.85
Natural Pine	-780.51	-502.17	-327.07
Mixed Pine	-392.39	-277.28	-192.60
Upland HdWd	-273.54	-203.12	-143.96
Lowland HdWd	-61.48	-77.86	-63.97

Higher interest rate makes joint optimal rotation closer to timber optimal rotation, that's why under 0.06 and 0.08 of interest rate, joint optimal rotations of both planted pine and natural pine are the same of timber optimal rotation. High interest rate makes loss in timber SEV less as well as carbon SEV we obtained at age 60.

Chapter 6

Conclusions

The analysis in this study has four important contributions which have implications for carbon management in North Carolina’s forests.

First, we can estimate timber and carbon yield from FIA plots data. The approach in the analysis illustrate that we can use FIA plot data to estimate timber yield curves and these yield curves allow us to estimate carbon yields for those plots.

Second, separate carbon pools estimates can be used to examine the impact of different protocols. Comparisons among DOE, CCX and VCS protocols shows creditable carbon amount in each forest management type is unique but optimal rotations are similar under all protocols. Under CCX and VCS protocols land owners can get higher revenue but not much more than the DOE protocol, for two major reasons One is because the understory vegetation carbon pool do not change much over time, and another is both down dead wood and forest floor carbon pools are decreasing with age. It is also important to understand that making these deductions decrease the total revenue, but there are also studies that suggest that markets can adjust to reflect cost differences in protocols showing that to compensate decrease creditable carbon, increasing carbon price and methodological legitimacy are possible to happen in market.

Third, at current carbon prices, impacts are small. When carbon price is low, the joint rotations is one to three years longer with additional carbon SEV from $2.91 to $6.44 ton/ha. However, current carbon prices are extremely low [give value]. However, if the area is large, the total impact may be significant. In addition, low carbon price makes minimizes differences between protocols.

Last but not least, sensitivity analysis shows that discount rate during the time of rotation age has more influence on rotation age extension than carbon price and emission rate. However, carbon price is the primary driver for applying carbon sequestration to get more income. When the land owners consider extending the rotation age, they should also consider about the loss of timber revenue, because extension of joint rotation accounts the effect on timber revenue, even the timber volume will possible be larger but after applying the discounting could lead to a certain loss of timber revenue. In order to affect management, it is important that the price of carbon can be established high enough to stimulate carbon storage in the field. Sohngen and Brown (2008) also indicated how carbon price affect the rotation age extensions. It is true that current forest management activities are not driven by current carbon offset prices, but it should be and would be.

Forest carbon markets have just started and may have flaws, but as an important role in climate change, a high-quality scheme should be defined and accounted with constant rules managing uncertainties and done in a manner making the costs reasonable to be feasible for land owners to participate in carbon sequestration.

There are some issues might interest to forest owners and policy makers are not well resolved in this analysis and it is important to recognize them. First, we set carbon and timber price constant over time. Second, we not include risk analysis in this study. Third, we modeled income only from final harvest but there might be thinning during the rotation. In addition, we not include any costs for activities like periodic monitoring, verification, and transaction. The costs of these activities are not included here because the rules of an optimal monitoring and verification system are likely to be quite complicated, and difficult to estimate.

Although accounting for these other factors could be important, the results of this study do estimates of timber and carbon yield from plot data and direct information about how different protocols affect creditable carbon. Further research is necessary to better characterize the carbon pools and apply the forest yield growth model to other states using their own plots data and establish a regional carbon sequestration model to give a better picture for policy maker to make carbon offset market feasible. Work is underway.

Key terms, units and abbreviations

Buffer or Reserve – The pool of credits of allowances held in reserve in case of intentional or unintentional losses of stored carbon to the atmosphere. This is different from deductions made for uncertainty, leakage, or other purposes, as these other discounts are simply subtracted from the total amount of carbon generated.

Business-as-Usual (BAU) – The management scenario expected in the absence of offset project implementation.

Carbon Pool – A specific component of the forest biological system that is capable of both storing and releasing carbon.

Creditable Carbon – The amount of stored carbon that may be reported, registered, or claimed by the project developer. In a fully functioning carbon market, creditable carbon is the portion of gross carbon storage eligible for sale.

Leakage – And induced shift in activity or activities, resulting in a change in emissions or sequestration outside the boundaries of a particular policy, market, or entity.

1 metric ton = 1,000 kg = 2,205 lb = 1.10 short (U.S.) tons

1 hectare (ha) = 2.47 acres (ac)

1 metric ton carbon = 3.664 metric tons Carbon Dioxide Equivalents (CO_2e)

CAR	Forest Project Protocol (Climate Action Reserve 2007)
CCX	Chicago Climate Exchange
FIA	U.S. Forest Service Forest Inventory and Analysis Program
GFC	Georgia Forestry Commission
NPV	Net Present Value
DOE	U.S. Department of Energy 1605(b) Technical Guidelines for Voluntary Reporting of Greenhouse Gases
VCS	Voluntary Carbon Standard

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