ANALYZING FACTORS AND THE ECONOMICS OF AFFORESTATION AS A NATURE-BASED SOLUTION FOR MITIGATING CARBON EMISSIONS IN GEORGIA, UNITED STATES

by

MADISEN FULLER

(Under the Direction of Puneet Dwivedi)

ABSTRACT

Afforestation is gaining popularity as a nature-based solution for mitigating carbon emissions. Therefore, a need exists for understanding the economics of carbon stored on an acre of an afforested stand to better situate the afforestation as a tool for mitigating carbon emissions relative to other competing technologies. Additionally, it is vital to understand the factors affecting the location of afforested lands for locating the most efficient and significant places to utilize the available resources optimally. This thesis aims to ascertain the potential role of afforestation in mitigating carbon emissions for ensuring the balance between planet, people, and prosperity. Georgia, a southern state in the United States, is selected as a case study. First, we developed stand-level economic models for determining the unit cost of carbon stored on an acre of afforested stand in South Georgia. Second, we used historical land use data and developed advanced regression-based models for estimating the parcels of land in SW Georgia, which are likely to experience future afforestation. We find afforestation to be environmentally and economically feasible for mitigating carbon emissions in Georgia. The results of the thesis will also be beneficial to other southern states, as these states share a similar climate, ownership, political, social, and ecological forestry landscape.

INDEX WORDS: Afforestation; Forest Carbon; Economics; Land Use Change

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MADISEN FULLER

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MADISEN FULLER

Major Professor:	Puneet Dwivedi
Committee:	Bob Abt
	Daniel Markewitz
	Yukiko Hashida

Electronic Version Approved:

Ron Walcott
Dean of the Graduate School
The University of Georgia
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CHAPTER 1

INTRODUCTION

Background

The concentration of global atmospheric carbon dioxide (CO_2) has been rising rapidly due to the increased use of fossil fuels for meeting the energy needs of the growing population and global development. The total concentration of CO_2 in the atmosphere is currently 414 ppm as of 2020[1], a 47% increase since pre-industrialization. The increased concentration of atmospheric CO_2 has led to a rise in global temperatures, with NASA estimating a 1-degree Celsius (or 2-degree Fahrenheit) increase between 1880 and 2019[1]. This trend is substantiated because 19 out of 20 of the warmest years on record have occurred since 2001[1]. This is expected to have massive long-term effects such as longer growing seasons, increased droughts, heatwaves, changing rain patterns, and rising sea levels in the United States alone[1].

Global efforts are being made to mitigate climate change impacts, mostly focusing on technological improvements such as alternative energy sources. However, there has been increased interest in using nature-based solutions to mitigate climate change[2–8]. Nature-based climate strategies combine the understanding of dynamic natural systems with social and economic theory to harness the extant ecosystem services for carbon reduction, land restoration, and climate change mitigation[3]. Nature-based climate solutions typically focus on urban ecology[2], agricultural lands[7], water[8] and wetlands[4], renewable energy sources[6], and forest ecosystems[5].

Forests can be used as a climate change solution in four main ways, i.e., increased forestland area, increased carbon density within forests, use of forest products, and reduced emissions by stopping deforestation[5]. The area of forestland can be increased through afforestation, or the establishment of forestland in areas previously classified as another land use, such as cropland or pastureland. This does not include increased forestland area resulting from re-planting forest stands, or reforestation. This climate mitigation strategy can increase global carbon stock while simultaneously providing environmental, economic, and social benefits[9].

In light of multiple benefits associated with afforestation, including but not limited to climate change mitigation, several global initiatives have been launched. For example, the Trillion Tree Initiative, a campaign with an expanded network of stakeholders, aims to plant one trillion trees by 2050[10]. Already, several organizations in the United States have announced plans to promote afforestation. For instance, the American Forest Foundation recently pledged to conserve, improve, and grow 84 million trees nationwide[11]. Therefore, it is critical to determine trends in historical land use and combine the information generated with data on land characteristics and economic profitability for ensuring the optimum utilization of financial resources for achieving afforestation targets worldwide.

Information on historical changes in land use, land characteristics, and social and economic conditions can be used for probabilistic regression models that predict future changes in forest land and carbon stock. One research effort determined global locations for afforestation at the lowest costs, finding most of the least-cost regions are mostly in Sub-Sahara, Southeast Brazil, Southeast Asia, and other developing regions[12]. Research from 2020 in New Zealand developed a logistic model to determine spatially explicit causes of afforestation and found that afforestation is most likely to occur in the northeast region[13]. Similarly, an analysis explored afforestation potential and economics in western Canada, finding a moderate amounts of land that is appropriate afforestation and that the number of potential afforested acres declines when the economics of afforestation were included[14]. Within the United States, a study estimates that by 2051, afforestation will create an increase in carbon storage, production of timber, higher food yields, and decreases in habitat for modeled species[15]. Despite a handful of studies[12–16], a significant portion of the literature estimating changes in forestland and carbon impacts are focused on deforestation, mostly focusing on tropical countries (e.g., India[17–19] and Brazil[20–22]) and regions (SE Asia[23,24] and Africa[25,26]).

The United States currently has 766 million acres of forestland[27], i.e., 8% of the total global forestland[27]. It is the largest producer of roundwood worldwide, supplying 29% of the total roundwood harvested globally[27]. Out of the total forestland currently present in the United States, 44.1 million acres were afforested between 1920 and 2017[27]. It is expected that the present trend of afforestation will continue in the future with a rise in the average age of farmers and ranchers, coupled with increasing urbanization where the rural population is migrating to cities, leaving land behind[28]. At the same time, the United States accounts for over five billion tons of CO_2 emissions annually[29]. The forestlands of the United States are a net sink for carbon, offsetting 9% of total annual carbon emissions nationwide[30]. The southern region of the United States consists of 13 states (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia), which together account for only 32.1% of total forestland in the nation. However, the region supplies 63.4% of the total roundwood harvested nationwide and sequesters about 10% of the total carbon sequestered by forestlands in the country[31].

Loblolly pine plantations cover 70.9% of the plantation forestland area in the Southern United States and are the dominant source of southern timber supply[27]. The prevalence of loblolly pine plantations in the Southern United States has grown significantly, accounting for roughly 70.9% of the total pine plantations in the region[27]. Technological improvements related to cultivation, tree planting, thinning, fertilization, and genetic changes have led to increased management for the growth of pine plantations[32]. This increased frequency and productivity of loblolly pine plantations has led to much discussion of its importance in ensuring forestry as a net carbon sink at the national level. For this reason, several studies have focused on the economics of loblolly and other southern pine plantations in the Southern United States[33–39]. For example, one study estimates a 31% increase in carbon accumulation in the Southeastern United States by managing pine plantations for bioenergy use[39]. A 2009 study elucidates the economic importance of carbon payments for forest stand carbon, estimating an increase in the Land Expectation Value (LEV) from $1,384 to $2,807 when these payments are included in a slash pine plantation in the SE United States[33]. Similarly, various studies have focused on trends in forestland in the Southern United States[12–16].

Despite the existing afforestation trends and carbon benefits of loblolly pine plantations, the literature on the economics of carbon stored on an acre of afforested loblolly pine stand does not exist to the best of our understanding. The state of Georgia, located in the Southern United States, serves as a case study for several reasons. First, Georgia has the most extensive acreage (about 25 million acres, 8 million of which are under pine plantations) under forestry among all the states located east of the Mississippi River. Second, about 3.9 million acres of land have moved to forestry between 1920 and 2017[27]. Third, Georgia has a large industry supporting 148,414 jobs and contributing $36.3 billion to the state's economy in 2018[40]. Finally, about 1.8 billion tons of carbon is already stored in the forestlands of Georgia. These trends indicate that directed afforestation efforts could significantly enhance carbon stored on the forestlands of Georgia, thereby generating multiple environmental, social, and economic benefits.

Goal and Objectives

The goal of this thesis is to add to the current knowledge on the feasibility and impacts of afforestation as a climate change mitigation strategy. The two objectives of the study are:

a) Estimate the cost of carbon sequestered on an afforested acre of loblolly pine in Georgia for informing national and global afforestation efforts.

b) Estimate land with potential for afforestation SW Georgia to determine the most cost-effective incentives to increase afforestation.

CHAPTER 2

THE COST OF CARBON ON AN ACRE OF AFFORESTED LOBLOLLY PINE STAND IN SOUTH GEORGIA, UNITED STATES[1]

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[1] Submitted to Scientific Reports: Fuller and Dwivedi (2020)

Abstract

The Trillion Trees Campaign and Trillion Trees Initiative are part of the global climate change mitigation efforts to increase forest carbon storage through afforestation. It is vital to understand the economics of carbon stored on afforested lands for evaluating the role of afforestation towards mitigating climate change across all the potential nature-based solutions. In this study, we estimated the cost of carbon stored on an acre of loblolly pine (*Pinus taeda*) over a 100-years simulation period in the Lower Coastal Plain Region of the Southern United States. We varied inherent site indices, interest rates, and carbon discount rates for ascertaining the impacts on the cost of the total carbon stored across three carbon pools (stand, finished wood products, and wood present in landfills). Here, we show that the net cost of carbon stored on an acre of afforested land currently ranges between -\$0.48 /ton and -\$9.19/ton over a 100-years simulation period when only the cost of silvicultural practices is taken into account. The cost of stored carbon increases significantly with the rising urgency of mitigating climate change. Considering the cost effectiveness of carbon stored on an acre of afforested loblolly pine stand, afforestation should be promoted as a strategy for carbon management as early as possible for reducing the overall cost of mitigating climate change.

Introduction

The Trillion Trees Campaign and Trillion Trees Initiative are part of the global climate change mitigation efforts to increase forest carbon storage through afforestation. It is vital to understand the economics of carbon stored on afforested lands for evaluating the role of afforestation towards mitigating climate change across all the potential nature-based solutions. In this study, we estimated the cost of carbon stored on an acre of loblolly pine (*Pinus taeda*) over a 100-years simulation period in the Lower Coastal Plain Region of the Southern United States. We varied inherent site indices, interest rates, and carbon discount rates for ascertaining the impacts on the cost of the total carbon stored across three carbon pools (stand, finished wood products, and wood present in landfills). Here, we show that the net cost of carbon stored on an acre of afforested land currently ranges between -\$0.48 /ton and -\$9.19/ton over a 100-years simulation period when only the cost of silvicultural practices is taken into account. The cost of stored carbon increases significantly with the rising urgency of mitigating climate change. Considering the cost effectiveness of carbon stored on an acre of afforested loblolly pine stand, afforestation should be promoted as a strategy for carbon management as early as possible for reducing the overall cost of mitigating climate change.

Afforestation is gaining popularity as one of the nature-based solutions[6] for mitigating climate change worldwide, including the United States. Nature-based climate strategies combine the understanding of dynamic natural systems with social and economic theories to harness the extant ecosystem services for carbon reduction, land restoration, and climate change mitigation[6]. The United States currently has 766 million acres of forestland[7], i.e., about 8% of the total global forestland[7]. It is the largest producer of roundwood worldwide, supplying 29% of the total roundwood harvested globally[7]. Out of the total forestland currently present in the United States, 44.1 million acres were afforested between 1920 and 2017[27]. Domke et al.[41] reported that there exists a potential to increase carbon sequestration capacity by about 20% (206.6 million tons) annually by fully stocking all understocked productive forestland in the United States. Though the future of afforestation is uncertain and often debated, it is expected that the present trend of afforestation will continue with a rise in the average age of farmers and ranchers, coupled with migration of rural population to urban centers[28]. The United States is already significantly contributing to the global efforts envisioned in the Trillion Tree Campaign (launched in 2006) by planting 150.7 million trees between 2006 and 2020[11]. Additionally, the Trillion Trees Initiative, launched in 2020 by the World Economic Forum, is creating an extensive network of global stakeholder groups meant to increase global afforestation through reducing deforestation, improving forest protection, and advancing restoration[10]. As a result, several organizations have recently announced their plans to promote afforestation nationwide in the coming years. For example, American Forest Foundation recently pledged to conserve, improve, and grow 84 million trees nationwide[11].

According to the USDA Forest Service, the Southern United States is comprised of thirteen states (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia). This region covers only 32.1% of the total forestland present in the nation but annually supplies 63.4% of total softwood roundwood harvested nationwide[27]. As a result, the southern region is also referred to as the wood basket of the United States. This high contribution to the national softwood production is typically attributed to 48.2 million acres of land under softwood plantations across southern states[27]. Out of the total forestland under plantations in the Southern United States, about 70.9% is planted loblolly pine (*Pinus taeda*)[27]. The planted loblolly pine is the primary source of forestry output in the Southern United States, as loblolly pine is a relatively fast-growing native species whose current productivity is approaching 8 tons/acre/year, much higher than 1 ton/acre/year in the 1920s[42]. It is also a dominant species for reforestation and afforestation efforts across the region, accounting for 85% of the planted seedlings each year[43].

The United States accounts for about five billion tons of carbon dioxide equivalent emissions per year[29]. The forestlands of the United States are a net sink for carbon, offsetting an estimated 9% of total annual carbon emissions nationwide[30]. The southern forestlands sequester 10% of the total carbon annually sequestered by forestlands nationwide[31]. Carbon stored and annually sequestered on planted loblolly pine stands both on reforested and afforested lands is vital for ensuring that the forestry sector is a net sink of carbon at the national level. Several studies have focused on the economics of loblolly and other pine plantations in the Southern United States in the presence of payments for net carbon sequestered[33–39]. However, no study, to the best of our knowledge, has yet characterized the cost of carbon stored on afforested lands in the Southern United States. Some studies have determined the cost of carbon stored on afforested lands in other regions[14,44–47]. These studies mostly focus on carbon stored in stands and do not account for multiple rotations or carbon stored in finished wood products and wood present in landfills, thereby possibly overstating the cost of carbon stored on afforestation lands. Furthermore, most studies do not use varying discount rates for the overall carbon stored to facilitate our understanding of the economic viability of afforestation as a potential solution for mitigating carbon emissions relative to other potential nature- or technology-based solutions. This is a significant gap in our understanding, as the carbon saved today will be valued more by society than that same amount saved in the future with a rising urgency for mitigating climate change reflected in the selected carbon discount rate.

This study aims to estimate the cost of carbon sequestered on an acre afforested with loblolly pine in Georgia, a state located in the Southern United States, for informing national and global afforestation efforts, especially in light of the Trillion Trees Campaign and Trillion Trees Initiative. The three objectives of the study are: (i) estimate carbon stored across three carbon pools (stand, finished wood products, and wood present in landfills) over time, (ii) determine the profitability ($/acre) of an acre of afforested loblolly pine plantation; and (iii) determine the per-unit cost of stored carbon ($/ton) in the presence of varying carbon discount rates with an acre of afforested loblolly pine plantation in South Georgia.

We selected Georgia as a case study for this study for several reasons. First, Georgia has the largest forestland (24.6 million acres) across all the states located East of the Mississippi River[27]. Second, about 65% of the total land in Georgia is under forestry cover[27]. Third, the forestry industry, directly and indirectly, supported 148,414 jobs in Georgia and generated an economic output of $36.3 billion in 2018[40].

Fourth, Georgia alone supplied 10.7% of total softwood harvested in the country in 2017, the highest in the country or 17.3% of total softwood harvested across southern states[27], the highest in the region. Fifth, 32% of the total forestland in Georgia is planted with pines, out of which the majority is under loblolly pine plantations[27]. Finally, about 3.9 million acres have been afforested in Georgia between 1920 and 2017[27]. Therefore, Georgia provides a gateway for understanding the economics of carbon stored on afforested lands in the United States, in general, and in the Southern United States, in particular. Georgia has different trends than other states in the region, with the states of Louisiana, Mississippi, and Arkansas having higher rates of growth and Florida showing net decreases in forestland. The findings of this study could be easily compared to other plantation species of significance at the global level for understanding the role of afforestation as a potential carbon mitigation option relative to other nature- or technology-based solutions.

Methods

Selected Scenarios

We selected an acre of afforested loblolly pine stand in the Lower Coastal Plain Region of South Georgia, United States, as a system boundary for this study. For assessing the impact of site productivity on the roundwood production, we selected three inherent site indices of 50, 60, and 70 feet. The site index is the average height of the dominant and co-dominant trees on a stand at the 25th year of plantation growth and is used as an indicator of site productivity. With forestry management, the realized site index in the 25th year can be greater, reflecting greater growth. For each site index, we assumed three real interest rates (4%, 5%, and 6%) as the cost of capital. Additionally, we assumed four discount rates (0%, 1%, 3%, and 5%) for discounting stored carbon. Carbon discount rates represent the social cost of carbon storage and are often included in the analysis to represent differences in urgency placed on reducing carbon emissions[48,49]. For example, a society with high urgency of reducing emissions will have a higher carbon discount, resulting in a lower perceived value of carbon that is stored in the future. Accurately and consistently determining levels of carbon storage allows for the estimation of an associated price of carbon that will incentivize afforestation as a prominent land management strategy. We selected these carbon discount rates based on previous studies[48–51].

Growth & Yield

We used a loblolly pine Growth & Yield (G&Y) Model developed by Gonzalez-Benecke et al.[52] for ascertaining the availability of three roundwood products (pulpwood (PW), chip-n-saw (CNS), and sawtimber (ST)) relative to stand age for selected site indices. G&Y models simulate biological growth of a forest stand using advanced mathematical modeling tools and techniques[53–56]. The information generated directly feeds into forest management plans for ensuring the continuity of wood availability and meeting regulations and other societal needs. We used the G&Y Model developed by Gonzalez-Benecke et al.[52] for several reasons. First, it is the most advanced G&Y Model available in the public domain. Second, it is relatively easy to use as it is a spreadsheet-based model. Third, this model has been used by several studies for understanding the issues around carbon, intercropping, bioenergy, and economics in the Southern United States[38,53,57–59]. We followed standard silvicultural practices reported in Table 1 for operationalizing the selected G&Y Model.

Net Present Value

We used Equation 1 for estimating the Net Present Value (NPV) of an acre of afforested loblolly pine plantation. In Equation 1, t is the simulation period, and r is the real interest rate. TV is the total market value of roundwood products estimated by multiplying the market prices of PW, CNS, and ST with the yields of PW, CNS, and ST at a given stand age, respectively. TC is the cost per acre of land for site preparation, management, taxes, fertilization, and the opportunity cost associated with loss of an acre of hay land income, which is estimated to be \$129.83/acre according to University of Georgia Extension for non-irrigated Bermuda hay (round rolls)[60]. Parameters for calculating NPV are reported in Table 1. We calculated the NPV of all possible rotation ages (stand age ranging from 20 years to 50 years) over a 100-years simulation period. The rotation age at which NPV was highest was selected as an Optimal Rotation

Age (ORA) for further analysis, assuming that a landowner will select a rotation age that maximizes NPV over a 100-years simulation period.

$$Net\ Present\ Value\ (NPV) = \sum_{t=0}^{t=T} \frac{TV_t - TC_t}{(1+r)^t} \qquad (1)$$

Carbon Balance Estimation

For a given ORA at a particular site index, the trajectories of carbon in the forest stand, carbon in finished wood products, and wood present in landfills were assessed over a 100-years simulation period. Stand carbon is comprised of carbon stored in the biomass of a forest stand, including biomass from stem-wood, bark, foliage, branches, tree crowns, taproots, lateral roots, fine roots, dead trees, needle and branch-fall, harvest residues, and thinning residues. We estimated the carbon stored in an acre of loblolly pine stand using the carbon output from the selected G&Y model[52]. We also included net changes in soil carbon in our analysis resulting from the conversion of pastureland into forestland. We followed Smith et al.[61] for ascertaining changes in the soil organic carbon numbers on an acre of afforested land in South Georgia.

We also considered other carbon pools which were consisted of carbon stored in finished wood products (e.g., single-family housing, multiple-family housing, paper in use, etc.) and wood present in landfills. To determine the estimated carbon sequestered by all loblolly timber, we assumed that the total carbon content is 25% of harvested roundwood by weight. We selected a simplified system boundary (Fig. 1) for ascertaining the carbon stored in finished wood products and wood present in landfills over a 100-years simulation period. We used parameters reported in Table 2 for operationalizing Fig. 2. Finally, we followed Dwivedi et al.[34] for modeling the carbon stored in finished wood products and wood present in landfills over time. We assumed that the decay of wood products is exponential over time.

Cost of Stored Carbon

For a given ORA at a particular site index, the present value of the total net costs at a given simulation year was divided by the perceived value of the total carbon stored (stand carbon, carbon stored in finished wood products, and carbon present in wood-products in landfills) for the same simulation year. We determined the per-unit cost of one ton of stored carbon at a given simulation year, by dividing the difference between the present values of cost and present value of incomes by the perceived value of the total carbon stored for the same simulation year. Using these two methods for estimating the per-unit cost of carbon stored, we were able to provide a better understanding of the economic viability of afforestation as a potential tool for mitigation carbon over time. Additionally, we calculated the cost of stored carbon at several site indices, carbon discount rates, and interest rates, keeping ORAs constant for estimating the impact of changes in critical parameters on the per-unit cost associated with one ton of carbon stored on an acre of afforested loblolly pine plantation in South Georgia. It is important to note that this study does not account for the market impacts that would occur from the increased timber supply.

Results

Growth & Yield

The trajectories of G&Y for an acre of loblolly pine plantation located in the Lower Coastal Plain Region of South Georgia for selected site indices are reported in Fig. 2. From planting to thinning years, forest biomass mostly consisted of pulpwood. After thinning, chip-n-saw dominated the product classes, and the availability of pulpwood decreased. Eventually, chip-n-saw volume began to stabilize, and the majority of total roundwood availability was occupied by sawtimber. This was expected as with a rise in the stand age, small-diameter roundwood products start graduating to large-diameter roundwood products as trees gain girth and height. A stand with a site index of 50 feet was thinned at the 17th year of the plantation, whereas a stand with the same inputs at a site index of 70 feet was thinned at the 12th year of plantation. This was attributed to a higher growth rate on sites with higher site indices.

Net Present Value and Present Value of Costs

NPVs for an acre of selected loblolly at a given rotation age over a 100-yearsimulation period at selected interest rates and site indices are reported in Fig. 3. The NPV at a given rotation age is typically higher for a higher site index at a given interest rate because the availability of biomass is greater at higher site indices. We also noticed the NPV at a given rotation age is typically lower for a higher interest rate at a given site index. Overall, the NPV was positively related to the site index and inversely related to the interest rate. Fig. 4 shows the distribution of the present value of costs and incomes for an acre of selected loblolly at a given rotation age over a 100-years simulation period at selected interest rates and site indices. Based on the assumptions, the present value of costs was the same at a given rotation age across selected site indices. The present value of costs increased with an increase in rotation age over a 100-years simulation period and decreased with an increase in the interest rate for a selected site index. The present values of incomes were consistently higher than the present values of costs after a certain threshold of rotation age subject to selected site indices and interest rates. Table 3 reports ORAs, i.e., those rotation ages at which NPVs were highest for a given combination of site index and interest rates.

Carbon Storage

Fig. 5 shows the changes in the perceived value of stand carbon over a 100-years simulation period under four carbon discount levels for three interest rates. Since stand carbon is dependent on biomass available on the stand, its growth is cyclical with higher growth after planting and thinning and massive reductions in the year of harvest. When there was no discount rate on carbon, meaning there was no urgency put on climate change impacts, the total carbon levels were valued the same for each rotation during the simulation. As more urgency was placed on reducing carbon emissions, this same level of stand carbon was valued at a lower quantity as the simulation period increased. For example, with an interest rate of 6% and a site index of 70 feet, the perceived value of the stand carbon over the simulation period was 40.3 tons/acre with zero carbon discount rate. However, it was only 0.5 tons/acre with a 5% carbon discount rate.

The trajectories of carbon present in finished wood products and wood present in landfills differed from those shown for stand carbon. Fig. 6 plots the perceived value of carbon stored in this carbon source by site index, carbon discount rate, and interest rate. This carbon pool increased with each harvest and thinning, unlike stand carbon, which was reduced after thinning or harvest. Since the carbon lasts for the lifetime of the product used, the carbon was cumulative and increasing over time despite the decay of carbon in landfills, but this effect was lessened when a carbon discount rate was applied. For a stand with a site index of 70 feet and an interest rate of 6%, the total carbon stored in finished wood products and wood present in landfills at the end of the simulation period was 201.2 tons/acre. When discounted at a rate of 5% to account for climate change mitigation urgency, this carbon was only perceived to 2.46 tons/acre over the simulation period.

Fig. 7 combines the perceived value of carbon stored in the stand and carbon present in finished wood products and wood present in landfills to report the trajectories of the total carbon stock over a 100-years simulation period. The variability within harvest cycles resulted from the constant growth and reduction of stand carbon, but the general upwards trend reflects the cumulative nature of carbon present in the finished wood products and wood present in landfills. In the scenarios with no carbon discount, carbon stocks at the end of the simulation period were as high as 241.5 tons/acre with a 6% interest rate for a site index of 70 feet. But considering a scenario with a carbon discount of 5%, an interest rate of 6%, and a site index of 70 feet, the perceived value of carbon was only 2.95 tons/acre at the end of the simulation period. Lower interest rates and carbon discount rates resulted in higher total carbon stored during a 100-years simulation period.

Carbon Storage Cost Accounting

When both pools of carbon were considered, the per-unit net cost of stored carbon ranged from -\$0.48/ton in a stand with a 70 ft site index, 0% carbon discount, and 6% interest rate to -\$708.67/ton in a stand with a 50 ft site index, a 5% carbon discount rate, and a 4% interest rate at the end of a 100-years simulation period (Fig. 8). As with each individual pool of carbon, the total carbon stored in these pools changed significantly with changes in the interest rate and carbon discount rate at a given simulation year (Fig. 9).

Discussions and Conclusion

Afforestation is gaining popularity as a nature-based solution for mitigating carbon emissions. Therefore, a need exists for understanding the economics of carbon stored on an acre of an afforested stand to better situate the afforestation as a tool for mitigating carbon emissions relative to other competing technologies. In this context, this study assesses the economics of carbon stored on an acre of afforested loblolly pine plantation located in the Lower Coastal Region of South Georgia, United States. We considered carbon stored in the stand, finished wood products, and wood present in landfills for this study. We also considered three site indices, three interest rates, and three carbon discount rates for determining the overall cost of carbon stored on afforested lands over a 100-years simulation period. Additionally, we opted for two ways for estimating the cost of carbon stored on an acre of afforested loblolly pine stand in South Georgia. First, we used only the present value of total cost related to silvicultural activities for determining the cost of carbon stored. Then, we used the difference between the present value of total cost and the present value of total incomes for ascertaining the cost of carbon stored. This was done to develop a nuanced understanding of the economic feasibility of afforestation as a potential nature-based tool for mitigating carbon emissions in the United States, in general, and in the Southern United States, in particular.

Our results clearly suggest that: a) with a rise in site index, the thinning age decreases as trees grow faster on better sites; b) the availability of different roundwood products changes with stand age as influenced by the site index; c) NPV initially increases with an increase in rotation age but starts decreasing after a certain rotation age; d) interest rate significantly affects the NPV of a stand where a higher interest rate leads to a lower NPV and vice versa; e) carbon stored on the stand shows a cyclic pattern over time consistent with the thinning and harvesting cycles; f) carbon stored in finished wood products and wood present in landfills is significant part of the overall carbon stored from an acre of afforested loblolly pine stand; g) carbon stored in finished wood products and wood present in landfills is cumulative over time; h) the use of a higher carbon discount rate reduces the perceived quantity of carbon stored on an acre of afforested land over time; i) the cost of carbon stored on an acre of afforested land increases with time with a rise in the interest rates and urgency of mitigating climate change; and j) the cost of carbon stored on an acre of afforested land is positive at ORA when only present value of costs related with silvicultural practices are considered, whereas it is negative when profitability is accounted for in the analysis.

Our study informs ongoing deliberations on using nature-based solutions for mitigating climate change. We are finding that afforestation could be one of the most cost-effective tools for mitigating climate change. Considering higher carbon costs related to renewable technologies[62], we should promote afforestation as a strategy for global carbon management through suitable policy and monetary incentives. This is especially true as the cost of carbon stored on an acre of afforested land currently ranges between \$3.98/ton and \$9.19/ton but starts increasing significantly with the rising urgency of mitigating climate change. When making these comparisons, though, one must consider the differences in prices resulting from different methods, data, and interpretation. Study results would be different with the addition of carbon payments or accounting for changes in market prices resulting from the large-scale implementation of afforestation.

In this study, we have not included the impact of climate change on the growth and yield of loblolly pine stand. We have assumed that growth and yield will not change over the selected simulation period of 100-years. A model parametrizing the impact of climate change on the growth and yield of loblolly pine stand does not exist to the best of our understanding. The closest model is developed by Burkhart et al.[63], but it does not model any potential changes in aboveground and belowground carbon pools with respect to projected changes in climate. Recently, Gonzalez-Benecke et al.[64,65] have used 3-PG (a process-based model) for quantifying the impact of climate change on the growth and yield of loblolly pine stands across southern states. However, we were not able to use 3-PG for this study, as 3-PG supports projections till 2100 only, i.e., 80 years from now instead of the 100-years simulation period selected for this study. We also assumed that the prices of roundwood products and costs of silvicultural practices would not vary over the selected simulation period, as projecting them was beyond the scope of the study. However, we have undertaken a detailed sensitivity analysis by varying time, interest rate, and perceived urgency of carbon reductions for ascertaining any changes in the cost of carbon stored in an acre of afforested loblolly pine stand in South Georgia.

This study feeds into future studies focusing on the economics and potential of afforestation as a nature-based solution for mitigating climate change in the United States and other regions of the world. We also expect that our study will feed into global initiatives like the Trillion Tree Campaign and the Trillion Trees Initiative which are promoting afforestation as a potential solution for mitigating climate change worldwide. This study should guide decision-makers in increasing the effectiveness of available budgetary resources in mitigating climate change. However, caution should be exercised while promoting afforestation as a potential solution for mitigating climate change for ensuring social and environmental equities.

Tables

Table 2.1 Parameters used to estimate growth and yield and Net Present Value (NPV) of a loblolly pine stand in the Lower Coastal Plain Region of South Georgia, United States. Price of pulpwood (PW), chip-n-saw (CNS), and sawtimber (ST) are the average prices regionwide in 2018[66]. The opportunity cost of land is the 2019 rental rate of an acre of pastureland in the region[67]. We assumed chemical site preparation (herbicides), mechanical site preparation (sub-soiling, drum chopping), planting (605 seedlings/acre), first fertilization at year 2, thinning, second fertilization immediately after the thinning, and a final harvest[34]. We assumed that an acre of loblolly pine stand would be thinned at a stand age when at least 28 tons/acre of roundwood is available. The final harvest age was ascertained based on the stand age at which NPV was maximum. Once the final harvest age was determined, it was assumed that a landowner would follow the same rotation age over a 100-year simulation period.

Activity	Price	Units	Stand Age	Application
Mechanical Prep	200	$/acre	0	Two-Pass System
Chemical Prep	75	$/acre	0	Herbicides
Seedlings	50	$/acre	0	605 seedlings/ acre
Planting	75	$/acre	0	
Herbicide	40	$/acre	2	
Taxes and Mgmt	10	$/acre/year	Annually	
Op. Cost of Land	0	$/acre	0	
Fertilizer 1	87	$/acre	2	125 lbs/ac DAP, 135 lbs/ ac N
Fertilizer 2	165	$/acre	Post-Thinning	385 lbs/ac urea, 125 lbs/ac DAP

Table 2.2 Parameters for the carbon stored in finished wood products and wood present in a landfill.

Parameters	**Value**
Bark Loss	7%
Biomass: Lumber Conversion	65%
Biomass: Paper Carbon	29%
Paper Half-Life	2.6 years
Multi-Family Housing Half-Life	75 years
Single-Family Housing Half-Life	100 years
Sawtimber to Landfill	76%
Chip-n-Saw to Landfill	67%
Pulpwood to Landfill	34%
Paper Non-Degradable Portion	77%
Lumber Non-Degradable Portion	44%
Degradable Carbon Half-Life	14 years

Table 2.3 Summary of Net Present Value results for the study. Harvest age is the optimal rotation age at which the Net Present Value is highest over a 100-years simulation period over all rotation ages. Net Present Value is the difference between the present value of incomes and the present value of costs.

Interest Rate	**Site Index**	**Thinning & Harvest Age**	**Thinning Intensity**	**Net Present Value**	**Present Value of Costs**
	Feet	Years	% of Trees Removed	$/acre	$/acre
4%	50	17, 25	50%	539.70	1,315.53
	60	14, 25	50%	1,235.75	1,315.53
	70	12, 20	50%	2,090.83	1,484.17
5%	50	17, 25	50%	179.89	1,152.61
	60	14, 22	50%	705.55	1,226.63
	70	12, 20	50%	1,351.43	1,286.91
6%	50	17, 24	50%	-52.78	1,055.76
	60	14, 22	50%	359.93	1,101.00
	70	12, 20	50%	859.05	1,151.20

Figures

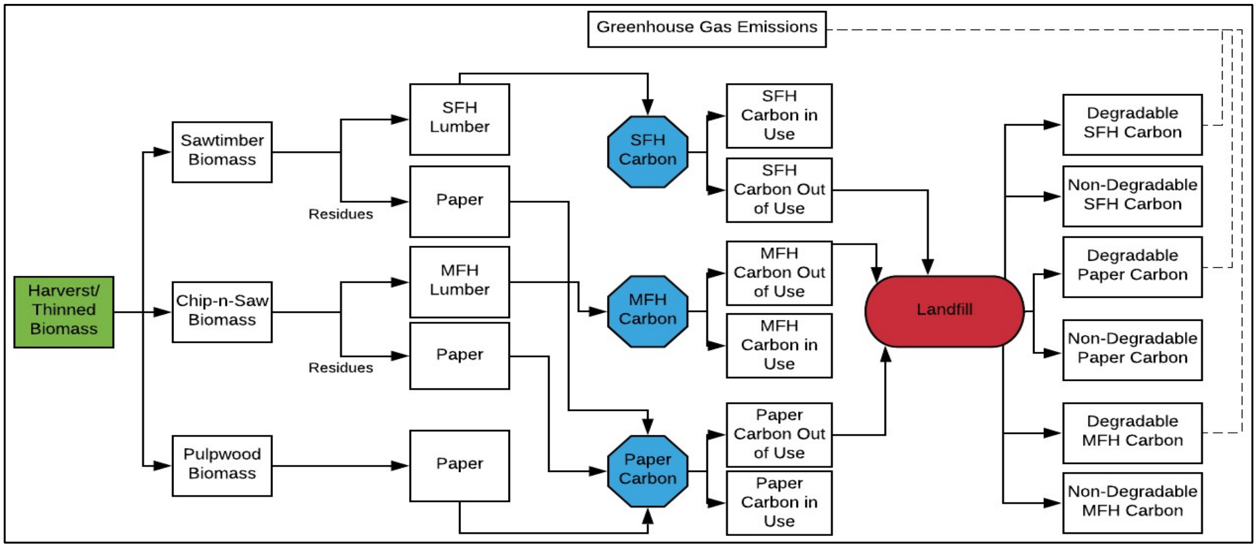

Figure 2.1 System boundary for estimating the carbon stored in finished wood products and wood present in landfills. We have not considered carbon emissions related to the manufacturing and transportation of finished wood products in this analysis. We acknowledge that Figure 1 only presents a snapshot of reality, and the actual flow of materials is more complex. MFH: Multi-Family Housing, SFH: Single-Family Housing.

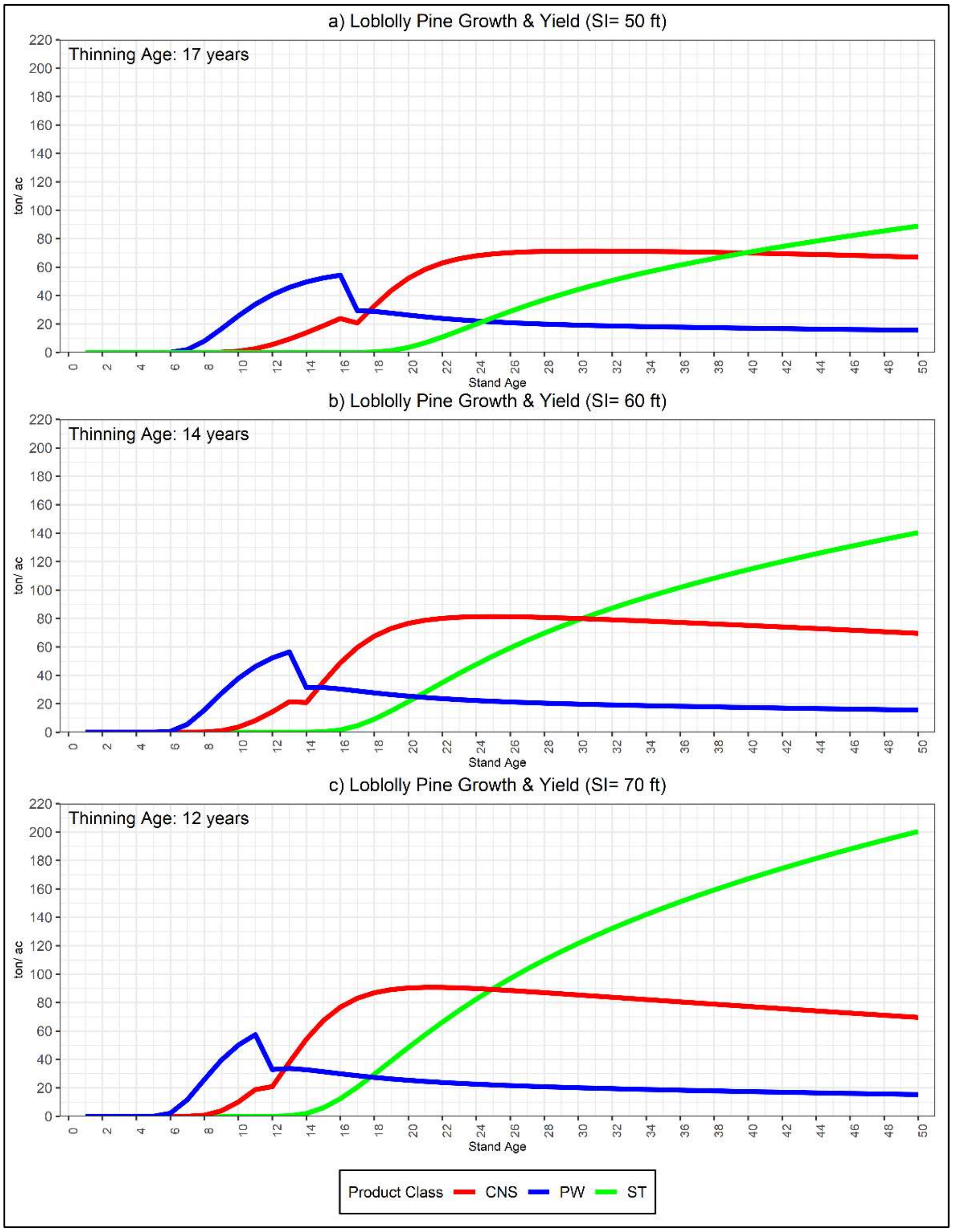

Figure 2.2 Growth & yield for loblolly pine stands with different site indexes. Growth and yield for sawtimber (ST), chip-n-saw (CNS), and pulpwood (PW) for a loblolly pine plantation in the Lower Coastal Plain Region of South Georgia. PW has a diameter at breast height (dbh) between 6" and 9", whereas the dbh ranges between 10" and 13" and greater than 13" for CNS and ST, respectively. We assumed that an acre of loblolly pine stand would be thinned at a stand age when at least 28 tons/acre of roundwood is available.

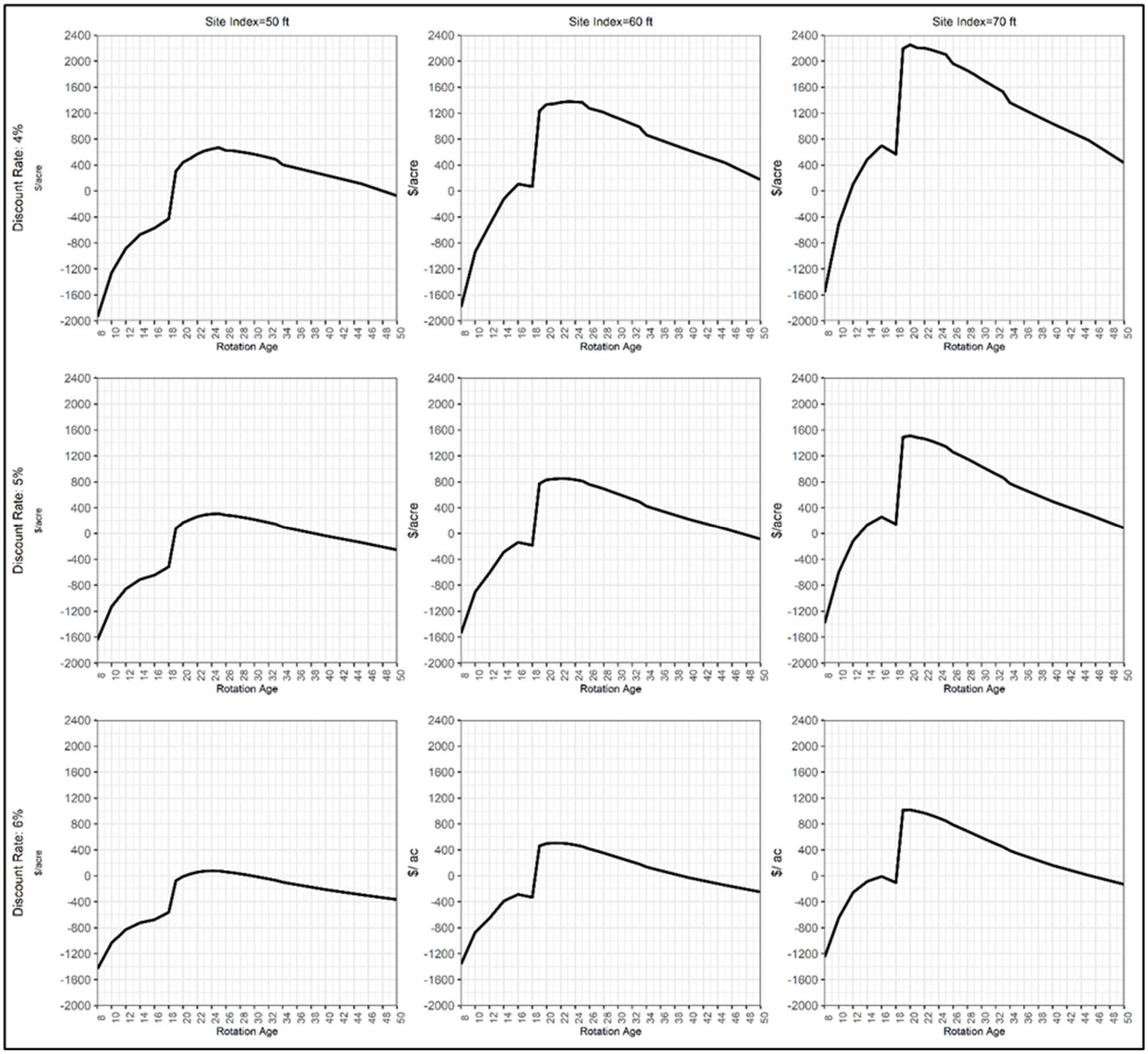

Figure 2.3 Net Present Value associated with an acre of afforested loblolly pine plantation in South Georgia at a given rotation age over a 100-years simulation period. Each point on the graph represents the NPV at year 100 for the associated rotation age.

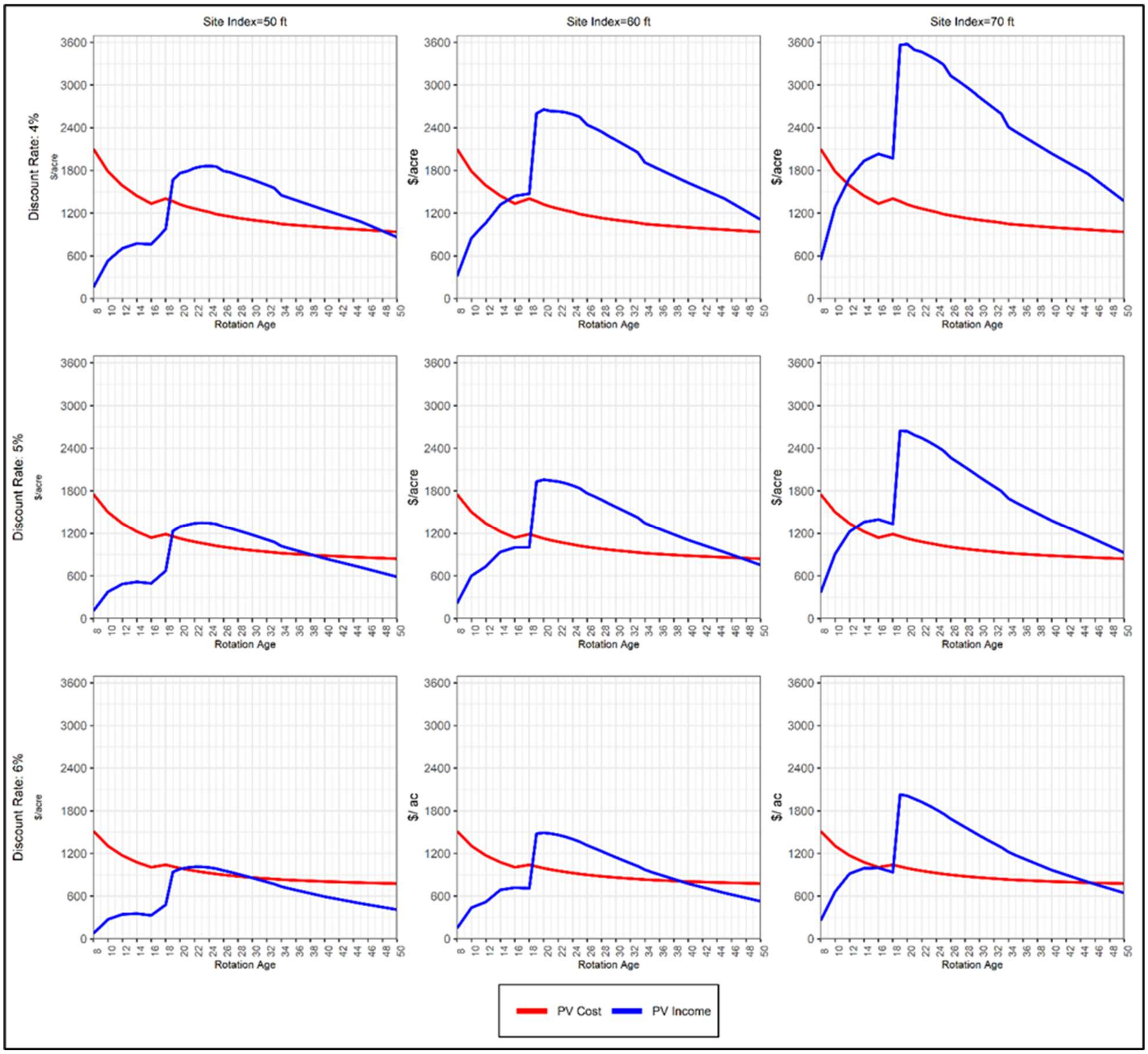

Figure 2.4: Present value of costs and income associated with an acre of afforested loblolly pine plantation in South Georgia at a given to rotation age over a 100-years simulation period.

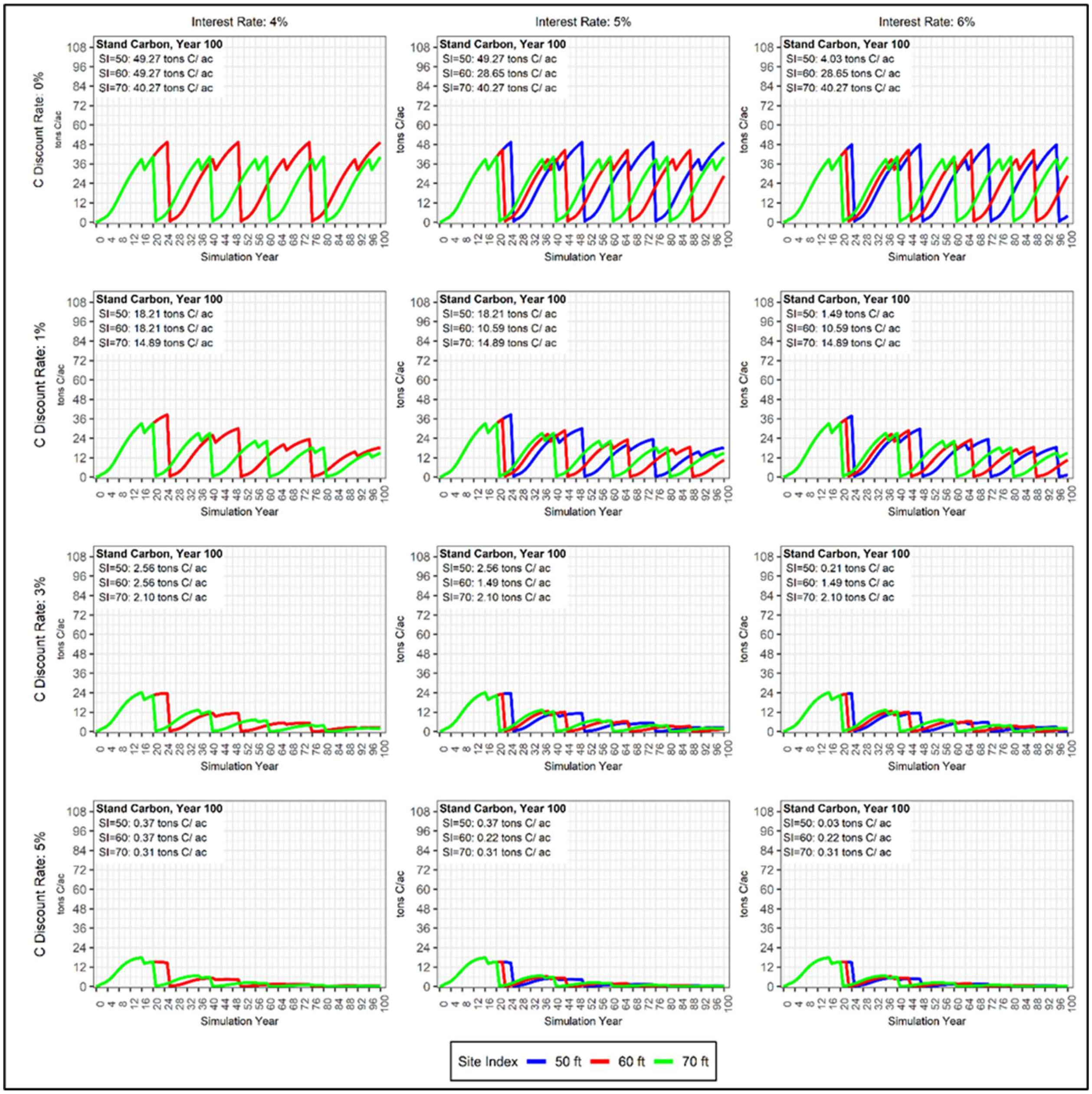

Figure 2.4 The perceived value of stored carbon on an acre of afforested loblolly pine stand in South Georgia over a 100-years simulation period.

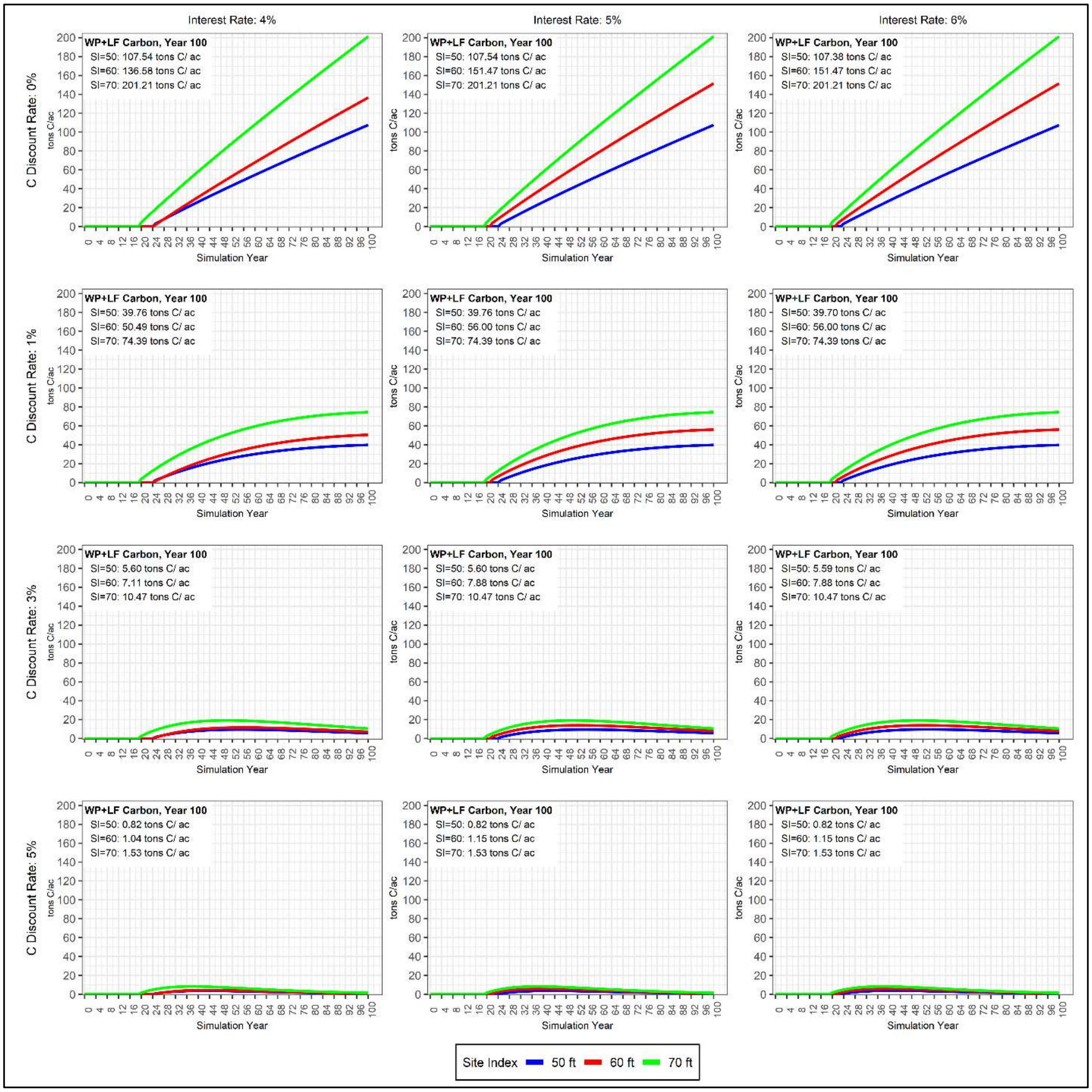

Figure 2.5 The perceived value of carbon stored in finished wood products and wood present in landfills over a 100-years simulation period. We are reporting moving averages for the rotation age for better understanding of the trajectory of stored carbon over time.

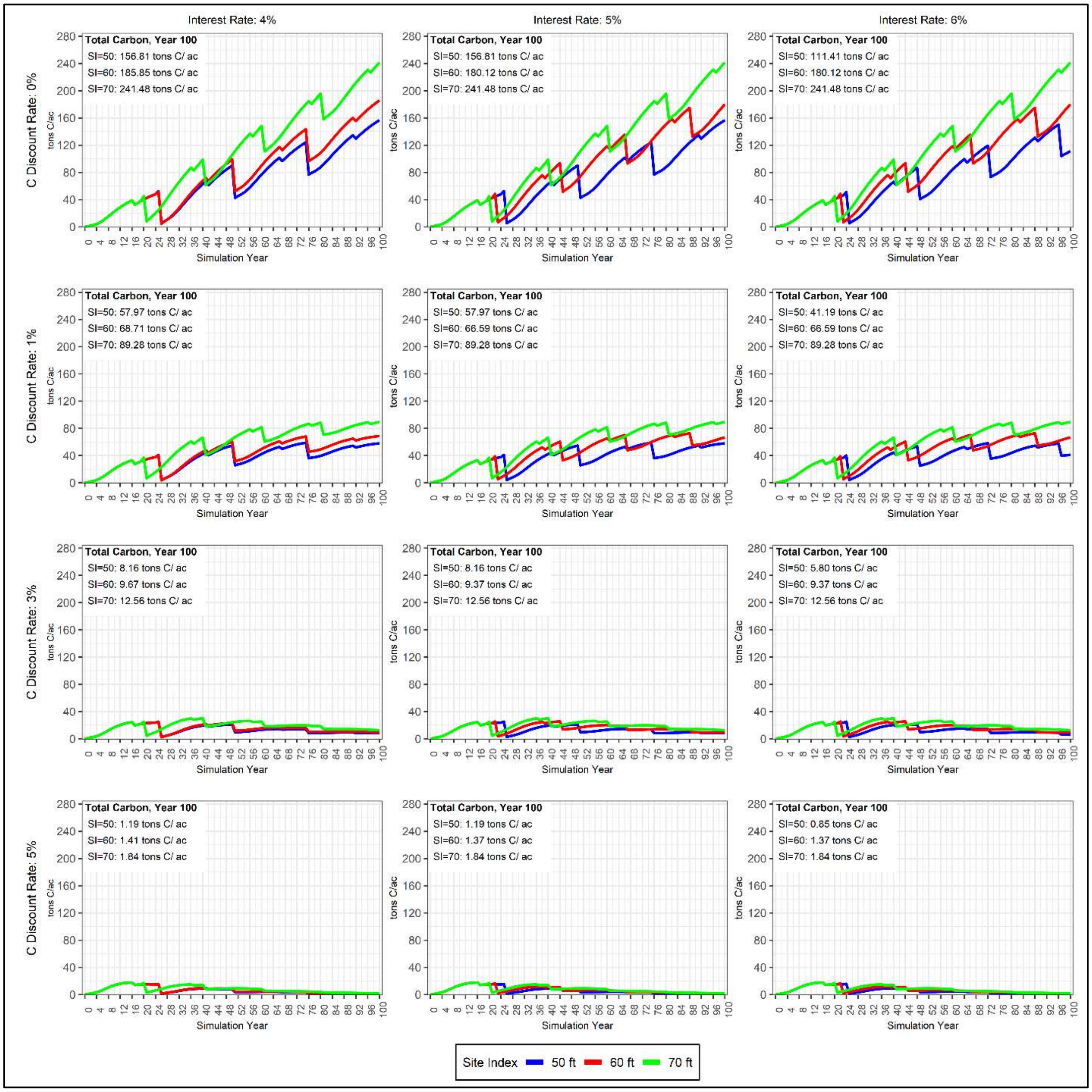

Figure 2.6 The perceived value of total carbon stored in stand, finished wood products, and wood present in landfills over a 100-years simulation period.

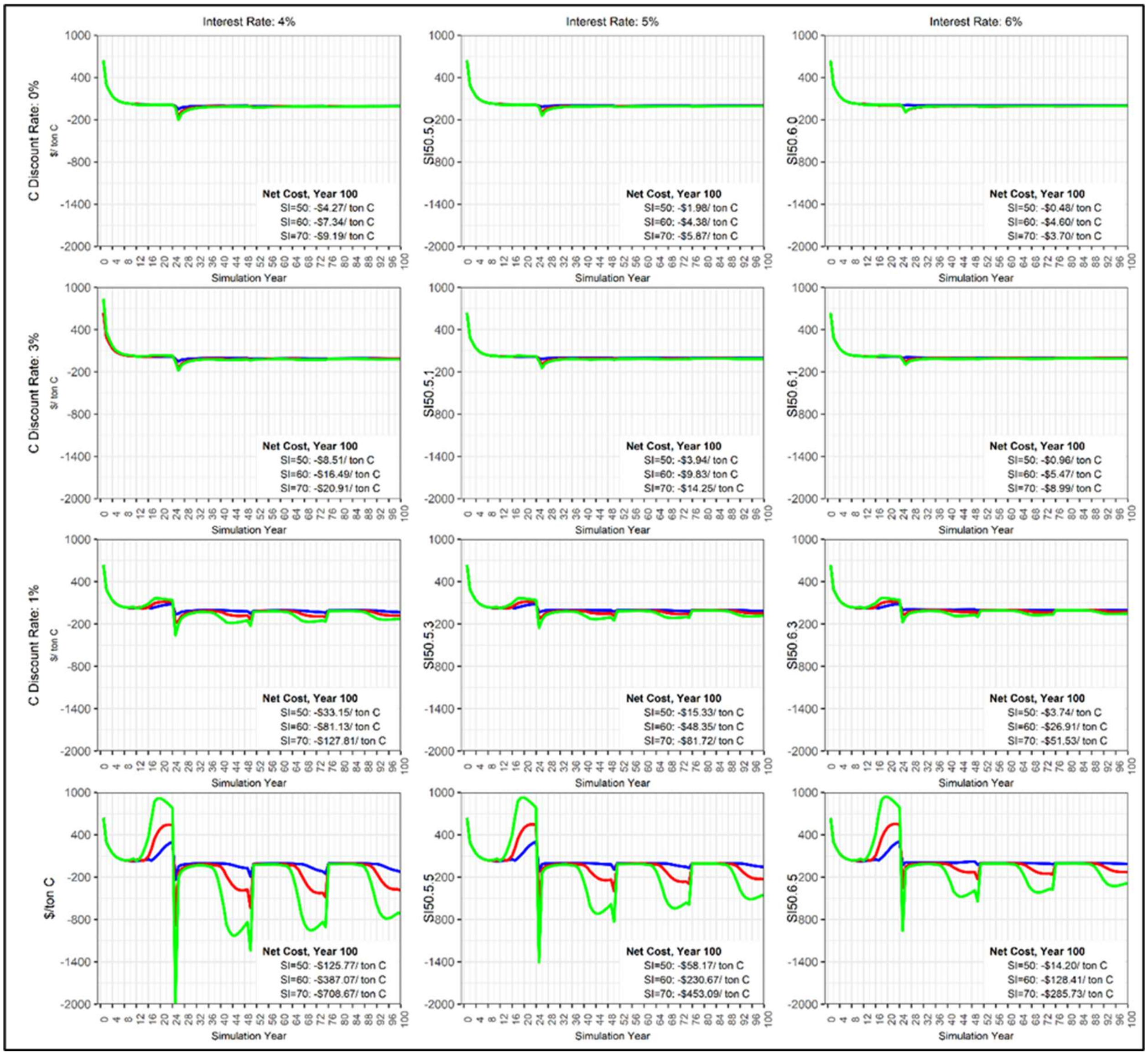

Figure 2.7 The present value of the cost of total carbon stored on an acre of afforested loblolly pine stand in South Georgia over a 100-years simulation period.

CHAPTER 3

DETERMINING FACTORS AFFECTING AFFORESTATION IN THE SOUTHWEST GEORGIA, UNITED STATES[2]

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[2] To be submitted to Forest Policy and Economics: Fuller and Dwivedi (2020)

Abstract

The reduction of carbon emissions is a vital step in mitigating global climate change and minimizing the environmental impacts of increasing average temperatures. The substantial role of forests in the carbon cycle has made them a popular and highly effective source of nature-based climate change solutions involving afforestation, reforestation, and restoration. This study assesses historical afforestation trends in the SW Georgia, determines spatially significant factors that are causing them, and uses a binary logit model to estimate the locations likely to experience afforestation in the future. Based on historical trends, we find that 42,315 acres have moved from cropland or pastureland into forest land. There were factors found to be significant in determining the afforestation of a parcel of land, including the elevation, distance to pastureland, distance to cropland, distance to the nearest timber mill, land capability, and the interaction between land capability and the distance to timber mills. We project that 12,445 acres in SW Georgia are expected to experience afforestation from cropland and pastureland between 2016 and 2031. This study creates a better understanding of optimal locations and conditions for growth in forestland to inform more effective policies to encourage afforestation as a global climate changes mitigation strategy.

Introduction

Afforestation is becoming increasingly popular as a nature-based[12] strategy for climate change mitigation. Growth in the total forestland area to increase carbon storage is being employed on both large and small scales globally. Afforestation is an effective way to increase carbon storage[68], but numerous positive externalities are resulting from this change in land use from an economic and social perspective[69–71]. These positive externalities have inspired global efforts for afforestation, such as the Trillion Trees Initiative, which was launched in 2006. The World Economic Forum launched this campaign to facilitate networks between global stakeholders aimed at ending deforestation, improving forest protection, and advancing forest restoration[10]. As suggested by its name, the Trillion Trees Initiative is aiming to plant one trillion trees globally on land, which was not previously forestland. To implement afforestation programs in the most efficient and effective ways, the feasibility and economics of this strategy must be assessed on global and regional scales.

The United States accounts for only 8% of the global forestland area[27], with a total of 766 million acres[27], but supplies 29% of the roundwood products in the global timber trade[27]. Forest area in the United States increased by 44.1[27] million acres between 1920 and 2017, a trend which is expected to continue with the increasing age of farmers and ranchers, increased global timber demand, and urbanization[28,72]. There is variation in the spatial distribution of total trees planted within the United States, with some regions showing more potential for economically, socially, and environmentally sound afforestation efforts. The 13 southern states in the United States supply 63.4% of national softwood harvested despite only accounting for 32.1% of the total forestland[27]. Additionally, 1 billion trees are planted annually[43] due to their significant role in the region's economy, but this value includes re-planted forests while this study does not. With 48.2 million acres of softwood plantations[27], which are continually improving in productivity[42], this region will be a significant contributor to national and global afforestation efforts.

Forests in the United States are estimated to offset 9% of national emissions[30], which totals to over five billion tons per year[29]. The carbon impact of reforestation and afforestation must be assessed to maintain the crucial role of forests as a net carbon sink at the national level. Of the total carbon annually sequestered in forests of the United States, 10% is sequestered by forests located across southern states[31], thereby making this region a critical case study when assessing the potential and economics of global afforestation. Within this region, the state of Georgia provides an interesting case study for afforestation efforts because of its role in the global timber industry, significant forestland area, increased forest plantation productivity, and existing afforestation trends[27].

A common way to predict future afforestation trends is with a logit model, a binary choice model that estimates the likelihood of an individual observation selecting one of the possible outcomes given observation characteristics. The results of logit models with similar land characteristics and specifications will vary heavily depending on the chosen location of the study area, which should focus on regions with high carbon storage potential and low expected costs. In the Southeastern US, land use is strongly market driven (i.e. wood and land prices) such that nature-based mitigation of carbon emissions might be achieved at low economic costs. Several studies discuss the carbon benefits of the increased volume of common tree species in the Southeastern United States[73,74]. Within the Southeastern United States, the state of Georgia has been extensively studied in the context of land use change[72,75], afforestation[73,74], and forest carbon storage[76,77]. A 2008 study assesses historical trends of land use change in three counties of Georgia, with results estimating a net increase in forestland, a doubling of urban land, and a 59% reduction in cropland[72].

Studies have estimated future changes in forestland utilization on a global[13,16,78], national[15,77,79], and regional scales[77,80]. Projections of global afforestation trends have also been estimated[81], but research on the but the active management and current trends of afforestation in the Southeastern United States requires continued development of projections to full incorporate drivers of future change. This type of analysis is vital in understanding the potential carbon benefits of afforestation efforts in the region to create the most effective and efficient policies. The goal of this study is to estimate potential growth in forestland in SW Georgia, informing national and global afforestation efforts such as the Trillion Trees Initiative. We do this through four objectives: (i) assess land utilization in Southwestern Georgia between 2001 and 2016; (ii) determine locations which experienced transitions of land use to or from forestland during this period; (iii) determine factors which most impacted land use change; and (iv) use these factors to estimate the likelihood of a parcel of land in this region to experience afforestation or deforestation in the future. This study will examine one sub-region in Georgia, but the methodology could be expanded in scope and scale to help determine whether these results are robust over time and regional scope.

Methods

Study Area

This paper assesses changes in land utilization between 2001 and 2016, the first and last year of data for the NLCD, for SW Georgia. There are 22 counties in the selected study area (Figure 3.1). This region covers 5.7 million acres, accounting for 15% of the state's total land area. This region currently compromised of a significant proportion of cropland, making it an ideal location to project existing trends of increased afforestation from cropland.

Land Use

Land Cover data was downloaded as a shapefile from the National Land Cover Database (NLCD) for the state of Georgia for the earliest and most recent years of 2001 and 2016. Developed land was classified together for this study, where the focus is on forestland, cropland, and pastureland. NLCD classifies land use under 15 categories in Georgia [82]. There are five land covers that were considered as forestland, including Evergreen Forest, Mixed Forest, Woody Wetlands, Shrubland, and Deciduous Forest. Cropland is defined as "areas used for the production of annual crops" by the NLCD and pastureland as "areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle"[82]. The general composition of land use was assessed using ArcMap for both study years to determine the most prominent land cover types. The Tabulate Area tool was used to assess which types of land uses were transitioning to and from forestland.

We next determined the number of pixels that experienced each type of land use transition during our historical study period. Each land use category was first assigned a unique numerical ID for each year using the "Reclassify" tool in ArcMap. These IDs were designed to, when added together, create unique values for any possible land use combination between 2001 and 2016. The "Raster Calculator" tool was used to create this output with a pixel count for each land use transition ID. This raster was then transformed into a point layer, giving the ID for each pixel in the study area. Lastly, a 30x30 meter grid was created for the study area, and spatially joined with the pixel-level land use data to allow for a spatially explicit comparison with independent variables used in the study.

Land Use Predictors

Based on previous studies, we selected the following variables which have been found to be significant in predicting changes in land utilization over time: average temperature range, elevation, distance to timber mills, distance to developed land, and land capability class[78,79,81]. Some studies include a variable for market prices and payments for carbon storage, but this study assumes these factors to be constant. Figure 3.2 shows the steps involved in transforming data for use in this model. Closer proximity to timber mills reduces the economic costs associated with the production of timber and, thus, increases profits and the motivation to transition a piece of land to forest land. The X-Y coordinates of timber mills in Georgia were found and used to calculate the distance between each cell in the study area and the nearest timber processing mill. Similarly, the distance to developed, crop, and pastureland was calculated for each cell because of the dynamic relationship between agricultural production, urban growth, and forestland[28]. Average temperature range and elevation are critical ecological factors in determining the transition of a parcel of land between forestlands. There are many studies indicating afforestation in regions with more tropical temperatures result in higher levels of forest area growth and more carbon storage[83]. There is also significant variation across the viability of different tree types with different elevations[84]. Land capability classification groups are based on soil characteristics related to the combination of factors such as damage risk, soil depth, effects of previous erosion, and productivity. There are eight classes of land capability ranging from 1, soils which have the lowest damage risk and use limitations, to 8, representing high-risk land with significant limitations to its use[85]. Figure 3.3 shows the spatial distribution of the land use indicators, and Figure 3.4 gives the distribution of these indicators for all land parcels in the Southwestern region of Georgia. Each of these variables was spatially joined with the 30x30 meter grid of each county, assessed at each parcel of land, and spatially joined with the land use data. The data sources and formats are shown in Table 3.1.

Binary Logit for Changes in Forestland

We employed a Logit Model to predict the probability of any 30 x 30 m plot of land used for cropland or pastureland in this Georgia region to experience afforestation between 2001 and 2016. The binary logit estimates response probabilities of a choice, which depends on the characteristics of individual observations rather than choice variable characteristics. The goal of this choice model is to estimate the probability of an observation responding with a certain choice given the individual characteristics of that observation. The described response probability is shown in Formula 1, where y is a random variable with values of {0, 1}, x is a K x 1 vector of conditional variables describing observations, i={1, … , i} and β_i is K x 1. The probabilities estimated from Formula 1 are then used to calculate the conditional log-likelihood for each observation, shown in Formula 2.

(1)

$$P(y_i = 1 \mid x_i) = \frac{\exp(x_i \beta_j)}{[1 + \sum_{h=0}^{J} \exp(x_i \beta_j)]}$$

(2)

$$\ell(\beta_j) = \sum_{j=o}^{J} 1[y_i = j] \log [p_i(x_i, \beta_j)]$$

Estimates for β_j are determined by maximizing the sum of all log likelihood values, shown in Formula 3.

(3)

$$\beta_j = Max \sum_{i=1}^{N} \ell(\beta)$$

With this framework in mind, we used a logit regression to estimate the probability for a 30x30 m plot of cropland or pastureland transitioning into forestland. We used parcel-specific dependent variables shown in Table 3.2 for estimating the probability for each land parcel to experience future afforestation. In terms of Equation 1, our model is estimating the probability that a parcel of land (y_i) will experience afforestation based on a vector of attributes for that parcel (x_{ji}). The Binary Logit Model for predicting changes in forestland was performed using the glm function in R, which gives several important pieces of output, including the log-odds estimates, standard errors, and p-values for each choice outcome.

A structural logit model was run to assess the role of each variable in predicting the likelihood of afforestation. The variables with the highest p-values, indicating lower fit, were removed one at a time until all variables were statistically significant at a 90% confidence rate. Next, a reduced model, including only the statistically significant variables, was estimated. The estimates are then used with 2016 values for independent variables to predict the probability of each cell to experience afforestation, which must be greater than 0.5 to be the likely outcome. Cells that have a probability of transition higher than 0.5 were then aggregated to determine the total number of parcels that will likely experience future afforestation.

Results

Land Use

Figure 3.5 represents the flows in forest- related land use between 2001 and 2016 for SW Georgia. The most prominent land type that transformed was cropland, followed by forestland, particularly evergreen forests and woody wetlands due to its location on the coast of the atlantic and gulf coastal region. There were losses of some forestland between 2001 and 2016, which transformed mostly to developed land, corroborating urbanization in the region. At the same time, there were gains in forestland, mostly coming from cropland. Table 3.3 shows the parcels of land that experienced afforestation from cropland or pastureland between 2001 and 2016.

Land Use Predictors

The distribution of each of the continuous independent variables is shown in Figure 3.6. Because of the likely relationship of the distance between a cell and a timber mill and the land quality, we also created an interaction term between these variables. From the full-form logit, we found that the following variables are significant: distance to timber mills, developed land, pastureland, or cropland, elevation, land capability classes 5 and 6, as well as the interaction between these two land classes and the distance to timber mills.

Logit Model for Changes in Forestland

The results of the reduced form logit are shown in Table 3.4. All included variables were found to be statistically significant with 90% confidence, with the most significant indicators being those measuring the distance between a parcel of land and a timber mill, developed land, cropland, and pastureland. There are positive relationships between afforestation potential and the following variables: Distance to cropland, developed land, timber mills, elevation, and land capability. This means that as these values increase, the potential for afforestation does too. By estimating the log-odds, we can assess the strength of these relationships to get a more meaningful interpretation. For example, the log odds for the distance to croplamd mills variable is 1.003, meaning that a one-unit increase in the distance to cropland a cell has 1.003 times higher probability of afforestation, holding all else constant. This is likely because of the existing trends of cropland transforming into forestland. The variable with the largest impacts on afforestation potential is the land capability class 6, with a parcel in this land class being estimated to increase afforestation potential more than two-fold.

The model estimates were then used to project future growth in forestland with respect to the significant variables, replacing any variables with 2001 data with the values for 2016. The total number of cells predicted to experience each afforestation transformation was then calculated by taking the sum of all cells, which have an afforestation probability higher than 0.5. This number is then transformed into acres, which results in an expected 9,417 acres in this region to experience afforestation from cropland and pastureland. Of these acres, most are expected to transition from the land which was previously classified as cropland.

Discussions

This study evaluates historical and projected changes in forestland, in the Southeastern United States, which has experienced growth in forestland from agricultural land between 2001 and 2016. We evaluate land use changes in SW Georgia as a case study. We first assessed the general distribution of land utilization in each year, finding that most of it consisting of forestland and cropland. We then found the number of acres that transformed into forestland between 2001 and 2016, most of which came from land which was historically classified as forestland, also referred to as reforestation. A binomial logit model was developed to estimate significant factors in predicting conversion to forestland, which included: elevation, distance to cropland, distance to pastureland, distance to timber mills, distance to developed land, elevation, land capability, and the interaction term for land class and distance to mills. A negative relationship was found between the probability of afforestation and the following variables: distance to pastureland and the interaction between land capability and distance to mills. Alternatively, increases in the distance to cropland, distance to developed land, distance to mills, and elevation were found to correlate with afforestation likelihood positively.

An important finding from this study is the positive relationship between land capability and afforestation probability, which increases as land quality gets lower. Focusing such efforts on regions that already have high forest growth potential will provide cost-effective options to reduce carbon emissions through forest sequestration. Additionally, a better understanding of the type of land best suited for afforestation is vital in accurately estimating the carbon benefits of afforestation and associated costs. For example, economic feasibility of afforestation from barren land has been found to be extensive[86], but the associated carbon benefits of afforestation might be more significant in land types with less costly transformation, such as cropland[87]. By aggregating the cell-level predictions for the entire county, the model estimates that there will be a net increase in forestland of 12,445 acres in this region given current trends in land use, results that are promising when discussing afforestation efforts in the Southern United States. If a parcel of land has a high probability of switching to forestland, it will be less costly and, thus, more efficient to incentivize the transition compared to the land which is unlikely to turn into forestland.

Conclusion

We showed that afforestation is already occurring in Georgia's Southwestern region, and there is a high potential for more forestland growth in the future. Combined with the reduction in cropland land, these results promote continued afforestation as a feasible climate change mitigation strategy in the Southwestern region of Georgia. However, this kind of assessment must be performed in other parts of Georgia and states located in the Southeastern United States to understand afforestation trends and projections better. Additionally, the prediction variables included will likely vary across research location based on the economic and environmental conditions. This study can inform global afforestation efforts, such as the Trillion Trees Initiative, in understanding optimal locations and conditions nature-based climate change mitigation strategies.

Tables

Table 3.1 Data sources and formats for dependent variables for estimating afforestation

Data	Source	Format
Land Utilization (2001 and 2016)	National Land Cover Database (NLCD)	.tiff
Land Capability (2016)	Natural Resources Conservation Service (NRCS)	Raster
Mean Temperature (1981-2010)	US Geological Survey Data Catalogue (USGS)	Shapefile
Elevation	US Geological Survey Data Catalogue (USGS)	Shapefile

Table 3.2 Dependent and choice variables used in the binary logit model

Independent Variables, (x_{ij})	**Afforestation Outcomes (y_{ij})**
Elevation	Cropland to Forestland
Distance to Developed Land	Pastureland to Forestland
Distance to Timber Mill	
Distance to Cropland	
Distance to Pastureland	
Temperature Range	
Land Capability Classification (1-8)	

Table 3.3 Historical afforestation from cropland and pastureland in SW Georgia.

Transition	**Acres**
Cropland to Evergreen	40,060
Cropland to Deciduous	117
Cropland to Mixed	445
Cropland to Shrubland	1,559
Cropland to Woody Wetland	17
Pastureland to Evergreen	110
Pastureland to Deciduous	2
Pastureland to Mixed	1
Pastureland to Shrubland	4
Pastureland to Woody Wetland	0

Table 3.4 Logit model estimates, standard errors, and odds ratios for determining changes into forestland between 2001-2016.

Obs: 8,558,944	**Estimate**	**Error**	**Odds Ratio**
Distance to Pastureland	-0.001	(0.00)***	0.999
Distance to Cropland	0.003	(0.0004)***	1.003
Distance to Developed Land	0.001	(0.00001)***	1.001
Distance to Timber Mill	0.00001	(0.00)***	1.000
Elevation	0.010	(0.001)***	1.010
Capability Class 5	0.329	(0.024)**	1.390
Capability Class 6	0.812	(0.056)**	2.251
Distance to Mills*Class 5	-0.00001	(0.00)***	0.999
Distance to Mills*Class 6	-0.00001	(0.00)***	0.999
Constant	-4.95	(0.011)**	0.007

Figures

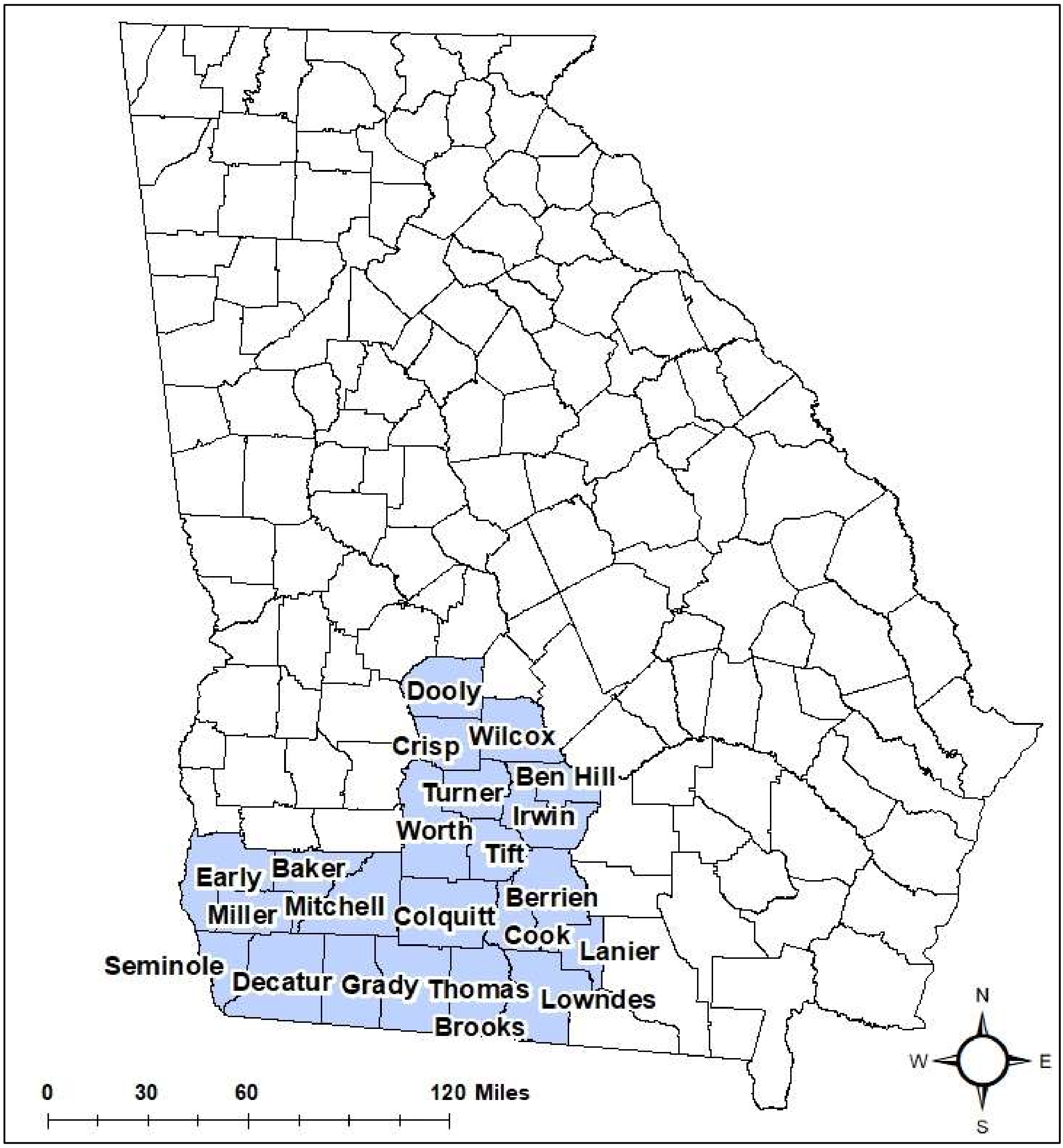

Figure 3.8 Counties included in the SW Georgia.

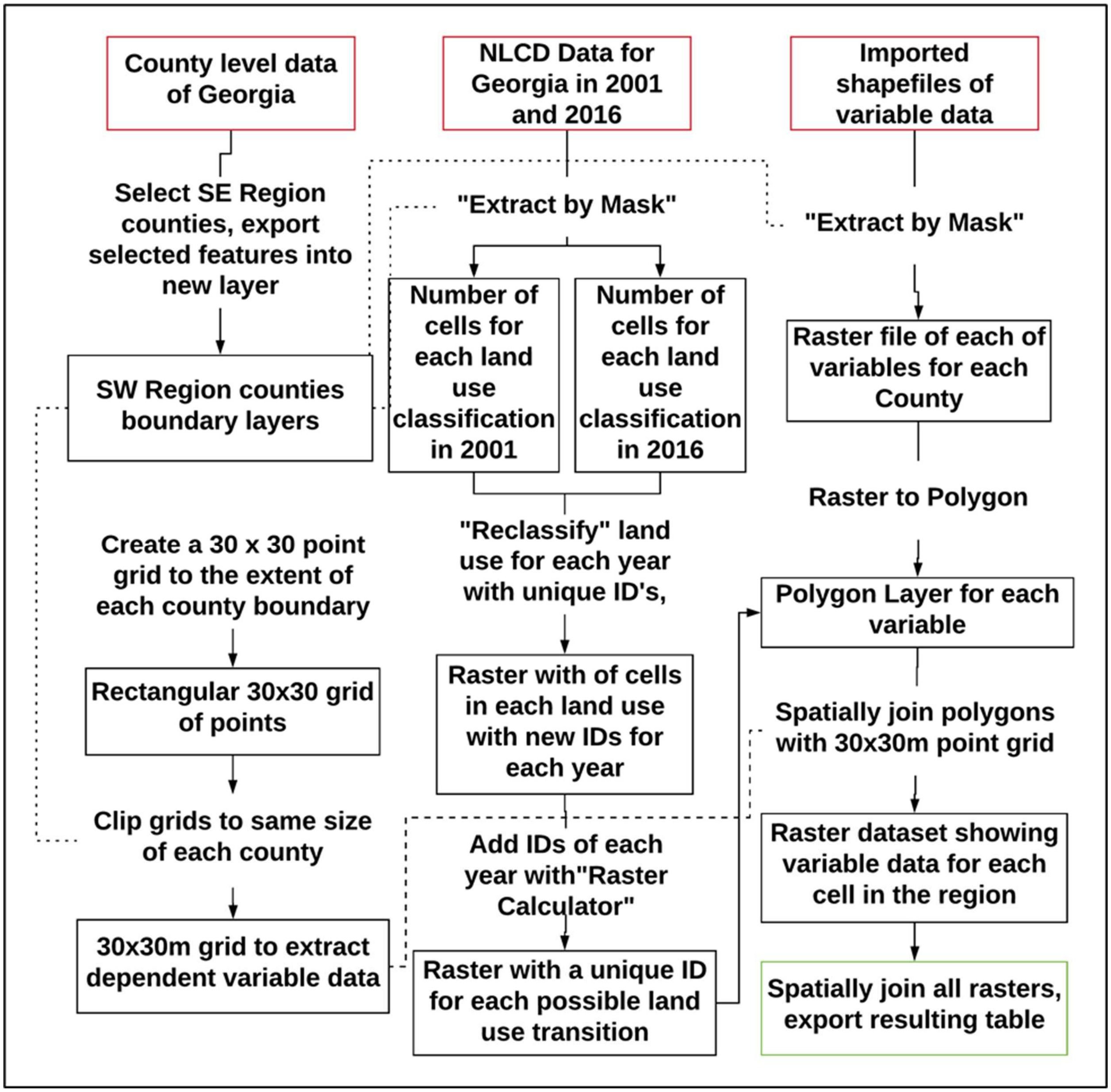

Figure 3.9 Flow chart of steps taken for transforming dependent variable data.

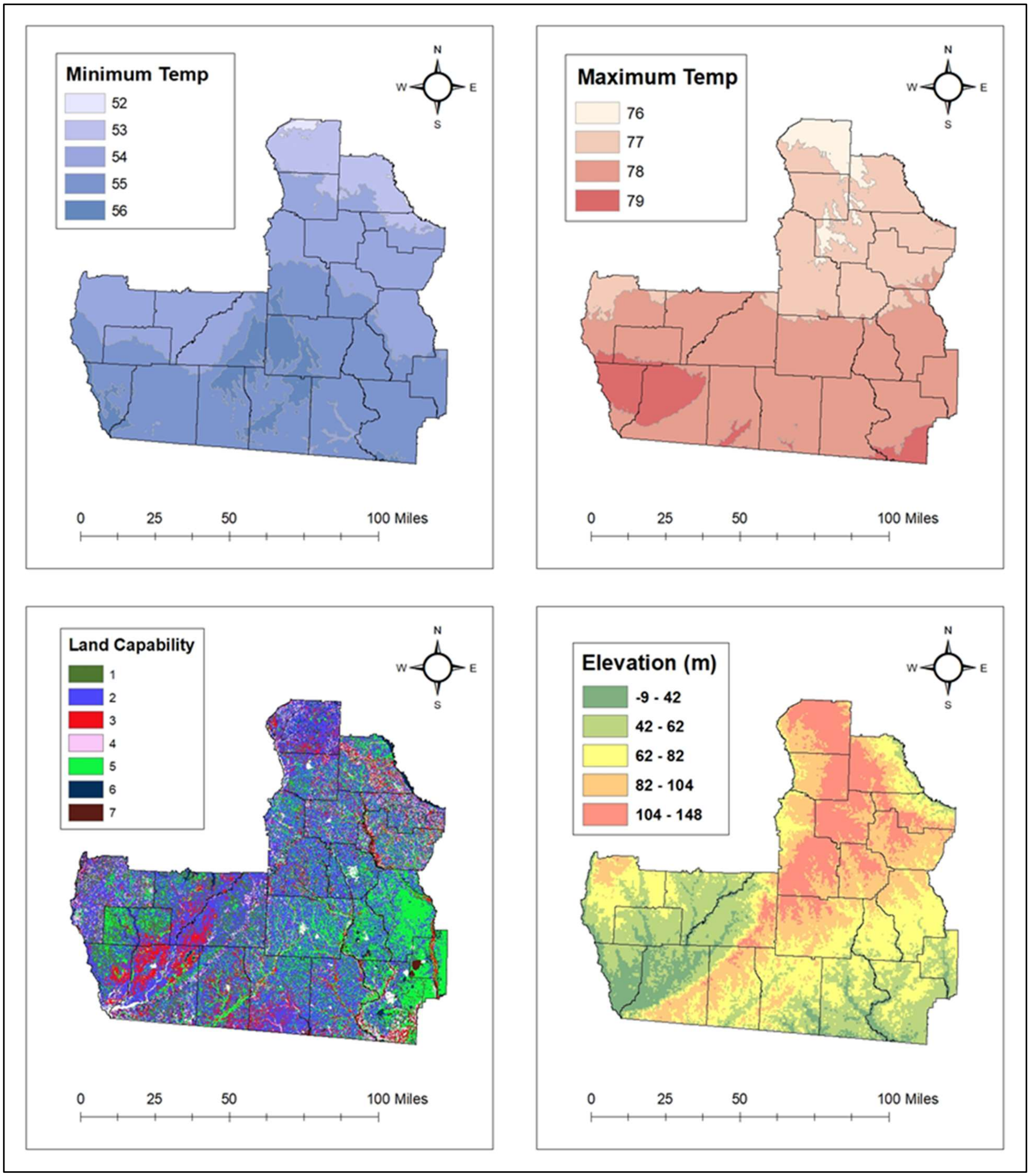

Figure 10.3 Distribution of independent variables in SW Georgia.

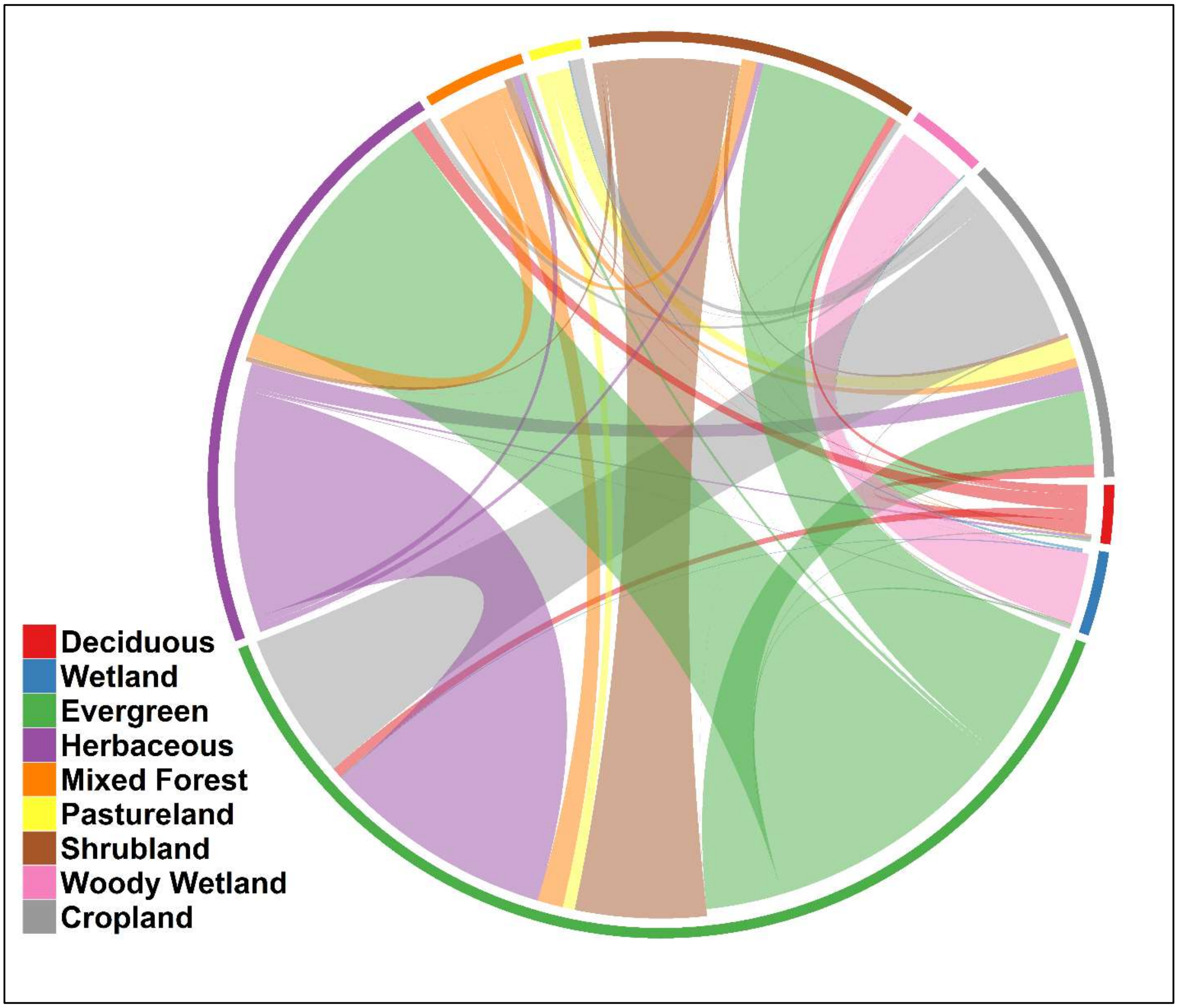

Figure 11.4 Flows between land use types in SW Georgia between 2001 and 2016. Each land type is represented by a different color, shown in the legend, and the intensity of these transformations are shown by the thickness of the flows between land types.

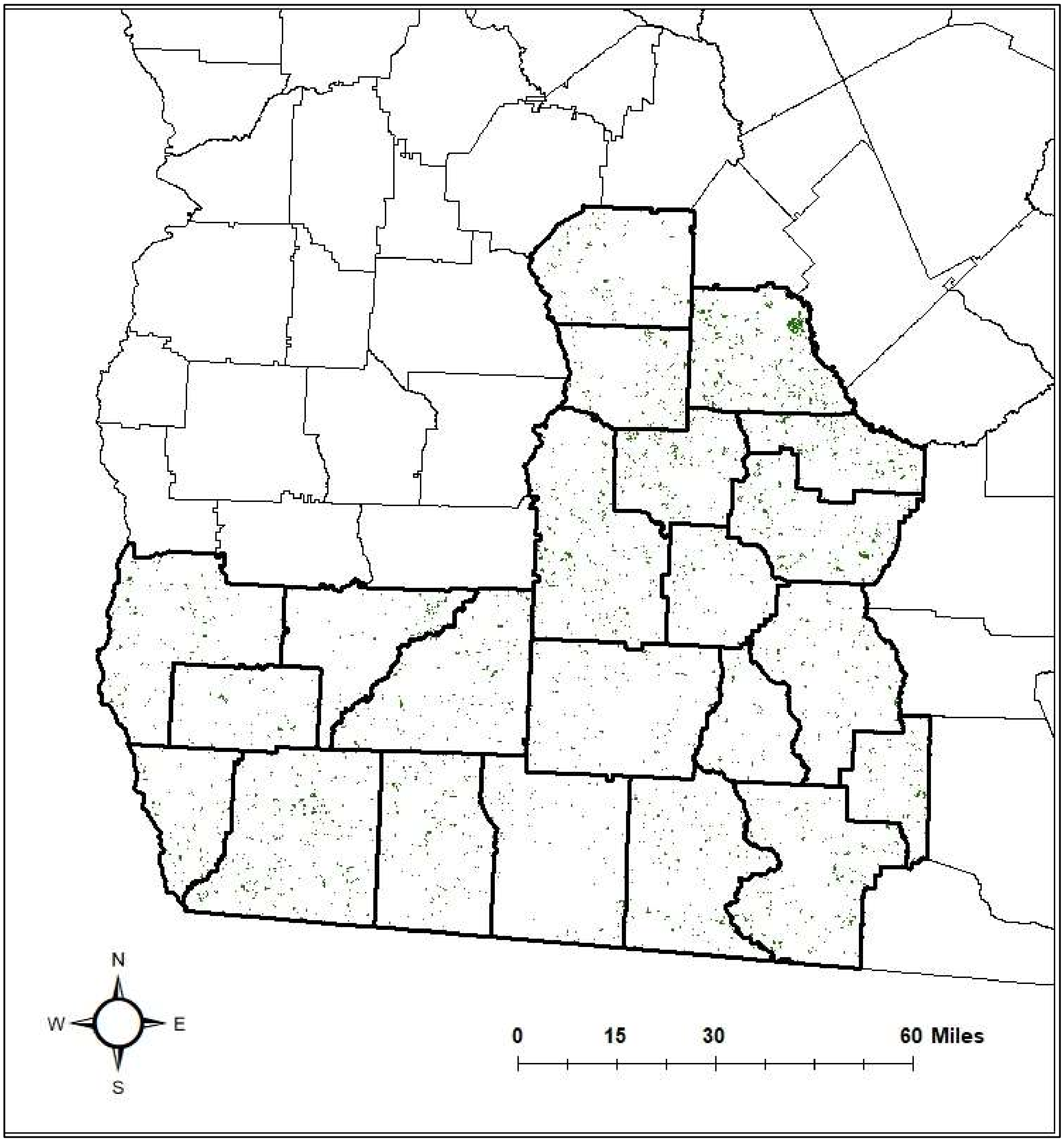

Figure 12.5 Land in SW Georgia afforested between 2001 and 2016

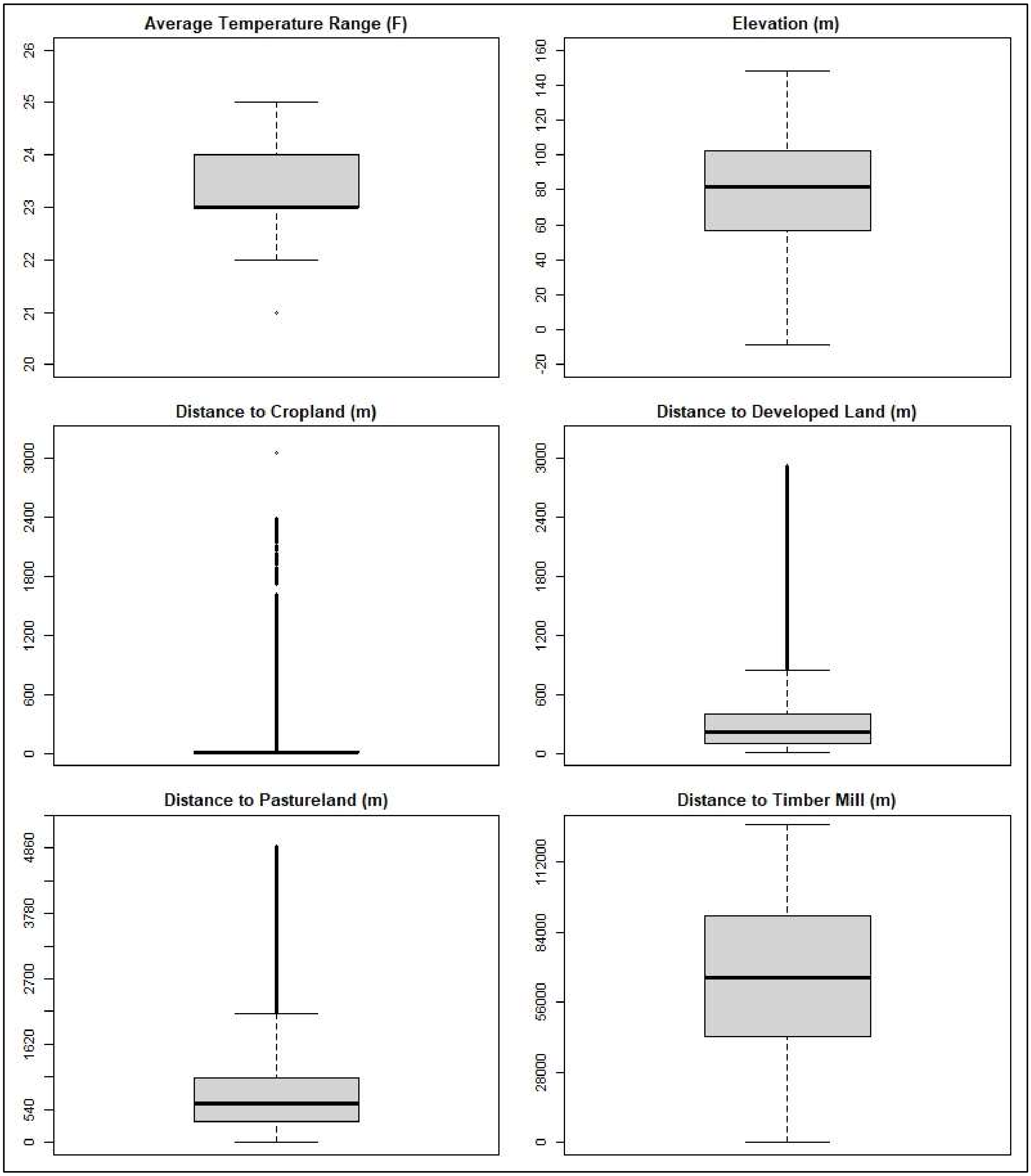

Figure 13.6 Distribution of independent variables in SW Georgia (2001).

CONCLUSION

This thesis provides useful insight into the global discussion regarding afforestation as a climate change mitigation strategy. In assessing the economics involved in converting an acre of loblolly pine plantation in the Lower Coastal Region of South Georgia, we find the area to be highly competitive in costs and carbon benefit. But as the perceived risk of climate change urgency increases, the present value of these costs increases exponentially. These results further emphasize the need for fast action related to afforestation efforts to increase carbon storage. Despite a higher current upfront cost, a landowner will have lower costs of storing carbon if they implement these strategies in a timely manner.

Another part of reducing overall costs to society of mitigating carbon emissions involves constructing these projects in regions that are likely to experience afforestation already, making the additional costs needed to transform the land much lower. We find that SW Georgia has already seen growth in forestland, particularly from cropland, in recent history due to the increased profitability of forestry in the region. Our binomial logit model projects these historical trends and estimates afforestation from cropland and pastureland to occur in more than 12,445 acres in the SW Georgia, a very promising trend given the business as usual assumptions. The results of these studies together highly support using Georgia as a case study for the global adoption of afforestation efforts.

These results will guide policymakers and foresters in enhancing the role of forestry in the necessary reduction of global carbon emissions by providing more accurate land-use projections and demonstrating improved methods for projecting land use trends for Georgia. The results and methods in these studies will also serve as an example for estimating carbon costs and predicting land use on larger regional, national, and global scales.

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