PROJECTING THE SUSTAINABILITY OF BIOPOWER GENERATION IN GEORGIA, UNITED STATES

by

MD FARHAD HOSSAIN MASUM

(Under the Direction of Puneet Dwivedi)

ABSTRACT

Carbon dioxide emission into the atmosphere from electricity generation has become a concern from a climate change perspective. Replacing coal in Georgia's power plants with biomass can be an effective strategy to reduce carbon dioxide emissions. This dissertation aims to assess the sustainability of using biomass to replace coal in the power plant. Chapter 1 provides a general introduction and literature review of the subsequent chapters. Chapter 2 evaluates nine feedstocks grown in Georgia—loblolly pine, corn stover, cotton stalk, bermudagrass, energycane, giant reed, miscanthus, napiergrass, and switchgrass—for their economic competitiveness and carbon emission compared to coal for power generation. Cost-benefit analysis and the framework of life-cycle analysis (LCA) was used to conduct this study. Torrefied wood chips were found to be the most economical and least carbon-intensive compared to coal. It would require a carbon tax of about $8 for every metric ton of carbon dioxide emitted by coal-electricity to make pine chips price-competitive against coal. Chapter 3 contains a market-clearing supply-chain model to satisfy timber demand at the traditional pulp and sawmills and additional bioenergy demand at the coal power plants of Georgia for 50 years. This chapter includes five forest types in Georgia—planted softwood, natural softwood, upland hardwood, bottomland hardwood, and mixed. It determines the number of acres harvested (varied by location, forest type, and age of the stands), quantity of timber produced and transported to the demand nodes (mills and power plants), and impact on stand carbon and carbon avoided via coal replacement. Replacing 10% coal with both pulpwood and logging residues was found to be the most beneficial from a carbon perspective. Chapter 4 analyzes the land use change in the presence of additional bioenergy demand in the coal-firing power plants for 50 years. Along with the variables analyzed in Chapter 3, this chapter analyzes how much acres would be available under each forest type. This chapter also includes grassland available in Georgia and assumes that coal is replaced by both wood-chips and grass-pellets. Replacing 100% coal with all three types of feedstocks (pulpwood, logging residues, and grasses) provided the highest carbon benefit when benefit from avoided carbon emission via coal replacement was accounted for with changes in the stand carbon. The research will feed into the current policy deliberations for reducing carbon emissions and making Georgia a carbon-neutral state.

INDEX KEYWORDS: forest biomass, life cycle analysis, abatement cost, linear programming, land use, supply chain

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DEDICATION

To my father, Mosaddeq Hossain, probably the happiest person to hear the news of my Ph.D.

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CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

Concerns related to climate change has increased substantially as global air temperature has increased by more than 1 ^{o}C since 1880 (NASA, 2020a). The current level of carbon dioxide, a major greenhouse gas responsible for global warming, in the atmosphere is 414 parts per million compared to 280 ppm in 1880 (NASA, 2020b). One of the major sources of carbon emission is energy generation. The United States consumed a total of 107 trillion MJ energy in 2018, out of which about 80% came from fossilized fuels such as coal, natural gas, and petroleum (US EIA, 2020a). Georgia, the third largest electricity generating and coal consuming state for power generation in the South Atlantic region, consumed approximately 330 billion MJ of energy from coal in 2018 (US EIA, 2020b). Approximately 12.5 million tonnes of coal was used in the coal-based power plants of Georgia in 2018 (US EIA, 2020b). About two-thirds of all carbon emissions from Georgia's power sector was from coal usage. The Clean Power Plan (CPP) was proposed in 2015 to reduce the dependence on coal for electricity generation and, therefore, to reduce the emission of CO_2 into the atmosphere. For Georgia, the plan suggested a 35% reduction by 2030 from the baseline year of 2012—from 724 kg to 476 kg CO_2 MWh^{-1} of electricity generated (US EPA, 2015). The CPP suggested finding suitable and available alternatives to coal.

Biomass can be that alternative in Georgia as it has 10 million hectares of forestland (Brandeis & Hartsell, 2016), about 1.7 million hectares of cropland, and approximately 0.78 million hectares of grassland (NASS, 2020). Georgia can supply approximately 6.2 million tonnes of biomass by 2030, at \$60 t^{-1} (NREL, 2019). Among forest-based potential feedstocks, pine trees constitute the highest amount of biomass, approximately 557 million m^3, which is 45% of all forest biomass in

Georgia (Brandeis & Hartsell, 2016). In addition to biomass from pine, agricultural waste from corn and cotton production and perennial grasses such as switchgrass, bermudagrass, miscanthus, and giant reed are potential perennial sources of biomass in Georgia (Boateng, Anderson, & Phillips, 2007; Brandão, Milà i Canals, & Clift, 2011; Dwivedi et al., 2015; Sahoo, Hawkins, Yao, Samples, & Mani, 2016). With proper inputs such as fertilizer and irrigation, perennial grasses can yield up to 34 t ha^{-1} of dry biomass every year (Álvarez & Helsel, 2014; Anderson, Parker, Knoll, & Lacy, 2016; Knoll et al., 2013; Lamb et al., 2018). Even a low input production system can yield between 8 to 20 t ha^{-1} of dry biomass annually (Coffin et al., 2016; Knoll, Anderson, Strickland, Hubbard, & Malik, 2012).

However, before replacing coal with biomass in the power plants, several economic and environmental sustainability questions must be answered. Biopower was often found to be expensive than coal-based electricity. Studies in the United States have found that the unit production cost of electricity from wood pellets range between \$96 and \$216 MWh^{-1} whereas coal-based electricity was \$95 MWh^{-1} (Brown, Favero, Thomas, & Banboukian, 2019; Dwivedi, Johnson, Greene, & Baker, 2016; Dwivedi & Khanna, 2014a, 2014b, 2015; Manouchehrinejad, Sahoo, Kaliyan, Singh, & Mani, 2019; US EIA, 2015). Additionally, biomass production, processing, and transportation emit GHGs that can reduce its carbon benefit over coal. Determining which feedstock can replace coal in Georgia's power plants with the least expense and least GHG intensity is a critical question.

Georgia's forestland requires special attention since forestland covers about 67% of the state and its forest industry was worth \$36 billion in 2018, supporting 150 thousand jobs (GFC, 2019).

About 45 million tonnes of wood are harvested annually (Brandeis & Hartsell, 2016). About 46% of the harvested wood was in the form of pulpwood, and along with logging residues, it could be the ideal choice to replace coal consumption in Georgia. However, additional biomass demand for coal is likely to have an impact on the number of acres harvested, thus influencing the stand age classes of forest stands and carbon stock in the aboveground forest biomass. Stand age will also be influenced since pulpwood and logging residues availability is dependent on the stand age. These harvesting decisions will need to be optimized to avoid potential losses from the supply chain and unforeseen costs. An optimization model encompassing long planning horizons such as multiple decades can help predict such changes in stand age and stand carbon. Additionally, since transportation is directly related to GHG emission, an optimization model that reduces the transportation distance between harvesting locations and power plants can increase GHG benefits for the environment.

Existing studies used linear programming for various supply chain decisions, including optimizing for when and where forest residues are to be converted into fuel and how the residues are to be transported and stored to satisfy demand at heating plants (Gunnarsson, Rönnqvist, & Lundgren, 2004; J. Kim, Realff, Lee, Whittaker, & Furtner, 2011; Nagel, 2000). However, these studies either lack a longer planning horizon that forest-based planning requires, or it does not look into the impact of harvesting for additional bioenergy demand. Other cost minimization or profit/yield maximization studies accounted for land allocation and scheduling in biomass harvesting subject to various forms of area restrictions (Constantino, Martins, & Borges, 2008; Goycoolea, Murray, Barahona, Epstein, & Weintraub, 2005; Khanna, Önal, Dhungana, & Wander, 2011; T. J. Kim, Wear, Coulston, & Li, 2018). However, land use changes due to replacing various percentages of coal replaced by biomass in the power plants on the state-level are nonexistent.

In this study, I determined the least expensive and the least GHG intensive feedstock for generating power in Georgia using the framework of Life Cycle Assessment (LCA). When forest biomass was determined to the most competitive feedstock against coal, I developed an optimization model that satisfies traditional demand at the timber mills and bioenergy demand under various percentages of coal replaced at the power plants for 50 years. I looked into the impact on stand carbon and carbon avoided via coal replacement. After that, I introduced land use changes between forestland and grassland in the presence of additional bioenergy demand. I estimated the impact on carbon benefit in the presence of grassland and land use change. This study is important in extending our understanding of the potential of displacing coal for electricity generation in Georgia using biomass-based feedstocks for mitigating climate change. It provides a clear understanding of potential changes in forestland in the presence of additional bioenergy demand.

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CHAPTER 2: ESTIMATING UNIT PRODUCTION COST, CARBON INTENSITY, AND CARBON ABATEMENT COST OF ELECTRICITY GENERATION FROM BIOENERGY FEEDSTOCKS IN GEORGIA, UNITED STATES[1]

[1] Masum MFH, P Dwivedi, and WF Anderson. Renewable and Sustainable Energy Reviews. 109514
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Abstract

In Georgia, coal-based electricity generation emitted about 26% of total greenhouse gas (GHG) emissions in 2016. Considering the availability of biomass resources in the state and advent of emerging technologies like torrefaction, biomass-based feedstocks could be directly used in existing coal-based power plants. We performed economic and environmental analyses of electricity derived from nine feedstocks (loblolly pine, corn stover, cotton stalks, bermudagrass, switchgrass, napier grass, giant reed, energycane, and miscanthus) over 25 years relative to coal-based electricity in Georgia. We assumed processing biomass via torrefaction before using the same to substitute coal at the power plant. Pine chips were the least expensive (\$113 MWh^{-1}) and the least GHG intensive (134 kg CO_2e MWh^{-1}) option for generating electricity, with the lowest abatement cost (\$17 t CO_2e^{-1}). Based on sensitivity analysis, the abatement cost could be as low as \$8 t CO_2e^{-1} for a 900 MW power plant, the most common capacity of coal-based electricity generating units in Georgia. Between the two agricultural residues, cotton stalk (\$26 t CO_2e^{-1}) had a lower abatement cost than corn stover (\$34 t CO_2e^{-1}). Among perennial grasses, switchgrass and giant reed had the lowest carbon abatement cost (about \$25 t CO_2e^{-1}) because of their low unit production cost of electricity. Other perennial grasses had comparable abatement costs, ranged between \$28 and \$30 t CO_2e^{-1}, except napier grass and energycane, which had the highest abatement cost (about \$38 t CO_2e^{-1}). A carbon tax of \$40 t CO_2e^{-1} could make bioenergy feedstocks found in Georgia competitive against coal for reducing carbon emissions from the electricity sector.

Abbreviations

$	United States dollar
CH_4	methane
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
DM	dry matter
GHG	greenhouse gas
GWP	global warming potential
ha	hectare
kg	kilogram
km	kilometer
L	liter
LEV	land expectation value
M	meter
t	tonne
MJ	megajoule
MWh	megawatt-hour
NO_x	oxides of Nitrogen
NPV	net present value
SO_x	oxides of Sulphur
TWh	terawatt-hour

2.1. Introduction

The United States consumed a total of 107 trillion MJ energy in 2018, out of which about 80% came from fossilized fuels such as coal, natural gas, and petroleum (US EIA, 2020). As a result, the electricity sector alone emitted about 1763 million metric tons of carbon dioxide (CO_2) in 2018, i.e., about 33% of all energy consumption related CO_2 emission in the same year nationwide (US EIA, 2020). The emission of CO_2 and other greenhouse gases (GHGs) contribute to global warming. For instance, the global mean surface temperature has risen by 0.9 ^{o}C between 1880 and 2017, due to the CO_2 emissions coming out of the consumption of fossil fuels for energy needs (NASA, 2020).

In 2017, Georgia was the third-largest electricity generating state (128 million MWh) in the South Atlantic Region of the United States (US EIA, 2018b). In the same year, power plants in Georgia used about 15 million metric tons of coal, making Georgia the third-largest coal consuming state for power generation in the South Atlantic Region of the United States. In Georgia, the electricity sector was responsible for about 26% of the total CO_2 emission in 2016, out of which 64% of the emissions were from coal consumed for generating electricity.

The Clean Power Plan (CPP) was proposed in 2015 to reduce the dependence on coal for electricity generation and, therefore, to reduce the emission of CO_2 into the atmosphere. For Georgia, the plan suggested a 35% reduction by 2030 from the baseline year of 2012—from 724 kg to 476 kg CO_2 MWh^{-1} of electricity generated (US EPA, 2015). The CPP suggested finding suitable and available alternatives to coal for electricity generation in Georgia. In this context, Georgia's 10 million hectares of forestland (Brandeis & Hartsell, 2016), about 1.7 million hectares of cropland, and approximately 1.22 million hectares of pastureland (NASS, 2020) could provide a steady supply of feedstocks for either co-firing with coal or replacing coal entirely with proper processing of obtained feedstocks using emerging technologies like torrefaction, an anaerobic thermochemical conversion process that increases the calorific value of biomass so that biomass is readily usable in the coal-firing power plants without losing thermal efficiency (van der Stelt, Gerhauser, Kiel, & Ptasinski, 2011).

This study determines unit electricity production cost and the associated carbon emission to the atmosphere, and subsequently, the abatement costs for electricity generated from various biomass-based feedstocks in Georgia. We also carried out uncertainty and sensitivity analyses for identifying the most likely range for the abatement cost. The result of this study will indicate the most cost and carbon efficient bioenergy feedstock option for electricity generation in Georgia. It will also help policymakers in making an informed decision about designing an optimal level of incentives for promoting biomass as a potential feedstock for electricity generation in Georgia. Our findings will apply to other southern states who share similar topography, common potential bioenergy feedstocks and rely on coal for meeting their electricity needs.

2.2. Literature Review

2.2.1. Biomass availability in Georgia

According to National Renewable Energy Laboratory (NREL, 2019), the southern states can supply approximately 208 million tonnes of biomass annually from crop residues, forest residues, energy crops, and urban wood waste by 2030 at the price of \$60 t^{-1}. Other regional level studies (Daystar et al., 2014; Ronalds Gonzalez et al., 2011) estimated that the total annual biomass supply in the southern region could be about 412 thousand dry tonnes from agricultural- and forestry-bases feedstocks. Georgia alone can supply approximately 6.2 million tonnes of biomass by 2030, at \$60 t^{-1} (NREL, 2019). Among forest-based potential feedstocks, pine trees constitute the highest amount of biomass, approximately 557 million m^3, which is 45% of all forest biomass in Georgia (Brandeis & Hartsell, 2016). In addition to biomass from pine, agricultural waste from corn and cotton production and perennial grasses such as switchgrass, bermudagrass, miscanthus, and giant reed are potential perennial sources of biomass in Georgia (Boateng, Anderson, & Phillips, 2007; Brandão, Milà i Canals, & Clift, 2011; Dwivedi et al., 2015; K. Sahoo, Hawkins, Yao, Samples, & Mani, 2016). Agricultural land with the least productivity can be converted to produce perennial bioenergy crops for a higher quantity of annual biomass supply. With proper inputs such as fertilizer and irrigation, these perennial grasses can yield up to 34 t ha^{-1} of dry biomass every year (Álvarez & Helsel, 2014; Anderson, Parker, Knoll, & Lacy, 2016; Knoll et al., 2013; Lamb et al., 2018). Even a low input production system can yield between 8 to 20 t ha^{-1} of dry biomass annually (Coffin et al., 2016; Knoll, Anderson, Strickland, Hubbard, & Malik, 2012).

2.2.2. Environmental impacts of bioenergy

A review of existing studies (Masum, Sahoo, & Dwivedi, 2019) suggests that the GHG intensity of electricity from wood pellets was about 180 kg CO_2e MWh^{-1} and electricity from chips was found to range from 15 to 90 (Dwivedi & Khanna, 2014a; Huang & Bagdon, 2018; Thakur, Canter, & Kumar, 2014), whereas GHG intensity of electricity from coal was 1168 kg CO_2e MWh^{-1} (US EIA, 2018a). Studies suggest that using forest biomass and/or perennial grasses such as switchgrass for electricity generation displaces carbon emission from fossil fuel usage, and production of these crops sequesters carbon in the soil (Cheng et al., 2016; Dwivedi, Bailis, Stainback, & Carter, 2012; Galik, Abt, Latta, & Vegh, 2015; Zhang et al., 2010). Switchgrass production showed higher carbon sequestration in the root system than corn, and corn had a higher level of aboveground carbon than willow at a less fertile site but showed no difference in a more productive site (Zan, Fyles, Girouard, & Samson, 2001). Using facility and forest-specific data from Southwest Colorado, Loeffler and Anderson (Loeffler & Anderson, 2014) found that if 20% of coal for electricity production is replaced by biomass, then emissions of CO_2, CH_4, SOx, and particulate matter decreased by 15%, 18%, 27%, and 82%, respectively. They reported that replacing coal with biomass under controlled combustion conditions is significantly more effective for GHG reduction compared to open burning.

2.2.3. Economics of bioenergy

Biomass becomes more expensive compared to its fossil fuel alternatives due to the aggregated cost of biomass production on forestlands or agricultural fields, biomass processing to make power-plant-ready feedstock that has similar energy density and moisture content compared to coal, operating and maintaining power plant, and transporting material along the whole supply chain. One of the earliest studies (Mitchell, Bridgwater, Stevens, Toft, & Watters, 1995) found unit electricity cost from wood chips to be \$100 MWh^{-1}. However, for Canada, significantly lower estimates for electricity from forest harvest residues or agricultural residues were reported, \$63 MWh^{-1} and \$50 MWh^{-1}, respectively (Kumar, Cameron, & Flynn, 2003). Later studies in the United States have found that the unit production cost of electricity from wood pellets range between \$96 and \$216 MWh^{-1} (Brown, Favero, Thomas, & Banboukian, 2019; Dwivedi, Johnson, Greene, & Baker, 2016; Dwivedi & Khanna, 2014a, 2014b, 2015; Manouchehrinejad, Sahoo, Kaliyan, Singh, & Mani, 2019) based on various management choices (intensive vs. non-intensive), feedstock choices (pulpwood only, logging residues only, or both), and transportation distances (transatlantic or domestic). These estimates are higher than the unit cost (\$95.1 MWh^{-1}) of coal-based electricity (US EIA, 2015). This increased cost of biomass is primarily due to the increased delivered price of processed feedstocks. Even without advanced processing cost such as the cost of torrefaction, the delivered cost of biomass can range from \$40 to \$71 t^{-1} for woody biomass (Daystar et al., 2014; R. Gonzalez et al., 2011; Ronalds Gonzalez et al., 2011; Lu et al., 2015; Mitchell et al., 1995), \$40 to \$103 t^{-1} for crop residues (Ronalds Gonzalez et al., 2011; Kamalakanta Sahoo, Mani, Das, & Bettinger, 2018; Shumaker, Luke-morgan, & Mckissick, 2009), \$41 to \$58 t^{-1} for perennial grasses (Aravindhakshan, Epplin, & Taliaferro, 2010; Khanna, Dhungana, & Clifton-Brown, 2008). The delivered price of torrefied woodchips briquettes was estimated to be \$274 per oven dry tonne (Kamalakanta Sahoo, Bilek, Bergman, & Mani, 2019).

2.2.4. Carbon abatement cost of electricity

Biomass is generally regarded as a more expensive but less GHG intensive option for energy compared to coal. Therefore, abatement cost may be necessary to make biomass price competitive with fossil fuel alternatives. Abatement cost could also be interpreted as a carbon tax on fossil fuel necessary to make biomass price competitive. One of the earliest studies (Hall, Mynick, & Williams, 1991) found the carbon abatement cost of electricity generation to be \$55 t CO_2e^{-1} in 1991. A significant development in estimating abatement cost occurred after the Energy Independence and Security Act (EISA) of 2007 that emphasizes clean renewable fuel production in the United States. Aravindhakshan et al. (2010) calculated an abatement cost of about \$7 t CO_2e^{-1} when switchgrass was used for electricity via direct combustion. Dwivedi and Khanna (2014a) also obtained \$7 t CO_2e^{-1} with slash pine biomass was used as chips. When pellets from slash pine were used for electricity, the abatement cost was estimated to be 38 t CO_2e^{-1} (Dwivedi & Khanna, 2015). When those pellets were transported from the United States to the United Kingdom, the abatement cost of electricity estimate was approximately \$7 t CO_2e^{-1} (Dwivedi, Bailis, Bush, & Marinescu, 2011).

2.2.5. Rationale

Most of the existing studies focus on either forest- or agriculture-based feedstocks in a disjointed manner. Additionally, there is a gap in the literature in comparing the economic and environmental performance of feedstocks derived from forestlands and agricultural lands using a similar system boundary and a common set of assumptions. The literature also lacks any estimate on carbon tax required to make biomass competitive against coal in the presence of advanced biomass processing technologies like torrefaction. This is especially true as the existing studies on torrefied biomass only look into technical aspects of the technology (Kulkarni, Baker, Abdoulmomine, Adhikari, &

Bhavnani, 2016; Meng et al., 2015). While dry biomass feedstock has energy densities between 14 and 19 MJ kg^{-1}, the energy density of sub-bituminous coal ranges between 23 and 28 MJ kg^{-1} (Buratti, Barbanera, Bartocci, & Fantozzi, 2015; Krerkkaiwan, Fushimi, Tsutsumi, & Kuchonthara, 2013; Morgan & Dekker, 1988). Torrefaction is necessary for using an existing coal power plant without losing boiler efficiency, as torrefied materials have comparable calorific value as sub-bituminous coal, 25.38 MJ kg^{-1} (Phanphanich & Mani, 2011). Therefore, this study determines the unit cost and GHG intensity of electricity derived from major biomass-based feedstocks, as a comparison between all primary feedstocks available for electricity production in Georgia or any other surrounding states is nonexistent. This study extends our understanding of the potential of displacing coal for electricity generation in the southern United States using biomass-based feedstocks for mitigating climate change.

2.3. Methodology

2.3.1. System Boundary

We estimated costs and GHG intensities starting from biomass production, farm and forest level management practices, biomass transportation, biomass processing, electricity generation, and distribution stage (Figure 2.1).

We considered nine feedstocks under three categories: loblolly pine (*Pinus taeda*) from forestry; corn (*Zea mays)* stover and cotton (*Gossypium arboreum*) stalk from agricultural residues; bermudagrass (*Cynodon dactylon),* energycane (*Saccharum officinarum*), giant reed (*Arundo donax*), miscanthus (*Miscanthus sinensis*), napier grass (*Pennisetum purpureum*), and switchgrass (*Panicum virgatum*) from perennial herbaceous grasses. We considered pelletization of all feedstocks except pine, as pine wood chips are cheaper and environmentally more benign than wood pellets (Dwivedi & Khanna, 2014a, 2015). Then, we torrefied all the feedstocks available in the form of chips (pine) and pellets (agricultural residues and herbaceous grasses).

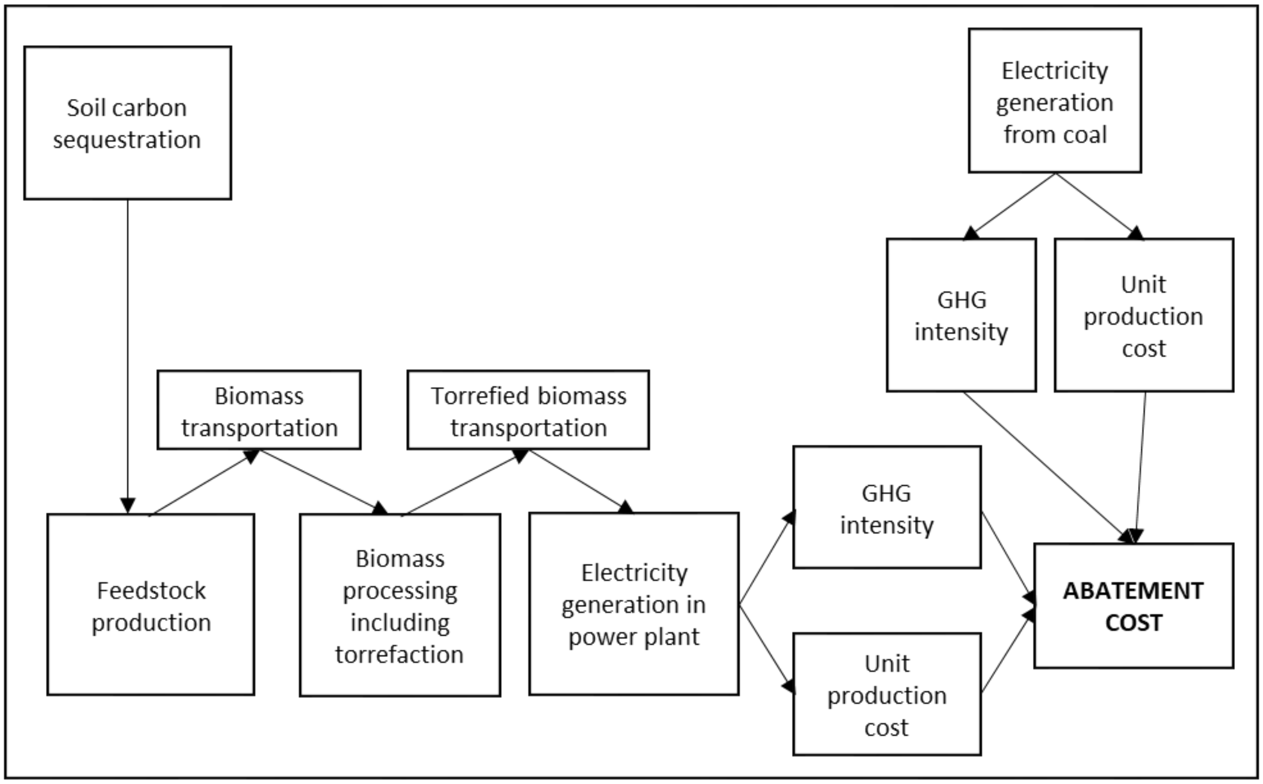

Figure 2.1: System boundary for ascertaining the carbon abatement cost of electricity generation

Since optimal rotation for loblolly pine is about 25 years in Georgia, for a fair comparison, we considered the production of all crops for 25 years. Pine (pulpwood only) was removed at thinning (age 15) and clear cut (age 25). Agricultural residues were harvested every year. Perennial grasses were harvested every year as well, except for the first year. We determined transportation distances from the harvesting site to the biomass-processing center where biomass would be pelletized and torrefied, based on the yield of each feedstock. We assumed another 50 km of transportation distance for torrefied biomass to the coal-based power plant to produce electricity. We estimated all costs at the net present value with a real discounting rate of 4%. We assumed no waste and/or ancillary products from the process of converting harvested biomass to electricity except 5% electricity transmission and distribution loss (US EIA, 2018b). The functional unit of this study was one MWh of electricity generated at a 100 MW power plant.

2.3.2. Data

2.3.2.1. Loblolly Pine

For loblolly pine, we used the Carbon Resource Science Center (University of Florida) growth and yield model (Gonzalez-Benecke, Martin, Jokela, & De La Torre, 2011) suited for the Lower Coastal Plain of Georgia to estimate sawtimber, chip-n-saw, and pulpwood availability for site index 21 m at 25th year of plantation. The site index is an indicator of site productivity, and this site was considered sufficiently productive. We considered harvesting only pulpwood for electricity generation. Pulpwood only was a pragmatic choice as sawtimber has better economic usage, and it caters to a different market. Power plants would buy pulpwood at a market price of \$15 t^{-1} (TMS, 2019), and the cost of transportation, biomass processing, and electricity generation would be added to that to calculate the unit cost of electricity production. As pulpwood was 25% of the total harvested biomass, during thinning at year 15 (73 t ha^{-1}) and final harvest at year 25 (46 t ha^{-1}), we attributed 25% of the total GHG emission to pulpwood production.

We collected data on the calorific value of dry feedstocks, including pine, from published studies and found that the values were similar (Table 2.1). Since calorific values of non-torrefied dry biomass resemble each other closely, we considered that the calorific value of torrefied feedstock would closely resemble each other as well.

Table 2.1: Calorific value of dry biomass across feedstock before torrefaction

Feedstock	Calorific Value (MJ kg^{-1} Dry Matter)	Reference
Pine	17.02 – 19.22	(Domalski, Jobe Jr, & Milne, 1986; Phanphanich & Mani, 2011; Reza et al., 2013)
Corn stover	17.65 – 17.72	(Domalski et al., 1986; Lizotte, Savoie, & De Champlain, 2015)
Cotton stalk	15.83 – 17.73	(Domalski et al., 1986; Gravalos et al., 2016; Sidhu & Sandhya, 2015)
Bermudagrass	17.15 – 18.67	(Boateng et al., 2007; Kim, Hansen, Hansen, Dvorak, & Kempen, 2001)
Energycane	17.22	(Henkel, Muley, Abdollahi, Marculescu, & Boldor, 2016)
Giant Reed	17	(Angelini, Ceccarini, & Bonari, 2005)
Miscanthus	14.4 – 18.8	(Bilandzija et al., 2017; Greenhalf, Nowakowski, Yates, Shield, & Bridgwater, 2013; Mos et al., 2013)
Napier grass	16.3	(Tsai & Tsai, 2016)
Switchgrass	17.30	(Gravalos et al., 2016)

2.3.2.2. Agricultural Residues

For corn stover and cotton stalk yield-related data, we used production guides published by the College of Agriculture and Environmental Sciences (CAES), University of Georgia (CAES, 2018a, 2018b). We considered the production system with irrigation and conventional tillage. We considered 1:1 crop to residues ratio for corn stover availability but considered only 10% of the stover (1.38 t ha^{-1}) for harvest as harvesting at a higher rate could lead to soil degradation and eventually to decreased future crop production. As 10% of the available corn stover was 5% of the total corn biomass volume, we only attributed 5% of the total GHG emissions to stover production. Harvested corn stover price was \$66.09 t^{-1}, which we calculated from Thompson and Tyner (Thompson & Tyner, 2014). They mentioned \$91.37 t^{-1} for the delivered cost (average of \$82.19 and \$100.56) and \$25.28 as transport cost. Subtracting the transport cost from the delivered cost gave us the farm-gate price.

For cotton stalks, we considered the farm-gate price for cotton stalks to be \$43.05 t^{-1}, crop to residues ratio to be 1:4, and sustainably harvestable stalk quantity to be 70% (K. Sahoo et al., 2016). According to the yield reported by CAES (2018b), 70% of the stalk volume was 3.77 t ha^{-1}. Since 70% of the cotton stalk refers to 56% of the total cotton biomass volume, we attributed 56% of the GHG emissions to stalk production. Data on calorific values of agricultural residues are presented in Table 2.1.

2.3.2.3. Herbaceous Grasses

For perennial herbaceous grasses, we acquired cost and yield-related data for Georgia (except energycane in Florida) from published studies (Table 2.2). Anderson et al. (2016) studied the fertilization ratio for bermudagrass production and found that 336-36-347 kg ha^{-1} of NPK yields the highest production (22.6 DM t ha^{-1}) in the presence of 1260 kg ha^{-1} of lime. The P amount used in their study was low only because the available P was high in the soils. In many instances, the P will need to be much higher if the soil is depleted. In our study, we have used 336-112-347 kg ha^{-1} of NPK based on the prescription authors suggested.

Table 2.2: Perennial crop data in published studies

Crops	DM yield (t ha^{-1})	Reference
Bermudagrass	22.6	(Anderson et al., 2016)
Energycane	34	(Álvarez & Helsel, 2014; Knoll et al., 2013)
Giant Reed	12.2	(Knoll et al., 2012)
Giant Miscanthus	11.0	(Coffin et al., 2016)
Napier grass	26.2	(Lamb et al., 2018)
Switchgrass	13.3	(Knoll et al., 2012)

Álvarez and Helsel (2014) did a production budget for energycane in Florida, and we adopted the cultural practices from that study. Despite the fact that they did this study for Florida, we used it because it had detailed cost-related data. However, we separated the unified harvesting, loading, and hauling cost and used matching unit harvest and transport cost across all feedstocks. In addition, we replaced the DM yield results with Knoll et al. (2013) study (34 DM t ha^{-1}), which suits better as they reported yield for Georgia's Lower Coastal Plains. Their estimate was similar to that of Fedenko et al. (2013) for comparable soil profile in Citra, Florida (33 DM t ha^{-1}). Lee et al. (2018) reported 6 t ha^{-1} $year^{-1}$ lower yields for a lower amount of inputs at Tifton, GA. Fedenko et al. (2013) corroborated similar yields for giant reed and giant miscanthus. However, they reported a higher yield for napier grass (33 DM t ha^{-1}) than Lamb et al. (Lamb et al., 2018), which we have adopted in our study as the study site of the latter study was located in southwestern Georgia. For giant reed and switchgrass, even though Knoll et al. (2012) did not include any fertilizer, we assumed annual application of 68 kg ha^{-1} of N as perennial grasses perform better in the presence of nitrogen fertilizers (Muir, Sanderson, Ocumpaugh, Jones, & Reed, 2001). To translate that change into higher yield, we considered the higher harvest data for the second year, which we assumed to continue for 25 years. Generally, there is no harvest in the first year for perennial grasses. Therefore, we did not consider any yield for all perennial crops in the first year. Data on calorific values of dry biomass are presented in Table 2.1.

2.3.3. Transportation distances

Transportation cost was dependent on biomass yield, biomass moisture content, and whether the feedstock could be dried on the field at no cost. We estimated the green biomass collection area, GBCA (km^2) by using equation (2.1) –

$$GBCA = \frac{TBR\ x\ GR}{GBS}\ x\ (1 + NPL) \qquad (2.1)$$

where TBR was the amount of torrefied biomass (t) required in the power plant; GR was the ratio of green biomass to torrefied biomass, which depended on moisture content and usable biomass ratio; GBS was the annual green biomass supply in t km^{-2}, and NPL was the assumed non-productive land ratio (0.4).

Total torrefied biomass required, TBR (t), at the power plant was estimated using equation (2.2) –

$$TBR = \frac{PPC \ x \ OH}{CV_{TWC} \ x \ CE} \tag{2.2}$$

where PPC was the power plant capacity (100 MW); OH was the total number of operating hours in the power plant per year (7451 hours), which is the product of number of days in a solar year (365.25), number of hours per day (24), and load factor (0.85); CV_{TWC} was the calorific value of torrefied biomass (7.04 MW t^{-1} or 25.36 MJ kg^{-1}); and CE was the conversion efficiency of a 100 MW power plant (31.7%). From area (GBCA) estimation, transportation distance (km) was calculated using the standard formula for radius.

2.3.4. The unit production cost of electricity

2.3.4.1. Loblolly Pine

As per standard silvicultural practice (Table S2.1), we assumed 1494 loblolly pine seedlings ha^{-1} to be planted at year zero following herbicide application. Half of the surviving trees were harvested as pulpwood during thinning operation at year 15. During harvest operation, the felling rate was assumed to be 47 t $hour^{-1}$ with \$3.85 t^{-1}, and skidding, delimbing, and loading rate was assumed to be 112 t $hour^{-1}$ with \$1.95 t^{-1} (Jernigan, Gallagher, Mitchell, Smidt, & Teeter, 2016). Harvesting was followed by chipping operation, which would generally be done on-site. We calculated the total torrefied wood chips produced from loblolly pine (WC_{LP} in t ha^{-1}) using equation (2.3).

$$WC_{LP} = PW_{GREEN} \; x \; (1 - MC_{WC}) \; x \; BU_{WC} \; x \; \frac{1}{1 - MC_{TWC}} \tag{2.3}$$

where PW_{GREEN} is the pulpwood available at year 15 during thinning and year 25 during the final harvest in each hectare of forestland (Gonzalez-Benecke et al., 2011). MC_{WC} is the moisture content of wood chips, assumed to be 55% or 0.55, the average value of the range reported by Mora et al. (2011). BU_{WC} is the ratio of biomass (0.8) used to produce wood chips (Dwivedi et al., 2011). MC_{TWC} is the moisture content of torrefied wood chips, 3% or 0.03 (Phanphanich & Mani, 2011). We calculated the total electricity generated from loblolly pine (EC_{LP} in MWh ha^{-1}) using equation (2.4).

$$EC_{LP} = WC_{LP} \; x \; CV_{TWC} \; x \frac{1}{3.6} x \; CE \; x \; (1 - TRAN) \tag{2.4}$$

where CV_{TWC} is the calorific value of torrefied wood chips at 300 ºC, 25.38 MJ kg^{-1} (Phanphanich & Mani, 2011). 1/3.6 is the conversion factor from MJ kg^{-1} to MWh t^{-1}, CE is the conversion efficiency of a 100 MW power plant, 31.7% (Bridgwater, Toft, & Brammer, 2002), and TRAN is the electricity transmission loss 5% (US EIA, 2018c). We did not consider pelletizing the wood biomass as it incurs an additional cost, and pine chips are economically more viable than pellets (Dwivedi & Khanna, 2015). The costs of biomass production, harvesting, drying, torrefaction, and electricity production are reported in supporting information (Table S2.2).

Finally, we calculated the cost of generating 1 MWh of electricity from biomass ($71.65 MWh^{-1}) at the power plant (CoE_{PP}, power plant operating cost) using equation (2.5).

$$CoE_{PP} = \text{LCoEC} - \frac{DCoC \; x \; TCC}{TEC} \tag{2.5}$$

where the levelized cost of electricity (LCoE) from coal ($95.1 MWh^{-1}) in 2015 (US EIA, 2015). LCoE refers to all the cost of generating a specific unit of electricity, in the power plants, in discounted real dollars. In 2017, the delivered cost of coal (DCoC) at the power plant was $46.94 t^{-1}, total coal consumed (TCC) was 599 million metric tons, and total net electricity generated from coal (TEC) was 1,199 TWh (US EIA, 2018a).

2.3.4.2. Agricultural Residue

For corn stover and cotton stalk, we adopted silvicultural practices presented in the CAES production guides (Table S2.3 and S1.4). After collecting harvested biomass with prices mentioned before, power plants will experience cost for transport, pelletization, torrefaction, and electricity production. Assumptions related to torrefaction cost and electricity distribution loss were the same as loblolly pine. Pelletization cost was assumed to be $70 t^{-1}.

We calculated total torrefied pellets produced by both agricultural residues (WP_{BM} in t ha^{-1}) using equation (2.6).

$$WP_{BM} = H_{BM} \; x \; (1 - MC_{BM}) \; x \; BU_{BM} \; x \; \frac{1}{1 - MC_{WP}} \tag{2.6}$$

where H_{BM} is the harvested biomass (t ha^{-1}). MC_{BM} is the moisture content of harvested biomass. For corn stover and cotton stalks, MC_{BM} was considered to be 15.5% and 12%, respectively (Milbrandt, 2005). BU_{BM} is the ratio of biomass used for pellet production (0.9, assuming a 10% loss). MC_{WP} is the moisture content of the torrefied wood pellet, 3%, similar to torrefied wood chips from pine. We estimated the total electricity generated from agricultural residues EC_{BM} (in MWh ha^{-1}) using equation (2.7).

$$EC_{BM} = WP_{BM} \ x \ CV_{WP} \ x \ \frac{1}{3.6} \ x \ CE \ x \ (1 - TRAN) \quad (2.7)$$

where CV_{WP} is the calorific value of torrefied wood pellet, assumed to be 25.38 MJ kg^{-1}, similar to torrefied wood chips from pine.

2.3.4.3. Herbaceous Grasses

For herbaceous biomass, establishment costs, \$1405 ha^{-1} were considered only for the first year and was calculated from Álvarez and Helsel (2014). Although these grasses are perennial in nature, additional reseeding may become necessary. However, we did not include any reseeding operation in our study. We did consider continuing an annual fertilizer application. Bermudagrass production required 336, 112, and 448 kg ha^{-1} yr^{-1} of N, P, and K, respectively (Anderson et al., 2016). For energycane, 2.24 t ha^{-1} of lime was applied at year zero for site preparation. Complete silvicultural practice for energycane production is provided in the supporting information (Table S2.5).

For giant reed, miscanthus, and switchgrass, only N fertilizer was assumed at 68 kg ha^{-1} yr^{-1} rate. The napier grass study had 168 kg ha^{-1} yr^{-1} of N fertilizer and 45 kg ha^{-1} yr^{-1} of K fertilizer, and no

P fertilizer. Even though various data sources (Table 2.2) used different fertilizer prices, we considered the same fertilizer price across the feedstock for a fair comparison. Additional cost parameters for generating electricity from herbaceous biomass are provided in the supporting information (Table S2.6). We calculated total torrefied pellets produced by herbaceous biomass (WP_{BM} in t ha^{-1}) using equation (6). For oven-dry perennial grasses, MC_{BM} was assumed to be 5%. We estimated the total electricity generated from herbaceous grasses (EC_{BM} in MWh ha^{-1}) using equation (2.7).

2.3.5. GHG intensity

2.3.5.1. Loblolly pine

We estimated GHG intensity ($GHG_{ELEC\text{-}LP}$, t CO_2e MWh^{-1}) of electricity generation from wood chips using equation (2.8).

$$GHG_{ELEC-LP} = (GHG_{SITEPREP} + GHG_{FERTILIZER} + GHG_{HARVESTING} + GHG_{CHIPPING} + GHG_{DRYING} + GHG_{TORREFACTION} + GHG_{TRANSPORT} + GHG_{BURN})/EC_{LP} \quad (2.8)$$

where $GHG_{SITEPREP}$ is the GHG emissions related to site preparation with herbicide application, 281.75 kg CO_2e ha^{-1}. This number is 25% of the emission reported by Dwivedi et al. (2011) as pulpwood only contributes that much of the total volume. $GHG_{FERTILIZER}$ is the emissions related to fertilizer application. Table S2.7 in the supporting information contains GHG intensities from various fertilizers, along with other inputs and operations such as disking, chemicals, fuels, and transportation. The parameter $GHG_{CHIPPING}$ refers to the emission-related to chipping of feedstocks (4 kg CO_2e t^{-1}) (PRé Consultants, 2013). GHG_{DRYING} refers to the emission-related to decreasing the moisture content of the biomass and getting it ready for torrefaction, 7.6 kg CO_2e t^{-1} of dried biomass (Haque & Somerville, 2013). $GHG_{TORREFACTION}$ refers to the emission-related to fossil fuel usage for torrefying the biomass, i.e., 68 kg CO_2e MWh^{-1} of electricity. We calculated this value from CO_2, CH_4, and N_2O emission from torrefaction mentioned in Adams et al. (2015) and converting it to CO_2e with standard conversion factors (US EPA, 2018). $GHG_{TRANSPORT}$ indicates to the emission-related to all transports, 0.20 kg CO_2e t^{-1} km^{-1} (US EPA, 2018), including transporting feedstock to the biomass processing center and transporting processed biomass to the power plant. The parameter $GHG_{WC\text{-}BURN}$ refers to the non-biogenic GHG emission-related to burning wood chips, 34.4 kg CO_2e t^{-1} (WDNR, 2010). $GHG_{HARVESTING}$ included felling, skidding, delimbing, and loading operations. We estimate GHG intensity from each of these operations using equation (2.9).

$$GHG_{HARVESTING} = 10.32 * 0.044 * MT * MH \tag{2.9}$$

where 10.32 is the CO_2e conversion factor (kg) from CO_2, CH_4, and SOx emission from one gallon of diesel fuel (US EPA, 2018), 0.044 is the ASAE standard (gallon $horsepower^{-1}$ $hour^{-1}$) for estimating fuel consumption, MT is machine time or the amount of time machine worked, and MH is the machine horsepower. For the felling operation, 282 HP machines are used generally. For skidding, delimbing, and loading, machines with 260 HP are used in the field.

2.3.5.2. Agricultural Residues

We estimated GHG intensity ($GHG_{ELEC\text{-}AR}$, t CO_2e MWh^{-1}) of electricity generation from agricultural residues using equation (2.10).

$$GHG_{ELEC-AR} = (GHG_{CHEMICAL} + GHG_{FERTILIZER} + GHG_{FUEL} + GHG_{PELLETIZATION} + GHG_{TORREFACTION} + GHG_{TRANSPORT} + GHG_{BURN})/EC_{AR} \quad (2.10)$$

where $GHG_{CHEMICAL}$ is the emission-related to the application of herbicide, insecticide, and disease control (Table S2.3 and S2.4). For GHG emissions from disease controlling chemicals, we assumed emissions from fungicide (Table S2.7). The parameter GHG_{FUEL} refers to the emission-related to the usage of pre-harvest and harvest fuel. The parameter $GHG_{PELLETIZATION}$ refers to the emission-related to the pelletization (155.7 kg CO_2e t^{-1} (Dwivedi et al., 2011). The parameter GHG_{BURN} refers to the emission-related to burning pellets (34.4 kg CO_2e t^{-1}).

2.3.5.3. Herbaceous Grasses

We estimated the GHG intensity of electricity generation from herbaceous grass-based pellets ($GHG_{ELEC\text{-}HG}$, t CO_2e MWh^{-1}) using equation (2.11).

$$GHG_{ELEC-HG} = (GHG_{ESTABLISHMENT} + GHG_{HERBICIDE} + GHG_{FERTILIZER} + GHG_{HARVESTING} + GHG_{PELLETIZATION} + + GHG_{TORREFACTION} + GHG_{TRANSPORT} + GHG_{BURN})\ x\ \frac{1}{EC_{HG}} \quad (2.11)$$

where $GHG_{ESTABLISHMENT}$ is the GHG emission-related to fallow land maintenance and land preparation—initial herbicide application, disking, lime and insecticide application, 1687 kg CO_2e ha^{-1}. We assumed this GHG intensity for the establishment to be the same across all herbaceous grasses as detailed data for all crops separately was not available to the best of our knowledge. Therefore, we calculated this amount for energycane (Álvarez & Helsel, 2014) and set it as standard establishment practice. $GHG_{HERBICIDE}$ is the GHG emission-related to the further herbicide application, only applicable to energycane. The parameter $GHG_{HARVESTING}$ refers to the emission-related to the usage of diesel fuel for harvesting, assumed to be 2 L t^{-1} of harvested biomass.

Table 2.3: GHG sequestration due to land-use changes from bermudagrass to perennial grasses

Crop	CO_2 sequestered, t ha^{-1}	References
Energycane	7.12	(Sainju, Singh, & Singh, 2017)
Giant Reed	19.4	(Monti & Zegada-Lizarazu, 2016)
Miscanthus	6.60	(Zang et al., 2018)
Napier grass	8.29	(Sainju et al., 2017)
Switchgrass	2.04	(Collins et al., 2010)

Since no land is devoted to the perennial grasses for economic purposes, except bermudagrass for hay, it is important to consider GHG variations due to land use changes. In this analysis, we considered GHG sequestration in soil due to land use changes from hayland (i.e., bermudagrass) to other perennial grasses (Table 2.3), assuming that future land for growing herbaceous grasses is most likely to come from hayland. These estimates, except for switchgrass, were obtained by taking the difference between the amount of soil-carbon sequestered by bermudagrass and the amount of soil-carbon sequestered by other grasses, with no previous land-use in both cases. In other words, the land was not directly converted from bermudagrass to other grasses. However, for switchgrass, the land was converted from bermudagrass, and a difference in soil carbon was estimated.

2.3.6. Abatement cost

We used equation (2.12) to estimate the abatement cost (\$ kg CO_2e^{-1} emission) for all bioenergy feedstocks.

Abatement cost =

$$\frac{Unit\ cost\ of\ electricity\ form\ biomass - unit\ cost\ of\ electricity\ from\ fossil\ fuel}{GHG\ intensity\ of\ electricity\ from\ fossil\ fuel - GHG\ intensity\ of\ electricity\ from\ biomass} \quad (2.12)$$

The levelized cost of electricity (LCoE) from conventional coal is \$95.1 MWh^{-1} (US EIA, 2015). GHG intensity of electricity from coal is 1168 kg CO_2e MWh^{-1} (US EIA, 2018a). After calculating abatement cost in \$ kg CO_2e^{-1}, we converted the amount to \$ t CO_2e^{-1}.

2.3.7. Uncertainty Analysis

2.3.7.1. Uncertainty in yield, cost, and GHG emission

We used @Risk software to perform sensitivity analysis to evaluate the impact of different GHG intensities of inputs on the abatement cost of generating electricity from all feedstocks (https://www.palisade.com). For fertilizers, herbicides, and insecticides, we selected a triangular distribution using the range and standard deviation reported in Table 2.4 using Lal (2004). For GHG emissions related to pelletization, torrefaction, fuel usage, and transportation, we assumed a normal distribution with a standard deviation of 10% of the original values. We also assumed a normal distribution with a similar standard deviation for GHG emissions related to establishment practices for all perennial grasses, except energycane, for which we have detailed establishment activities. We allowed similar adjustments for all costs and biomass yield as well. We ran the simulation for 10,000 iterations. We used the Latin Hypercube sampling method (instead of Monte Carlo) as it uses stratified random samples from each interval (number of intervals equal number of iterations), and it is usually desirable in making nearly all sample means to fall within smaller standard error than Monte Carlo (Palisade, 2018).

Table 2.4: Range for various inputs used for uncertainty analysis*

	kg CO_2e kg^{-1} of input		
	Minimum	**Mean**	**Maximum**
N-fertilizer	3.30	4.77	6.60
P-fertilizer	0.37	0.73	1.10
K-fertilizer	0.37	0.55	0.74
Lime	0.11	0.59	0.84
Herbicides	6.23	23.10	46.20
Insecticides	4.40	18.70	29.70
Fungicides	4.40	14.30	29.33

*calculated from Lal (2004).

2.3.7.2. Uncertainty in power plant capacities

We also accounted for the sensitivity around using feedstock in various power plant sizes. We considered six power plant sizes with 100 (baseline), 300, 500, 700, and 900 MW capacity, with 31.7%, 37.37%, 40.01%, 41.74%, 43.04% of conversion efficiency respectively (Bridgwater et al., 2002). We considered power plant capacities up to 900 MW since the range of coal-based electricity generating units is between 800 and 950 MW (Georgia Power, 2019). For this particular uncertainty analysis, we decided to use the feedstock that would have the cheapest abatement cost.

2.4. Results and Discussions

2.4.1. Transportation Distances

Moisture content and drying characteristics played a crucial role in transporting different feedstocks. Harvested pine was transported with 55% moisture content, while corn and cotton needed to be transported with only 15.5% and 12%, respectively. In addition, the biomass ratio for pine was 80%, while harvested agricultural residues's biomass ratio was 90%. Therefore, the green biomass to torrefied biomass ratio was higher for pine than agricultural residues (Table 2.5). All perennial grasses can be dried in the field before transportation, except energycane and napier grass, which have thick and solid stems. Therefore, energycane and napier grass needed to be transported with moisture present in the biomass, approximately 70% (Álvarez & Helsel, 2014; Knoll et al., 2013) and 80% (Takara & Khanal, 2015), respectively, which resulted in the highest green ratio for napier grass, followed by energycane.

Table 2.5: Biomass transportation distance calculation for a 100 MW power plant

	Pine	Corn	Cotton	Bermuda	Energycane	Giant Reed	Miscanthus	Napier grass	Switchgrass
TBR (t)[a]	333667.86								
GR[b]	2.69	1.27	1.16	1.13	3.78	1.13	1.13	5.67	1.13
GBS (t km-^{2} year^{-1})[c]	484	138	376.6	2260	11322	1220	1100	13078	1330
NPL[d]	0.4								
GBCA (km^{2})[e]	2600.6	4292.1	1437.5	234.5	155.9	434.4	481.8	202.6	398.5
Transportation distance (km)	28.8	37.0	21.4	8.6	7.0	11.8	12.4	8.0	11.3

[a] Torrefied biomass required at the power plant; [b] ratio of green biomass to torrefied biomass; [c] biomass supply, available at the field; [d] non-productive land ratio; [e] green biomass collection area

2.4.2. The unit production cost of electricity

The cost of electricity was higher for all feedstocks than from coal. It was also higher than the estimates reported by the United States Energy Information Administration for the levelized cost of electricity from biomass, \$102 MWh^{-1} (US EIA, 2018d). Wood chips from loblolly pine proved to be the cheapest feedstock (\$113 MWh^{-1}) for electricity generation (Figure 2.2a) for a 25-year study period. Pine chips were closely followed by cotton stalk pellets with \$4 higher unit production cost. The cost from corn stover was comparable to the cost from perennial grasses. The cost of producing torrefied biomass followed the same pattern as electricity production cost, where pine chips were the cheapest feedstock to produce (Figure 2.2b).

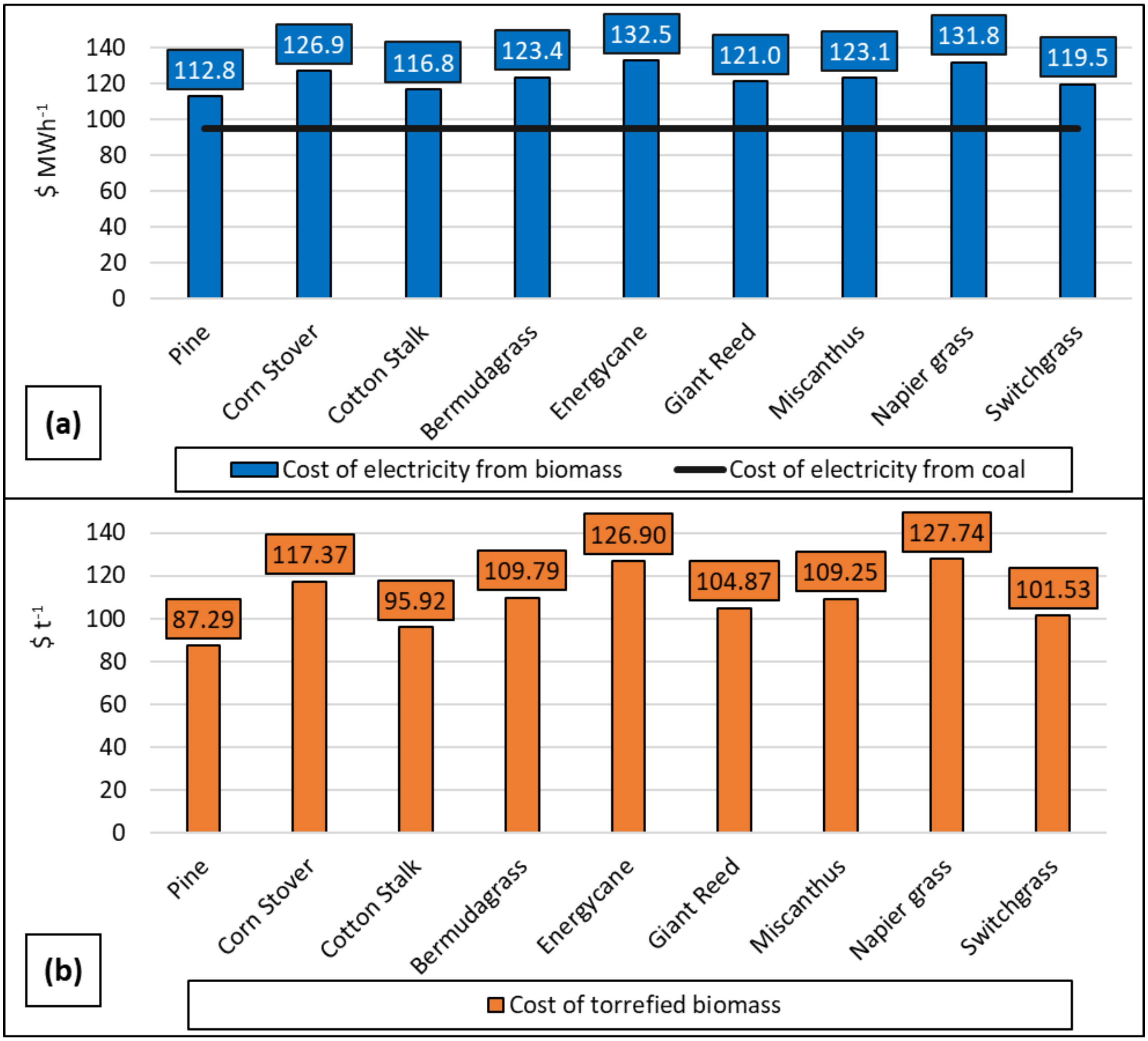

Figure 2.2: Unit production cost of (a) electricity and (b) torrefied biomass

The difference in the unit cost of electricity from perennial grasses was comparable, ranging from \$120 to \$133 MWh^{-1}. It seems logical, as the input system did not vary drastically. Even though napier grass and energycane had higher harvest outputs among perennial grasses (Table 2.2, section 2.3.2.3), they had high unit costs of electricity, \$133 and \$134 MWh^{-1}, respectively. It was because the harvesting and baling cost for these feedstocks were high as the green biomass of these feedstocks contained high moisture content (Figure 2.3). On the other hand, switchgrass had the lowest unit cost because of the low production cost of torrefied biomass.

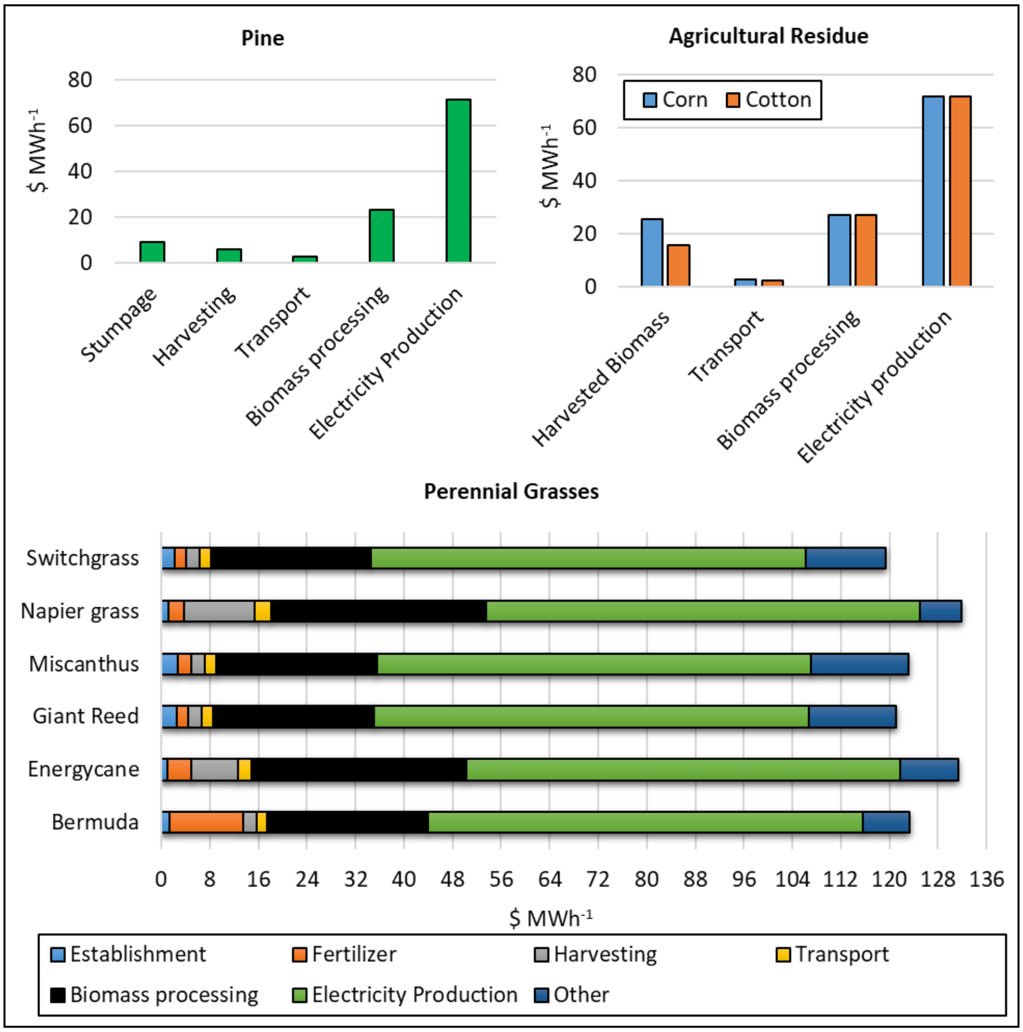

Figure 2.3. Cost breakdown during each stage of electricity production

For all the feedstocks across all three categories, the most expensive stage was the cost related to electricity production at the power plant, followed by biomass processing at the processing center. Approximately half of the cost of the overall system boundary incurred at the power plant for operation and maintenance. However, it is essential to understand that it was not biomass specific cost, as the power plant would have incurred this cost for coal as well. About one-quarter of the cost was due to biomass processing. It becomes obvious that the low input production system tends to be more profitable for biomass procurement from perennial grasses. Even though energycane and napiergrass were transported with high moisture content, transport cost was not significantly different compared to other perennial grasses, as the collection radius for these two feedstocks was short due to their high yield. Fertilization impact was similar across all perennial grasses, except bermudagrass, which required high fertilizer input for maximum yield.

A similar picture was revealed when we observed the cost share from a dry biomass perspective (Figure 2.4). The highest cost-intensive stage of producing power-plant-ready torrefied material was biomass processing. The processing stage outnumbered all other stages combined. If a more cost-effective system for biomass processing is developed in the future, then it will significantly reduce the cost of electricity from biomass.

Variation in yields caused the difference in unit production costs of electricity. Loblolly pine production system was less intensive than other production systems. This made it the cheapest feedstock for electricity. Alternatively, perennial grasses had the highest electricity cost due to the comparatively intensive production system. Corn had higher unit production cost than cotton stalk, mostly because sustainably harvestable biomass percentage was much lower for corn stover (10%) than cotton stalk (70%).

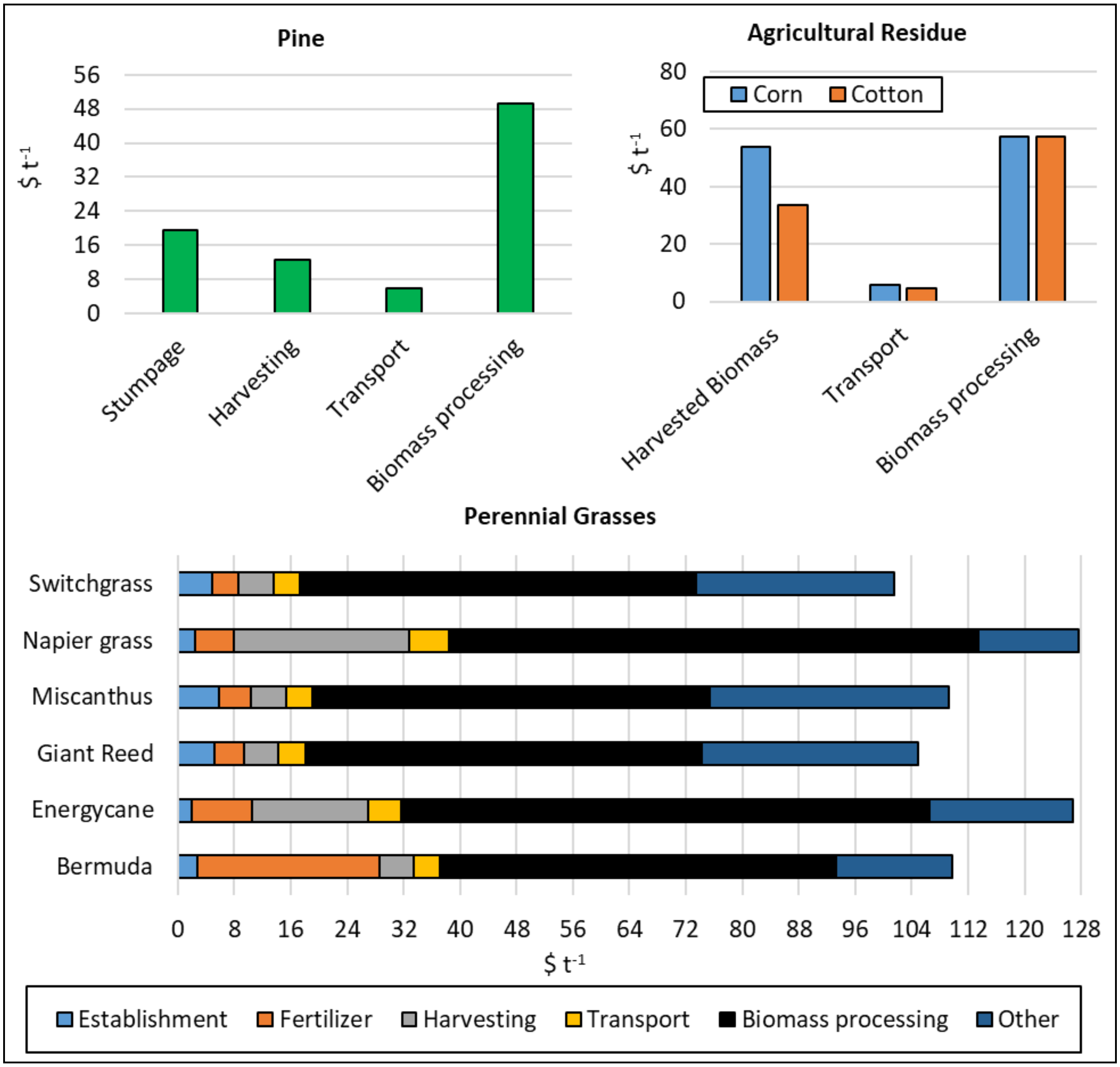

Figure 2.4. Cost breakdown with respect to dry torrefied biomass production. Biomass processing includes cost for chipping (pine only), drying, pelletizing (all feedstocks except pine), and torrefaction

The similarity across the perennial grasses, except energycane and napier grass, can be explained by the combined effect of a similar production system and the leveling effect of cost discounting for a 25-years study period. This result gives insight into biomass-based electricity production in perpetuity, asserting that the majority of perennial feedstocks will be nearly equally effective in terms of economic feasibility.

Even though perennial grasses had a higher unit production cost of electricity than other feedstocks, they can still be a sustainable source of feedstock from the yield perspective. Pine was harvested only twice in 25 years, and about 60% of harvested pine came from thinning operation at year 15. Only 1.38 and 3.77 t ha^{-1} of corn stover and the cotton stalk was sustainably harvestable without negatively affecting future production. It translates into a lower electricity production rate for pine and agricultural residues in a given amount of land. On the other hand, perennial grasses are high yielding feedstock that can provide higher biomass than pine chips or agricultural residues and hence, more electricity per hectare annually (Figure 2.5).

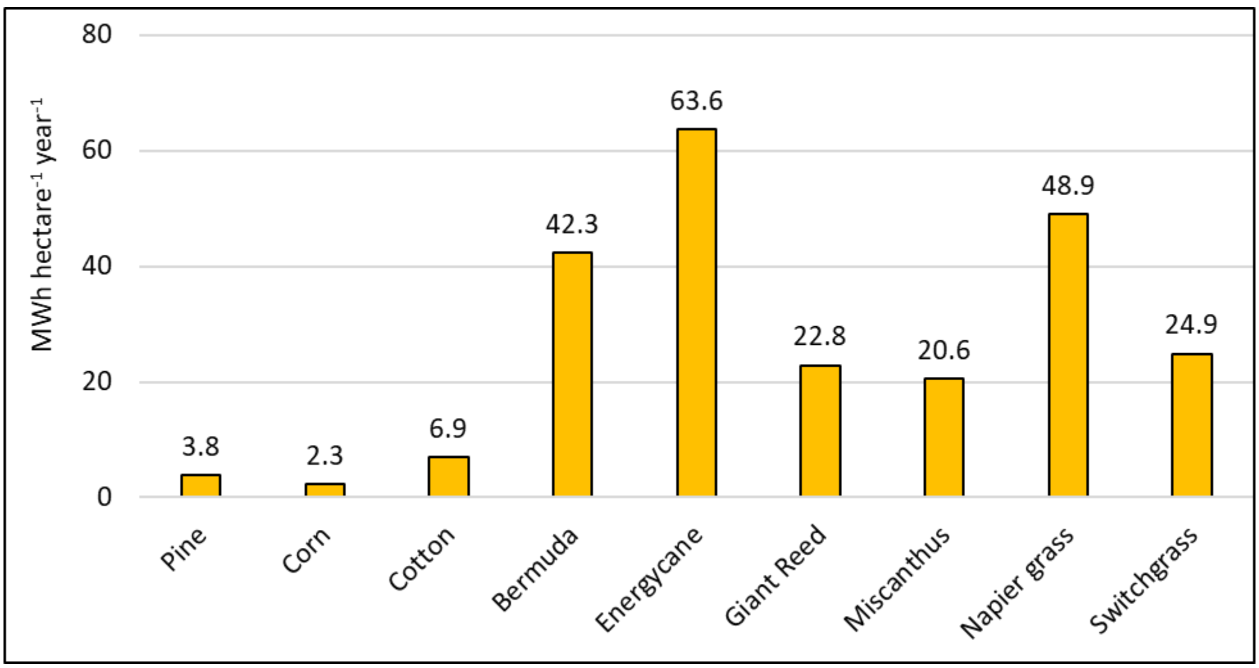

Figure 2.5. Amount of annual electricity produced per hectare from selected feedstocks

It was difficult to compare our unit production cost estimates with other studies because of two reasons. First, our system boundary was not comparable with others as we have considered a long study period of 25 years, with the exception of pine; second, most studies did not consider the added biomass processing cost of torrefaction. However, our estimates are moderately comparable to existing literature (Dwivedi & Khanna, 2014a, 2015; Shumaker et al., 2009) for intensive management of forestry feedstock, even though one study (Dwivedi & Khanna, 2014a) have considerably different biomass processing such as gasification. Our estimates are higher than a few studies (Dwivedi et al., 2016; Dwivedi & Khanna, 2014b, 2015), mostly due to our added biomass processing cost. For heat energy via raw combustion without any processing, studies have reported as low as \$7 MWh^{-1} of unit electricity production costs for switchgrass and miscanthus (Aravindhakshan et al., 2010; Khanna et al., 2008; McLaughlin et al., 1999). However, these estimates cannot be directly compared with our estimates for electricity generation due to differences in assumptions.

2.4.3. GHG intensity

The higher the amount of biomass, the higher the emission for transporting, biomass processing, and biomass burning for electricity. Therefore, instead of reporting overall GHG emission per hectare, reporting emission per MWh of electricity makes intuitive sense (Figure 2.6a). After attributing GHG emissions based on unit electricity, we found cotton stalk as the most GHG intensive option (325 kg CO_2e MWh^{-1}) for generating electricity, followed by corn stover (235 kg CO_2e MWh^{-1}), which was similar to bermudagrass. Pine chips were the least GHG intensive option, among all feedstocks, for generating electricity. We report lower estimates (134 kg CO_2e MWh^{-1}) than the studies that have used pellets, instead of chips, from slash pine or loblolly pine for electricity or have a larger system boundary, such as exporting to a different country (Dwivedi et al., 2011, 2016). Our estimate was higher than Dwivedi and Khanna (2014a), who also used chips, due to the added biomass processing in our study. High GHG from cotton stalks was due to higher GHG emission, compared to other grasses, during the feedstock production stage (Figure 2.6b).

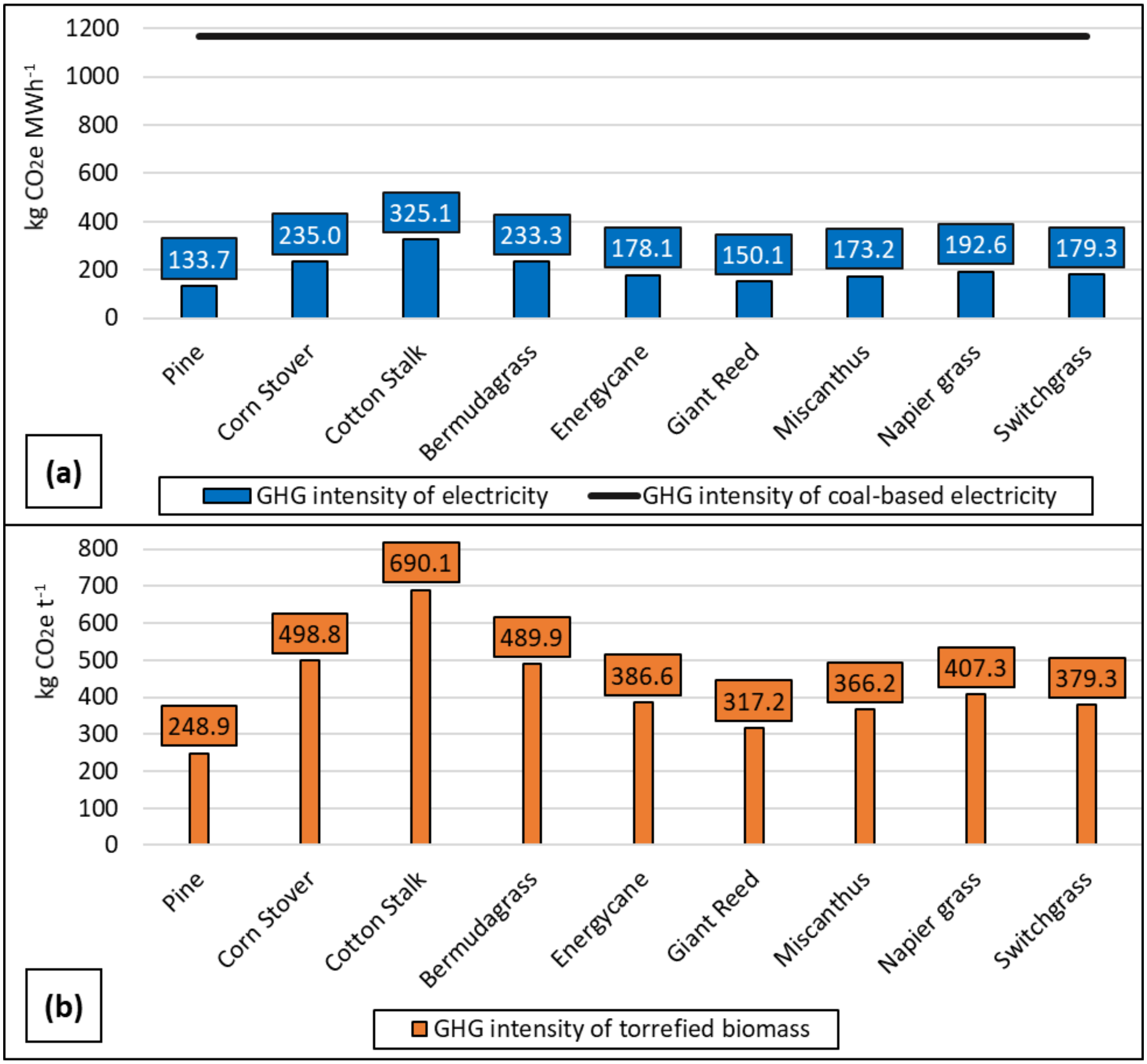

Figure 2.6: GHG intensity of producing (a) electricity and (b) torrefied biomass

The biggest GHG contributing stage for all feedstocks was the biomass processing stage (Figure 2.7). It is not surprising because pelletization and torrefaction are GHG intensive processes. It was about 141 kg CO_2e MWh^{-1} for all feedstocks, except pine (77 kg CO_2e MWh^{-1}) since there was no pelletization, but drying, involved in pine chips. The reason that made cotton stalks the highest GHG intensive option was the establishment stage, followed by the fertilizer usage. Fertilizer also made bermudagrass the highest GHG intensive perennial grass. Napier grass was the second most GHG intensive grass because of the increased harvesting and transportation activities required for high moisture content, which was also true for energycane that had very similar GHG intensity. For other grasses and agricultural residues, there was almost no variation in transportation as those can be dried in the field. About 17 kg CO_2e MWh^{-1} was emitted to the atmosphere during biomass burning. It is important to reiterate here that this emission is non-biogenic in nature.

The literature review suggested noticeable variations in soil carbon sequestration among bioenergy grasses (Table 2.3). Giant reed sequestered the most soil carbon when compared to bermudagrass, followed by miscanthus. Due to the high soil carbon sequestration rate of giant reed, it was the second least GHG intensive option for electricity after pine chips.

Unlike agricultural residues, the GHG share of the establishment stage for these perennial grasses was negligible. It is understandable as perennial grasses establishment only occurred in year 0, and we assumed no consequent establishment practices such as reseeding, soil re-testing, and denitrification. A similar argument is applicable to loblolly pine as we considered our optimal rotation age to be 25 years and establishment only occurred once in that period.

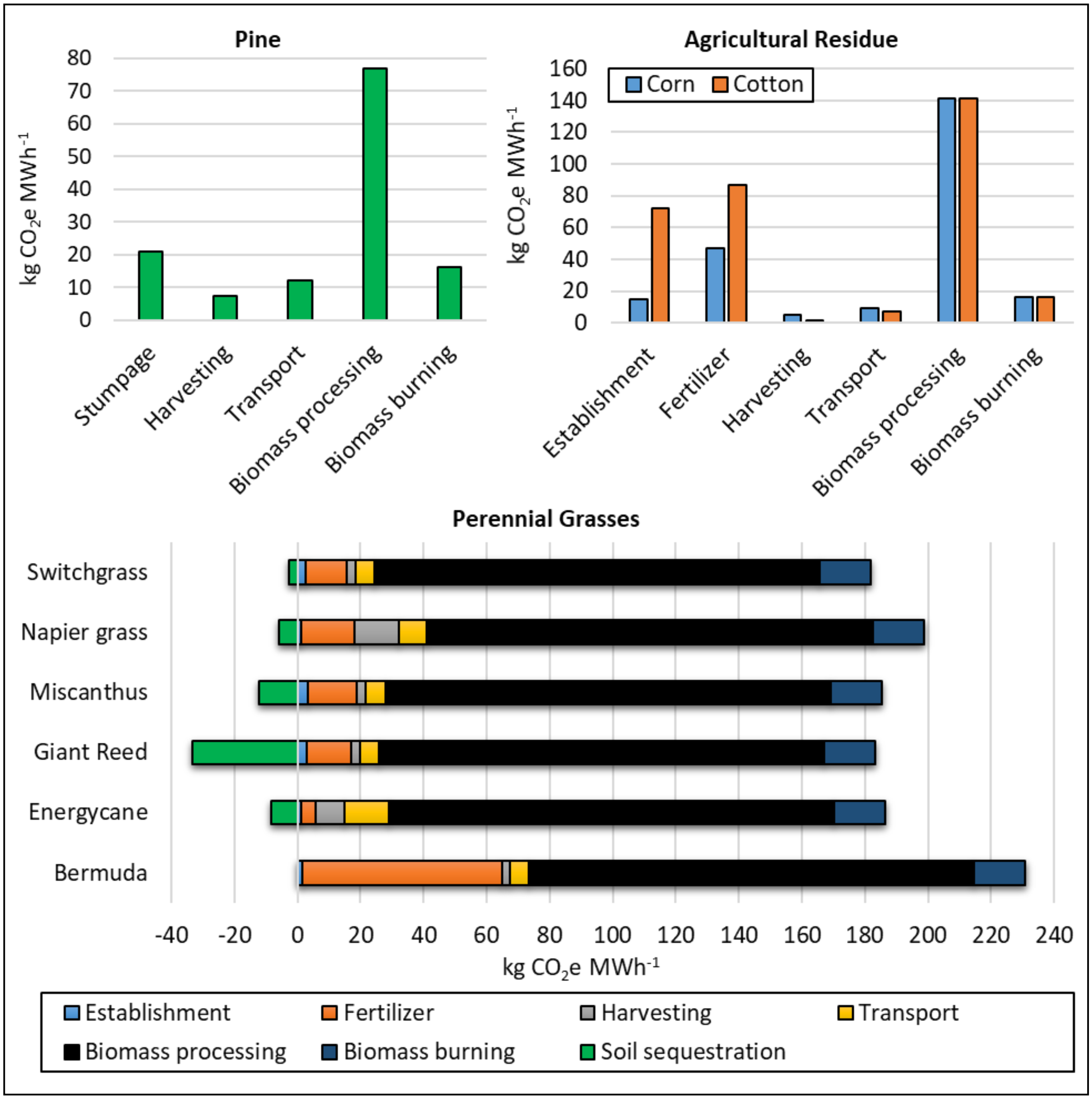

Figure 2.7: GHG intensities in different stages of electricity production. Biomass processing includes GHG emission for chipping (pine only), drying, pelletizing (all feedstocks except pine), and torrefaction

Other stages in electricity production from pine chips, such as fertilization and harvesting, were low in carbon intensity as well, as pine production only required three fertilizer applications over 25 years, and as we only considered harvesting pulpwood for electricity. That resulted in the lowest amount of GHG (134 kg CO_2e MWh^{-1}), referring that pine is the least carbon-intensive option for bioelectricity. Biomass (stumpage) production was the second-highest emission stage for electricity from pine. However, with the annual input system, agricultural residues' biomass production had higher GHG intensities than other feedstocks.

Finally, we can see the same relationship for GHG intensities with respect to dry torrefied biomass on a per tonne basis (Figure 2.8). From this analysis, it was obvious that the GHG variation primarily comes from the agricultural choices made for farming practices and moisture content present during transportation. Among those agricultural choices, fertilizers played a significant role that is apparent for bermuda, among other perennial grasses (Figures 2.7 and 2.8). Corn and cotton production were heavily dependent on fertilizers, while perennial grasses and loblolly pine are less so. Cotton production also included heavy herbicide use, which drove the GHG intensity higher. However, all feedstocks, including cotton stalk, emitted significantly less GHG than their fossil fuel alternative 1168 kg CO_2e MWh^{-1} (US EIA, 2018a).

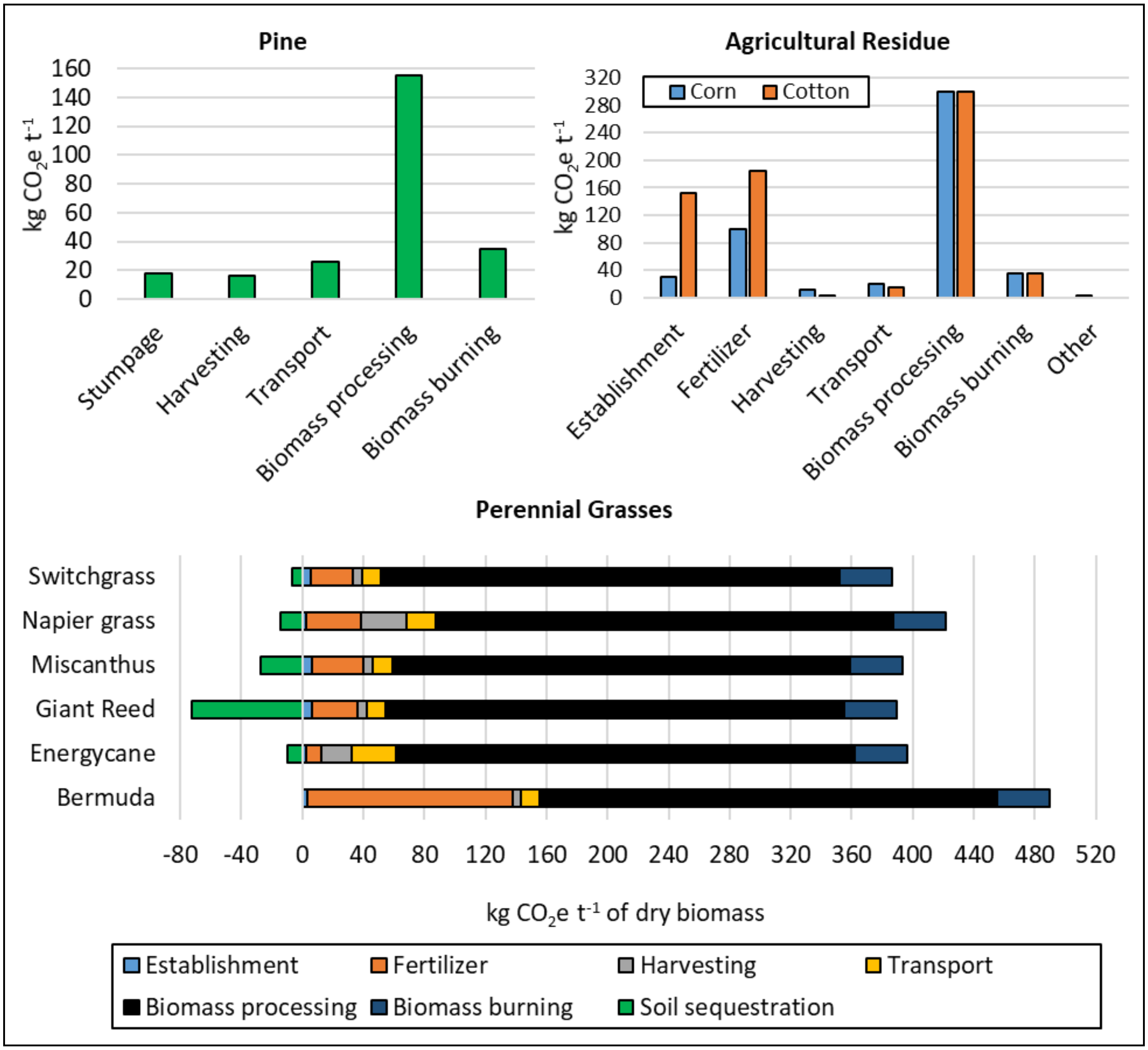

Figure 2.8: GHG emission breakdown with respect to dry torrefied biomass production

2.4.3. Abatement cost

Wood chips from loblolly pine had the lowest abatement cost (\$17 t CO_2e^{-1}) among all feedstocks (Figure 2.9) and therefore is the best biomass option for electricity generation in Georgia. This low abatement cost is due to the less intensive management system over the study period than the other feedstock production. It was followed by switchgrass (\$24.7 t CO_2e^{-1}), which had a similar abatement cost as giant reed and cotton stalks. We report the highest abatement cost for electricity from energycane, closely followed by napiergrass, due to their higher unit production costs and GHG emissions.

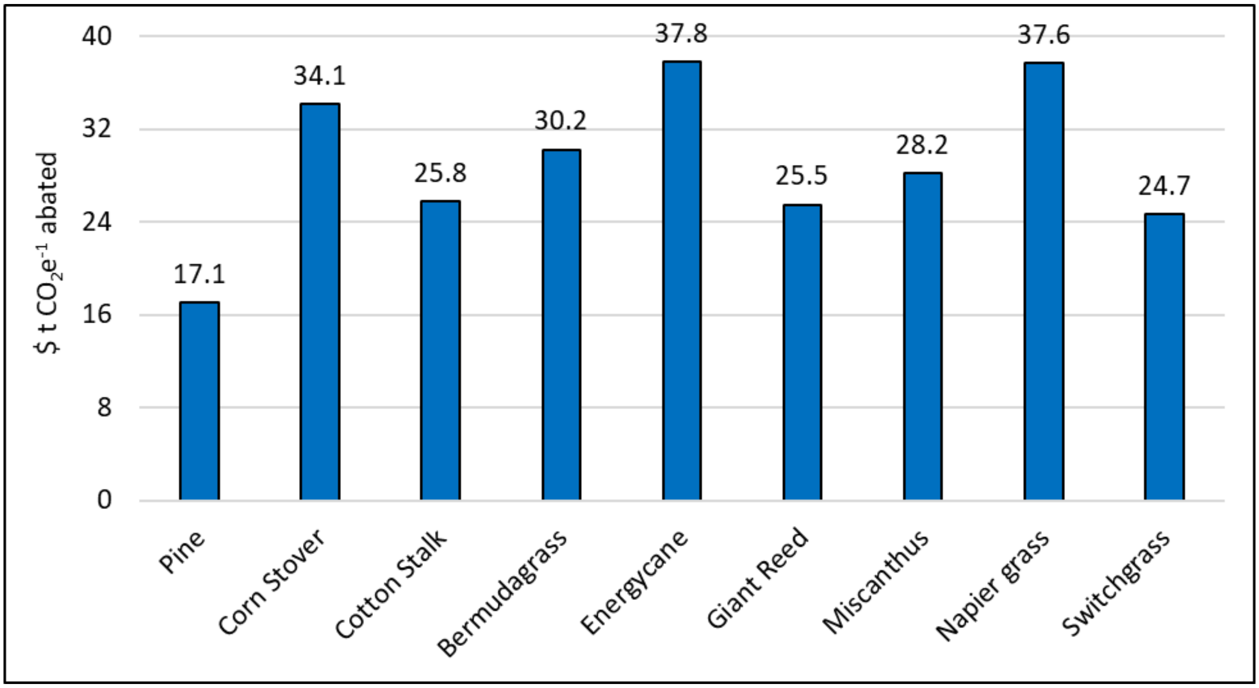

Figure 2.9: Carbon abatement cost of electricity generation from selected feedstocks

Our assessment of the abatement cost for electricity from pine chips was reasonable, given our system boundary. Our estimate was $13 higher than Dwivedi and Khanna (2014a) as we used only pulpwood and not all available biomass. In addition, we added torrefaction costs in our analysis that raised the unit production costs. Our estimate for the carbon abatement cost was $21 lower than Dwivedi and Khanna (2015) because their biomass processing included pelletization. However, our estimate was about $48 lower than Dwivedi et al. (2016), as their system boundary included exporting the wood pellets to the United Kingdom from the southern United States. Our estimate for switchgrass was about $18 higher than Aravindhakshan et al. (2010), as their estimates for yields were higher and delivered cost was lower. In addition, they did not consider pelletization or torrefaction. Our study suggests that forestry feedstocks, in general, will be the best candidates as feedstocks for electricity generation.

Pine chips showed the highest relative GHG savings and lowest abatement cost (Figure 2.10). Cotton stalk had low abatement costs, but it was not as efficient as other feedstocks in terms of GHG savings. This is due to the highest GHG intensity during the production phase. Energycane and napier grass showed the opposite picture to cotton stalk. These two grasses did have higher abatement costs, but they provided higher GHG savings than cotton stalks. Giant reed, switchgrass, and miscanthus provided both low abatement cost and high GHG savings and proved to be moderate all-rounders in both standards.

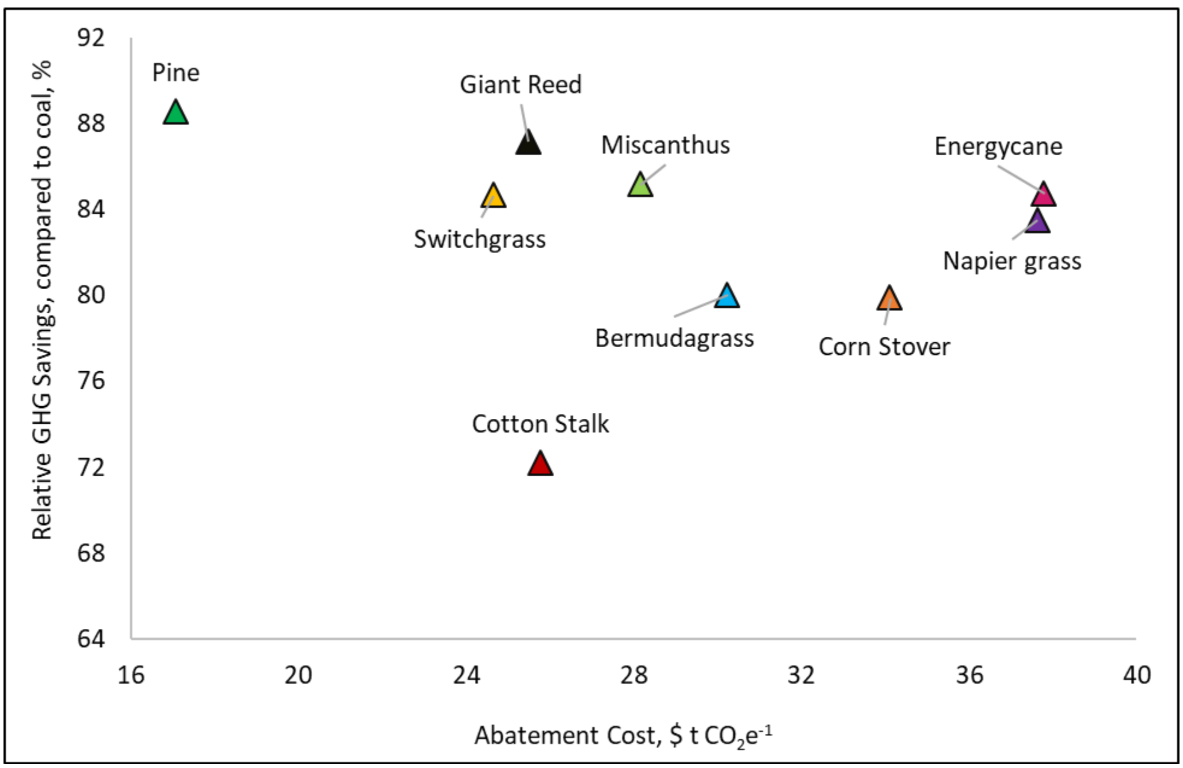

Figure 2.10: Relative GHG Savings and abatement cost of electricity generation from selected feedstocks

2.4.4. Uncertainty Analysis

2.4.4.1. Uncertainty in yield, cost, and GHG emission

With higher yields, improvement in technology, and subsidy in input prices, carbon abatement cost of electricity from pine chips can be as low as \$2.76 t CO_2e^{-1} (Figure 2.11) while as high as \$31.36 in the pessimistic scenario, two standard deviations below and above the mean abatement cost (\$17.07 t CO_2e^{-1}) respectively. With a 90% confidence interval, abatement cost for pine chips can range between \$16.95 and \$17.19 t CO_2e^{-1}.

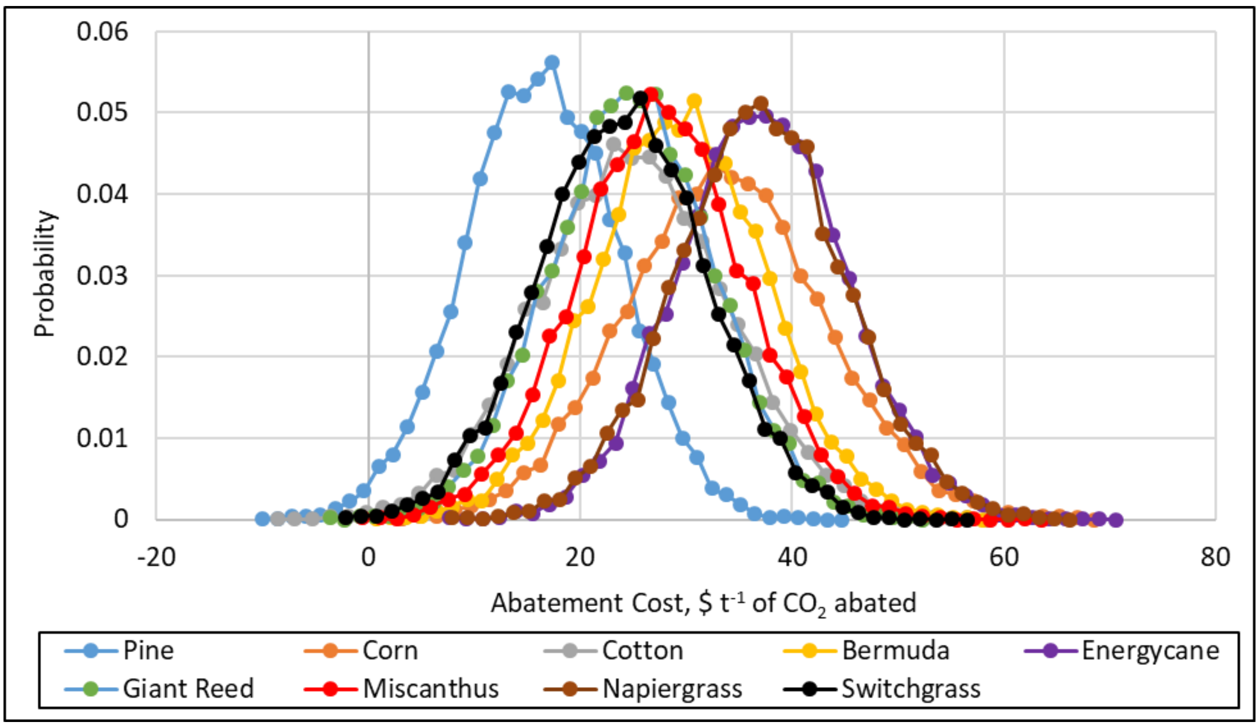

Figure 2.11: Uncertainty around the abatement cost of electricity generation from selected feedstocks

Higher abatement costs will be necessary for increasing the sustainable harvestable volume of feedstock for electricity. Abatement cost ranging \$25 to \$38 t CO_2e^{-1} will make all perennial herbaceous grasses competitive. Standard deviations are comparable across all perennial grasses, as well as agricultural residues, ranging between 8 and 9 t CO_2e^{-1}. The best perennial grass option, giant reed, can have an abatement cost between $10 and $41 t CO_2e^{-1} depending on optimistic and pessimistic parameters, two standard deviations below and above the mean, respectively. Cotton stalk had the highest uncertainty with the highest standard deviation around the mean, ranging from $8 to $44 t CO_2e^{-1}.

While we only reported the top five influential factors for the abatement cost of electricity from pine chips (Figure 2.12), the most impactful variable in the uncertainty analysis across all feedstocks was the power plant's operating cost. However, this cost would have incurred in electricity generation from coal as well. For electricity from pine, the most impactful biomass specific variable was the cost of torrefaction. For other feedstocks, the most significant factor was the cost of pelletization. It suggests that if we can reduce the cost of overall biomass processing, then the abatement cost will go down significantly and make biomass more sustainable for electricity generation.

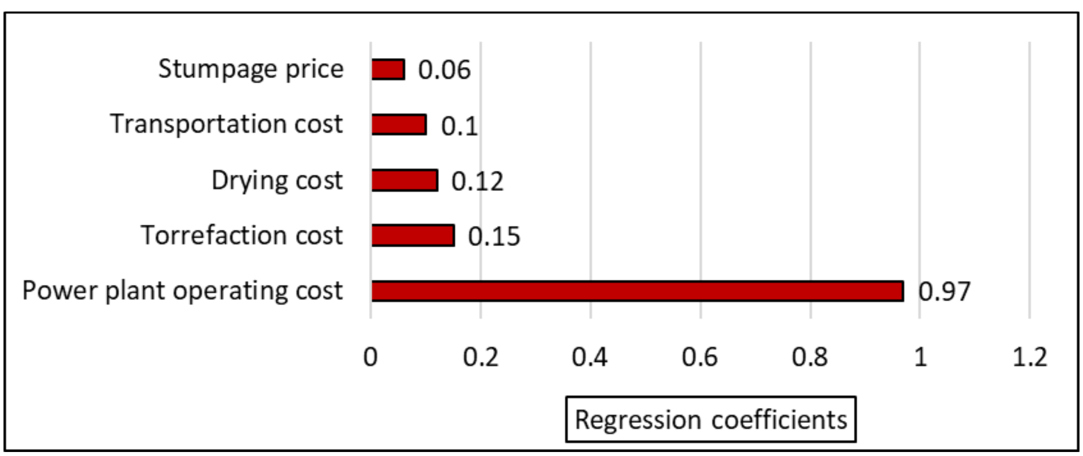

Figure 2.12: Standardized regression coefficients for the top five factors influencing the abatement cost of electricity generation from pine chips

2.4.4.2. Uncertainty in power plant capacities

Figure 2.13 shows the variation in unit production cost, unit GHG emission, and abatement cost of electricity generation with increasing power plant conversion efficiency for pine chips, the cheapest feedstock. Plants with 900 MW capacity can produce electricity from pine chips with \$104 MWh^{-1} than \$117 MWh^{-1} of our baseline of 100 MW. This unit cost is quite comparable to the biopower cost reported by EIA, \$102 MWh^{-1} (US EIA, 2018d). Unit GHG emission was down by approximately 7% for the highest capacity units compared to baseline. The abatement cost for electricity generation in Georgia can be as minimum as \$8.4 t CO_2e^{-1}, which is approximately 51% lower than our baseline scenario.

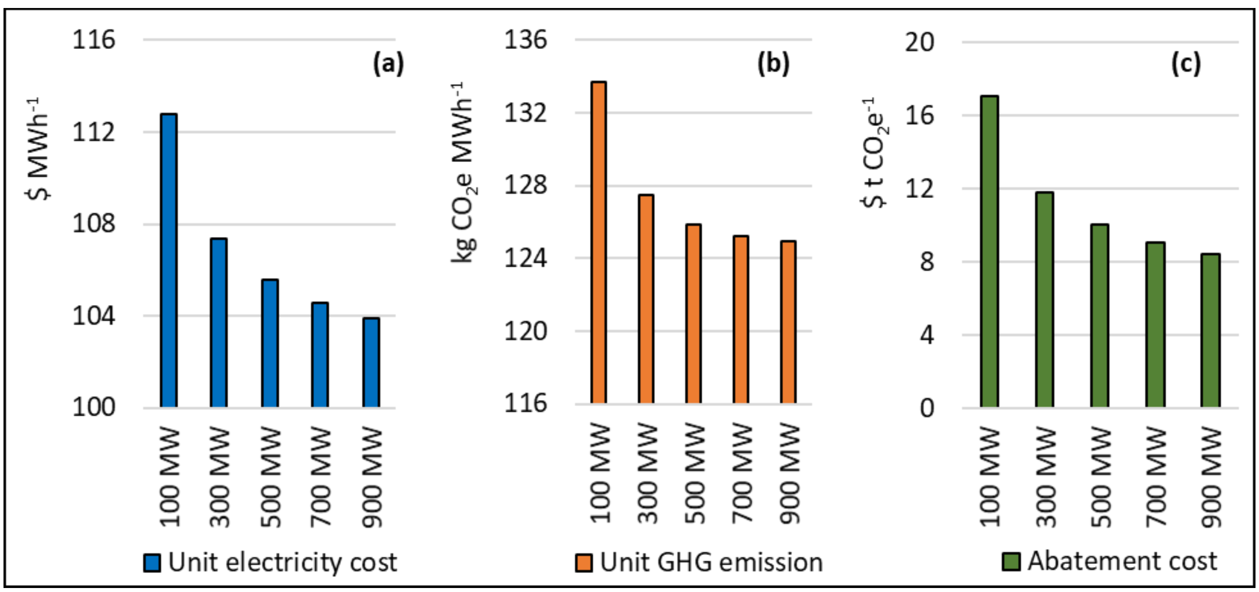

Figure 2.13: Variation in (a) unit production cost, (b) unit GHG emission, and (c) abatement cost of electricity generation from pine chips, for varying power plant capacities

2.5. Practical Implications of the Study

Based on the results of this study, power plants in Georgia could make an informed decision on selecting feedstock with minimum cost to replace coal. This study will feed into the ongoing deliberation of reducing carbon emission in the power sector. Challenges in the current research include, but are not limited to, the lack of information regarding how much variation in cost and GHG emission exists for torrefying a specific feedstock. We have assumed the same conversion factors for these categories across all feedstocks. We did not estimate for variations in various baling and storage techniques. We did not estimate the impact of generating biomass-based electricity on eutrophication, acidification, particulate matter emission effects, and other environmental impacts. Similarly, while considering land use change, we did not consider converting fallow land or marginal agricultural land into perennial grassland. That scenario could have given more insights into the carbon benefits of an herbaceous bioenergy system. Finally, we used only fertile soil with a site index of 21.3m for loblolly pine production, but soil quality is not static across Georgia. Therefore, caution is necessary for interpreting the abatement cost, as the value can be higher for less fertile soil. This work could be extended by accounting for variation in the feedstock specific transportation distances, processing, and storage. However, we did allow these costs and emissions factors to fluctuate, assuming a normal distribution, in our uncertainty analysis to capture the variation.

2.6. Conclusion

In this study, we compared all the major feedstocks for their potential as feedstocks for electricity production, and our primary findings indicated that biomass was a less carbon-intensive but costlier alternative than coal. Pine chips were the best candidate for producing electricity in Georgia as it had the lowest abatement cost. For perennial grasses, the cost of abating greenhouse gas emissions was higher than for cotton stalks, except switchgrass and giant reed. Corn stover was comparable to bermudagrass and energycane. Over the long study period, almost all herbaceous perennial feedstocks will be nearly equally effective in reducing the dependence on coal. Economic incentives, a minimum of about $17 for each tonne of CO_2 abated, are necessary to make biopower competitive. However, this carbon tax can be as low was about $8, considering the high capacities of power plants in Georgia.

The major argument this paper makes is that biomass can be a viable alternative source for carbon reduction from electricity generation in the United States, where a key share of electricity comes from coal and/or natural gas. This study will clarify how biomass can become an economically feasible bioenergy product and how economic policy can be suggested based on the findings. In conclusion, we provided useful insights into the competitiveness of bioenergy feedstocks in the electric sector over the long run in Georgia. Our results are also useful for other southern states that share a similar policy and energy infrastructure, agriculture, and forestry conditions and are looking to reduce the carbon intensity of electricity generation.

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Conflict of Interest

The authors declare no conflict of interest.

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CHAPTER 2: SUPPORTING INFORMATION

Table S2.1: Assumed standard silvicultural practices for loblolly pine.

Year	**Silvicultural practice (per hectare)**
0	Planting, 1494 seedlings
2	N – 151 kg, P – 28 kg
10	N – 252 kg, P – 28 kg
15	Thinning, 50% of the living trees
15	N – 252 kg, P – 28 kg
25	Harvesting (pulpwood only)

Table S2.2: Cost parameters for loblolly pine.

Input/Activity		**Amount**	**Unit**	**References**
Stumpage		15	$ t^{-1}	(TMS, 2019)
Harvesting	Felling	3.85	$ t^{-1}	(Jernigan, Gallagher, Mitchell, Smidt, & Teeter, 2016)
	Skidding	1.95	$ t^{-1}	
	Delimbing	1.95	$ t^{-1}	
	Loading	1.95	$ t^{-1}	
Transportation of feedstock		0.096	$ t^{-1} km^{-1}	(TMS, 2013)
Chipping		7.16	$ t^{-1}	(USDOE, 2011)
Drying		30	$ t^{-1}	(Haque & Somerville, 2013)
Torrefaction		50	$ t^{-1}	
Transportation of torrefied chips to power plant		0.096	$ t^{-1} km^{-1}	(TMS, 2013)
Electricity Production		71.65	$ Mwh^{-1}	(US EIA, 2018)

Table S2.3: Agricultural practices for annual corn production (CAES, 2018a).

Input/Activity	**Amount**	**Unit/ha**
Seed	79.07	Thousand
Lime	1120.85	kg
Nitrogen	269.00	kg
Phosphate	112.00	kg
Potash	224.00	kg
Herbicide	7.00	L
Insecticide	1.00	L
Disease control	0.70	L
Pre-harvest fuel	46.00	L
Harvest fuel	23.00	L

Table S2.4: Agricultural practices for annual cotton production (CAES, 2018b).

Category	Activity	Amount	Unit/ha
Seed (Including Tech Fees and Seed Treatments)		89.70	1000 seeds
Fertilizers	Lime- Custom Spread	726.00	kg
	Nitrogen	101.00	kg
	Phosphate (P_2O_5)	78.50	kg
	Potash (K_2O)	78.50	kg
	Boron, Sulfur, and Others	12.40	$
Weed Control	At Planting or PRE	1.90	L
	POST	9.46	L
	Layby	33.40	$
	Hand Weeding	24.71	$
Insect Control	Scouting	24.71	$
	Spray- Stink Bugs, Other Pests	2.00	Applications
PGR (Plant Growth Regulators)		1.02	kg
Irrigation		8.00	Applications
Machinery and Equipment	Fuel and Lube	50.00	L
Labor		5.00	Hrs
Ginning and Warehousing	Ginning	1345..00	kg
	Other (Hauling, Etc.)	6.00	Bale
	Storage and Warehousing	6.00	Bale
	Promotions, Boards, Classing	6.00	Bale
	Cottonseed Credit	681.00	kg
BWEP (Boll Weevil Eradication Program)		6.00	Bale

Table S2.5: Agricultural practices and cost parameters for energycane production (Álvarez & Helsel, 2014).

Category*	Activity	Rate	Unit/ha	Unit Price	#Times
Annual fixed cost		494	dollars		
Fallow land maintenance	herbicide + surfactant	4.69	l	7.93	2
	herbicide application		dollar	9.88	2
Land preparation	Soil testing and consulting		dollar	2.74	1
	Disking		dollar	37.05	3
	Lime application		dollar	12.35	1
	Lime material	2.24	t	50	1
	Laser leveling		dollar	148.2	1
	Calcium Silicate Slag	2.24	t	61.73	1.5
	Slag Application		dollar	12.35	1
Planting	All related activities		dollar	419.9	1
	Seed cost	7.41	dollar	25	1
	insecticide	16.81	kg	4.4	1
	Micronutrients	22.42	kg	1.122	1
Cultural Activities	Nitrogen	49.32	kg	0.97	4.17
	P_2O_5	56.04	kg	0.84	1
	K_2O	50.44	kg	0.64	4.17
	Chemical applications		dollar	9.88	2
	Herbicide (pre-emergence)	7	l	4.35	1
	Herbicide (pre-emergence)	9.35	l	4.35	1
	Herbicide (post-emergence)	7	l	4.35	1
	Herbicide (post-emergence)	2.35	l	4.35	1
	Oil (surfactant)	2.35	l	1.74	1
	Mechanical Cultivation		dollar	16.06	1
	Miscellaneous		dollar	203.27	1
	Interest		dollar	178.88	1

* Only cultural activities will repeat after the first year.

Table S2.6: Cost inputs for generating electricity from herbaceous biomass.

Activity	Cost ($)	References
Harvesting and Baling	7 t^{-1}	(Álvarez & Helsel, 2014), approximated
Transportation	0.096 t^{-1} km^{-1}	(TMS, 2013)
Pelletization	70 t^{-1}	
Torrefaction	50 t^{-1}	
Electricity Production	24.85 MWh^{-1}	(US EIA, 2018)

Table S2.7: Parameters to estimate GHG intensity from various inputs.

Input/Activity	GWP	Unit	References
Disking	21.3	kg CO_2e/ha	(Lal, 2004)
N-Fertilizer	4.77	kg CO_2e/kg of N	
P-Fertilizer	0.73	kg CO_2e/kg of P_2O_5	
K-Fertilizer	0.55	kg CO_2e/kg of K	
Lime-Fertilizer	0.59	kg CO_2e/kg of Lime	
Herbicide	23.1	kg CO_2e/kg of herbicide	
Insecticide	18.7	kg CO_2e/kg of insecticide	
Disease control	14.3	kg CO_2e/kg of fungicide	
Harvesting Fuel	2.73	kg CO_2e/l of diesel oil	(US EPA, 2018)
Drying Fuel	1.51	kg CO_2e/l of LP	
Transportation	0.2024	kg CO_2e/t^{-1} km^{-1}	

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CHAPTER 3: ESTIMATING OPTIMAL ALLOCATION OF TIMBER PRODUCTS TO REDUCE CARBON EMISSION FROM ELECTRICITY GENERATION IN GEORGIA, UNITED STATES[2]

[2] Masum MFH and P Dwivedi. To be submitted to Land Use Policy.

Abstract

To combat climate change, reducing carbon emission from coal consumption in the power sector can be an effective strategy in Georgia, United States. We developed a market-clearing price-exogenous linear optimization model satisfying both traditional timber demand and additional bioenergy demand to replace coal in the power plants for 50 years, maximizing social welfare. We used FIA unit level yield of five forest types (planted softwood, natural softwood, upland hardwood, bottomland hardwood, and mixed forest), timber demand, and price information, and developed three scenarios—Baseline (traditional timber demand and no coal replacement); Scenario 1 (traditional demand and 50% coal replacement by pulpwood only); and Scenario 2 (traditional demand and 50% coal replacement by pulpwood and logging residues). It would require approximately 496 and 331 thousand acres of additional annual timberland harvested in Scenario 1 and Scenario 2, respectively, compared to the Baseline (320 thousand acres). During 50 years, a total of 2.13, 3.2, and 3.1 billion tons of timber were produced in the Baseline, Scenario 1, and Scenario 2, respectively. The net change in stand carbon was positive in Baseline (151 million tons C) but negative in Scenario 1 (-295 million tons C) and Scenario 2 (-54 million tons C). Additionally, about 278 million tons of carbon was avoided by using biomass instead of coal in Scenario 1 and Scenario 2. Stand carbon sequestration and avoided carbon emission combined, replacing 50% coal with both pulpwood and logging residues, was more beneficial from a carbon benefit perspective, compared to no replacement. Sensitivity analysis of varying percentages of coal replaced by biomass in Georgia, 10% through 100%, suggested that replacing 10% coal in the power plant using both pulpwood and logging residues was the best-case scenario from the combined carbon benefit perspective.

Abbreviations

$	US dollars
Btu	British thermal unit
C	Carbon
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
GHG	greenhouse gases
MMBtu	Million British thermal unit
ppm	parts per million
tbf	thousand board feet
tons	US short tons

3.1. Introduction

Concerns about climate change have increased substantially in the last few decades as global temperature increased by a little more than 1.8 ^{o}F since the age of the industrial revolution (NASA, 2020a). This increase in temperature is an effect of rising carbon dioxide (CO_2) in the atmosphere, which is currently at about 414 ppm (NASA, 2020b). Burning fossil fuels such as coal, petroleum, and natural gas is the primary source of increased CO_2 in the atmosphere. In the United States, electricity generation was responsible for about 33% of all energy consumption related CO_2 emission in 2018 (US EIA, 2020a). Georgia, the third largest electricity generating and coal consuming state for power generation in the South Atlantic region, consumed approximately 315 trillion Btu of energy from coal in 2018 (US EIA, 2020b). Approximately 14 million tons of coal was used in the coal-based power plants of Georgia in 2018 (US EIA, 2020b). Approximately two-thirds of all carbon emissions from Georgia's power sector was from coal usage.

Using a renewable alternative to coal can substantially reduce CO_2 emissions from the power sector, which will eventually help mitigate the adverse impact of climate change. Woody biomass such as loblolly pine chips was more economical and less GHG intensive renewable alternative to coal for power generation in Georgia when compared to agricultural crop residues such as corn stover or cotton stalk or perennial grasses such as energycane, switchgrass, bermudagrass, napier, giant reed, and miscanthus (Masum, Dwivedi, & Anderson, 2020). Woody biomass can also be a sustainable choice as Georgia has approximately 24 million acres of forestland, from which about 50 million tons of wood is already harvested annually (Brandeis & Hartsell, 2016). About 46% of the harvested wood was in the form of pulpwood, and along with logging residues, it would be the ideal choice to replace coal consumption in Georgia. Sawtimber is not suitable for coal replacement due to relatively higher prices compared to pulpwood and logging residues due to higher prices compared to pulpwood.

However, several economic questions, primarily related to harvesting and transporting timber, that must be answered before replacing coal with biomass. Understanding where forest biomass will come from to meet the biopower demand is crucial as forest and SRWC (short rotation woody crops) biomass is predicted to initially supply up to half of the total biomass requirement of the United States (Latta, Baker, Beach, Rose, & McCarl, 2013). In Georgia, approximately 35 million tons of green woody biomass would be required annually, after satisfying the demand of currently existing pulp mills, to replace 100% coal (13.8 million tons) with torrefied biomass in the coal-fired power plants (US EIA, 2020b). To use biomass in coal-power plants, biomass needs to be torrefied as torrefied biomass has less moisture content and calorific value equivalent to sub-bituminous coal (Phanphanich & Mani, 2011). Harvesting location can vary based on the availability of pulpwood and logging residues, thereby influencing transportation distances from power plants. Analysis of yield and demand factors in biofuel cost minimization tactics revealed that a 50% reduction in biomass yield would increase biofuel cost by 11% (Lin, Rodríguez, Shastri, Hansen, & Ting, 2014). Therefore, harvesting decisions will need to be optimized to avoid potential losses from the supply chain and unforeseen costs. Reducing timber sourcing and allocation costs, especially with the additional demand for the coal power plants, makes economic sense for the economic stability of Georgia's substantial forest industry, worth $36 billion in 2018, that supported 150 thousand jobs (GFC, 2019). The economic argument for optimizing these decisions in the presence of additional bioenergy demands further attention as the global price of industrial roundwood is projected to rise by 30% in a scenario where wood from forests is used to meet increased bioenergy demand (Buongiorno, Raunikar, & Zhu, 2011). Reducing costs from biopower related activities are crucial since biopower is generally more expensive than electricity from coal (Dwivedi & Khanna, 2015; Masum, Dwivedi, & Anderson, 2020; Shumaker, Luke-morgan, & Mckissick, 2009; Tharakan, Volk, Lindsey, Abrahamson, & White, 2005).

Along with economic issues, there are environmental issues that require evaluation while replacing coal with biomass. Literature suggests that the quantity of forest area and quality of the forest area varies based on-demand scenario (Costanza, Abt, McKerrow, & Collazo, 2017). Additional biomass demand is likely to have an impact on the number of acres harvested, thus influencing the stand age classes of forest stands and carbon stock in the aboveground forest biomass. Average harvest age will also be influenced since pulpwood and logging residues availability is dependent on the stand age. An optimization model encompassing long planning horizons such as multiple decades can help predict such changes in stand age and stand carbon. Additionally, since transportation is directly related to GHG emission, an optimization model that reduces the transportation distance between harvesting locations and power plants can increase GHG benefits for the environment. In addition to impacting land-use change, changes in wood pellet demand have also shown impacts on biodiversity (Costanza et al., 2017; Duden et al., 2018). Therefore, it becomes evident that modeling the allocation of forest products and/or predicting the effect of increased bioenergy demand has significant economic and environmental consequences. Determining the optimal amount of biomass used for energy that is realistic, based on the economic and environmental factors such as current pricing, yield, and traditional timber demand makes intuitive sense from the sustainability perspective (Vukašinović & Gordić, 2016).

Existing literature used linear programming models with cost-minimization objectives to make suitable environmental decisions in the bioenergy sector (Freppaz et al., 2004; Frombo, Minciardi, Robba, Rosso, & Sacile, 2009; Huang, Chen, & Fan, 2010). Plant installation and maintenance; biomass transportation and collection costs were considered for minimization, and energy sales and renewable energy certificates were included as negative costs (Frombo et al., 2009). Biomass supply chain optimization, with GHG reduction in focus, was analyzed as well. A regional study performed in Alabama, Florida, and Georgia (Abt, Abt, & Galik, 2012) reported that harvesting wood for bioenergy could lead to increased carbon sequestration as a response to increased afforestation. GHG emissions minimization from biomass supply in Ireland found that the optimal scenario for the highest biomass insertion for power generation might not achieve the highest carbon reduction (Murphy, Sosa, McDonnell, & Devlin, 2016). Since biomass production spans a longer horizon in time while biomass collection and transportation decisions are made in medium to short time horizons, there is a need to coordinate between these two horizons (Ekşioğlu, Acharya, Leightley, & Arora, 2009). Linear programming models that can coordinate spatio-temporal decisions and determine the amount of biomass transported and processed with inputs such as biomass availability, transportation, and processing costs, authors found that transportation costs and biomass availability are the two major factors influencing the sustainability of biomass processing center. They also reported that the economy of scale is an essential factor—one big refinery was more cost-effective than multiple small ones. Linear programming has also been used by other studies (Gunnarsson, Rönnqvist, & Lundgren, 2004; J. Kim, Realff, Lee, Whittaker, & Furtner, 2011; Nagel, 2000) for various supply chain decisions, including optimizing for when and where forest residues are to be converted into fuel, and how the residues are to be transported and stored to satisfy demand at heating plants. However, the planning horizon for one of the studies (Gunnarsson et al., 2004) was only one year, where monthly time periods are considered. Other cost minimization or profit/yield maximization studies accounted for land allocation and scheduling in biomass harvesting subject to various forms of area restrictions (Constantino, Martins, & Borges, 2008; Goycoolea, Murray, Barahona, Epstein, & Weintraub, 2005; Khanna, Önal, Dhungana, & Wander, 2011; T. J. Kim, Wear, Coulston, & Li, 2018). However, the literature lacks a comprehensive study evaluating the impact on Georgia's forest stands when a certain percentage of coal is replaced in the power plant for a considerably long planning horizon.

We developed a market-clearing linear programming model from a social planner's perspective expanding 50 years that would satisfy i) the traditional timber demand in the pulp and sawmills, and ii) torrefied biomass demand to replace 50% coal in the coal-fired power plants of Georgia. We maximized the landowner's profit and minimized the cost for timber harvesting, transporting, and the opportunity cost of harvesting but not transporting timber. We determined the optimal acres harvested and optimal quantity of timber supplied on the FIA unit level. We analyzed the impact on stand age characteristics in Georgia's forests with and without additional bioenergy demand in the power plant. We also estimated the impact of such market shock on overall carbon savings by analyzing both stand carbon and avoided carbon emission via coal replacement in the power plants.

The overall goal of this research is to evaluate the sustainability of woody biomass in the presence of coal replacement in the power plant. Specific objectives are –

i) Optimizing the timber sourcing location of biomass to satisfy demand at pulp mills, sawmills, and power plants.

ii) Optimizing the quantity of biomass transported from each biomass production region to demand points.

iii) Estimating changes in stand carbon and avoided carbon emission via replacing coal in the coal-fired power plants of Georgia with biomass.

3.2. Methodology

3.2.1. Study area

Our study area consists of five FIA (Forest Inventory and Analysis) units in Georgia (Figure 3.1). Unit 1 to 3 are in the Coastal Plain region, and Unit 4 and 5 primarily fall in the piedmont region. About 64% of Georgia's area is forested (US Forest Service, 2020b), making Georgia suitable to replace coal with woody biomass. Georgia has three coal-fired power plants in operation – plant Bowen located in Unit 5, Hal B. Wansley power plant in Unit 4, and Scherer power plant in Unit 3 (US EIA, 2020b).

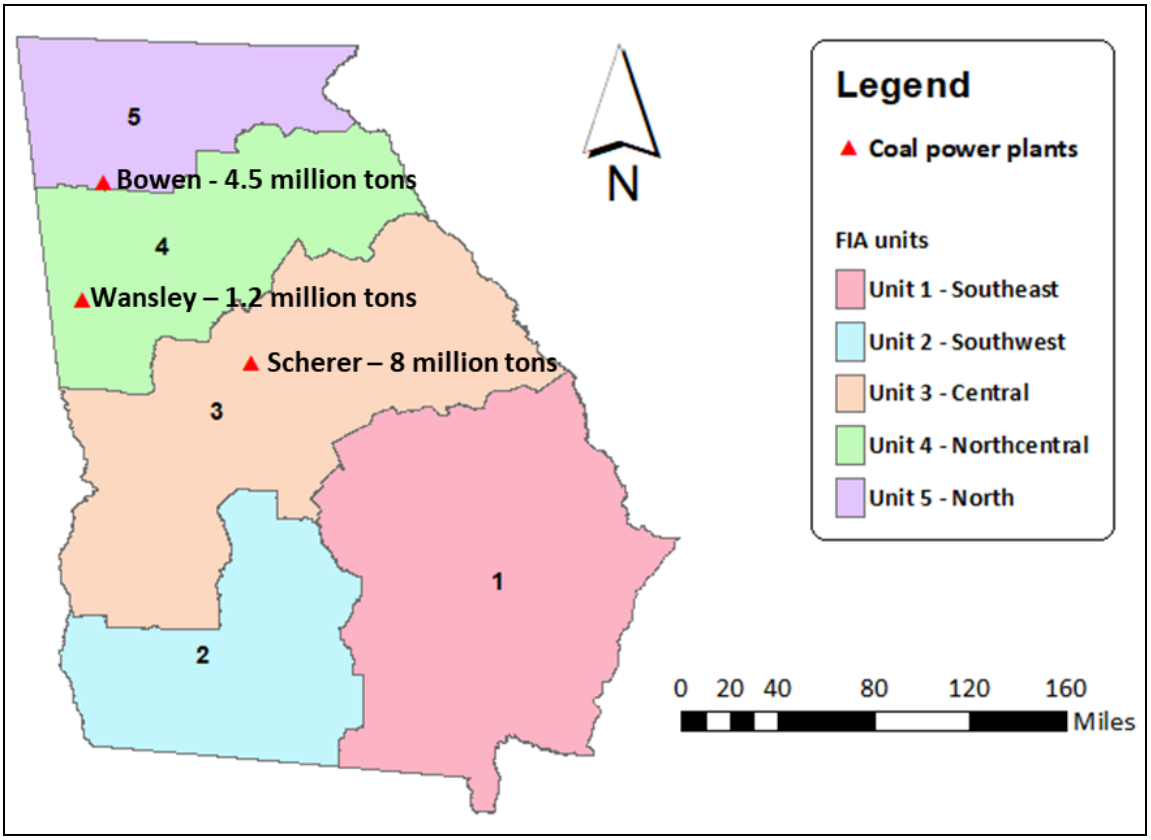

Figure 3.1: FIA units and coal power plants of Georgia

3.2.2. Data

'Unit' was defined as the supply node of timber—the FIA units described in section 3.2.1 (Table 3.1). 'Forest' was the forest type available in units—planted softwood, natural softwood, upland hardwood, bottomland hardwood, and mixed. 'Wood' was the type of wood these forest types provided—softwood and hardwood. As the names suggest, planted softwood and natural softwood provided softwood while upland hardwood and bottomland hardwood provided hardwood. Mixed forest provided both softwood and hardwood. FIA defined mixed forest as forests having 25% to 49% pine and red cedar (US Forest Service, 2015). For simplicity, we assumed 50% of the wood derived from mixed forest was softwood, and the remaining 50% was hardwood. In this analysis, we did not include the non-stocked forest type defined as land currently has less than 10% canopy cover but formerly met the definition of forest land (US Forest Service, 2018). In Georgia, planted softwood was the most common forest type (29%), closely followed by upland hardwood (27%) (Figure 3.2).

Table 3.1: Sets used in model and their definitions

Sets	Definition
unit	FIA units in Georgia, timber supply region
forest	Forest types – planted softwood (PS), natural softwood (NS), upland hardwood (UH), bottomland hardwood (BH), and mixed
wood	Wood types – softwood and hardwood
timber	Timber types– poletimber (PT), sawtimber (ST), and logging residues (LR)
age	Stand age class with 5-year interval, A1 to A21
time	Planning period with 5 year interval, T1 to T10; total planning horizon – 50 years
unitP	Aggregated pulpwood demand node of each unit
unitS	Aggregated sawtimber demand node of each unit
plant	Coal power plants in Georgia

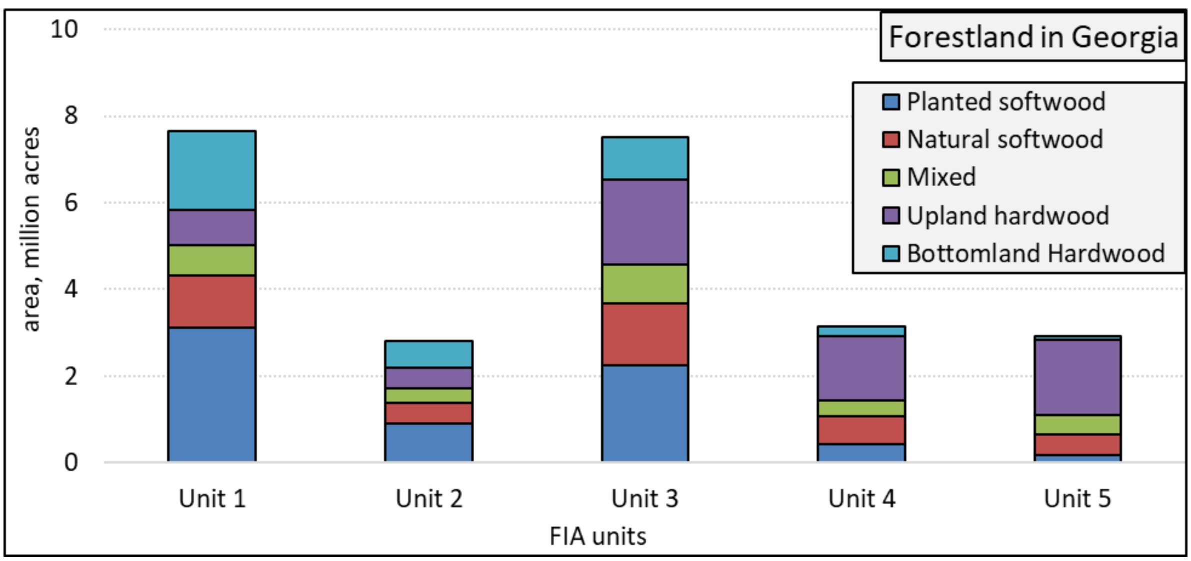

Figure 3.2: Forestland acreage in Georgia before the planning period of the study (US Forest Service, 2020a)

Planted softwood was the dominant forest type in Unit 1, Unit 2, and Unit 3, comprising 41%, 32%, and 30% of forest area, respectively. Upland hardwood was dominant in Unit 4 and Unit 5, constituting 47% and 59% of forest area, respectively. 'Timber'—poletimber, sawtimber, and logging residues—was available from each forest type and varied by stand age classes, declared as 'age', with an interval of 5 years, starting from 0-5 (A1) to 100+ years (A21). 'Time' referred to ten planning periods T1 to T10, each with 5-year intervals over the total planning horizon of 50 years; i.e., T1 referred to year 0 to 5, T2 referred to year 6 to 10, etc. 'UnitP' and 'unitS' were the aggregated demand nodes, respectively, for pulp mills and sawmills in FIA units. 'Plant' was coal-based power plants or the bioenergy demand node.

3.2.2.1. Growth and yield for supply

To estimate the timber availability, we developed growth and yield models for planted softwood, natural softwood, mixed, upland hardwood, and bottomland hardwood from FIA's net growth data (US Forest Service, 2020a). We collected average annual net growth (AANG) data of dry poletimber and sawtimber (FIA data code – 306) and tops and limbs (FIA data code – 332) for all forest types for each FIA units in Georgia. These data were extracted by the Evalidator tool developed by the FIA program. Poletimber data were considered for pulpwood, and tops and limbs data were considered for logging residues in our analysis. We only used unthinned and undisturbed plots from private timberland (FIA data code - 3) to filter the data and calculate timber availability to avoid any undesired data issues. However, in the optimization model, the total acreage available for timber supply includes all forestland (FIA data code - 2) and not just the filtered ones. To summarize, we assumed that all plots would have such yields given an unthinned and undisturbed scenario. As a result, our yield estimates could be higher as these yields come from plots that are not affected by fire and flood or any other natural disturbances.

To calculate timber available in each age class, we multiplied AANG by 5 to calculate net growth (NG). Then, we divided NG in each forest type by the respective acreage of timberland (FIA data code - 3) in that forest type to calculate yield. Using these yields, we calculated the cumulative yield or total timber available in each age class. Finally, we converted dry biomass to green biomass, assuming 50% moisture content in green biomass.

FIA reports poletimber and sawtimber availability in the early age classes such as years 0-5, 6-10. This is because a plot that primarily contains saplings may also contain a few older trees. To rectify this issue, we removed poletimber and tops and limbs availability up to year 10 and year 15 for softwood and hardwood, respectively. We also removed sawtimber availability up to year 15 and year 30 for softwood and hardwood, respectively. Additionally, we considered all softwood and mixed stands aged between 40 and 100+ years to be 40+ years.

3.2.2.2. Demand

For traditional timber demand, we adopted FIA data on timber harvested in 2017. This data was provided by the Southern Research Station, FIA, in Knoxville, Tennessee. Approximately 19.47 million tons of softwood pulpwood, 3.4 million tons of hardwood pulpwood, 17.47 million tons of softwood sawtimber, and 2.26 million tons of hardwood sawtimber were harvested in Georgia. Table S3.1 in supporting information contains information on the removal of each timber type on the FIA unit level. Additionally, for annual coal demand, we used the quantity of coal consumed in the coal-based power plants of Georgia, approximately 13.8 million tons (Table S3.2). The amount of torrefied biomass required to replace 50% of the coal was 6.9 million tons, and the green biomass requirement was calculated to be 17.5 million tons using 2.536 as the conversion factor

(Masum, Dwivedi, & Anderson, 2020). We considered torrefied chips instead of pellets as pelletization requires additional cost, incurs additional GHG emissions, and would only be necessary for long-distance transportation (Dwivedi & Khanna, 2014, 2015; Hoque et al., 2006).

3.2.2.3. Cost and prices

For harvesting cost, we used the 4th quarter, 2019 final harvest cost reported by TimberMart-South (TMS, 2020a). The cost of harvesting varied between units based on the topographical characteristics of the region. For units in the coastal plain (Unit 1 to Unit 3) and piedmont region (Unit 4 and Unit 5), the final harvest cost was \$11.67 and \$12.9 ton^{-1}, respectively. The assumed annual nominal tax was \$5 $acre^{-1}$, and was a function of planning period T. Table S3.3 in the supporting information contains cumulative land rent for each planning period. Cost of timber transportation was 0.15 ton^{-1} $mile^{-1}$ (TMS, 2020a). Distances from one unit center to other unit centers and to the power plants are presented in the supporting information (Table S3.4 and S3.5). Transportation distance within the unit was assumed to be 40 miles. The opportunity cost of harvesting but not transporting pulpwood and sawtimber \$4.8 and was \$12.5, respectively. These opportunity costs (OC) were calculated using equation (3.1)-

$$OC = value\ x\ margin\ x\ ratio \tag{3.1}$$

where the value was the market price of prevailing final products from pulpwood and sawtimber—paper (\$200 ton^{-1}) and lumber (\$357 tbf^{-1}), respectively; the margin was the net profit margin from finished products, 6% and 7% for paper and lumber products; and the ratio was the finished product to raw material ratio, 0.5 and 0.4 for pulpwood and sawtimber, respectively. We did not consider any opportunity cost for logging residues since, traditionally these were left on the logging site as per the definition.

We assumed no silvicultural inputs and, therefore, no silvicultural costs. Stumpage prices in 4th quarter, 2019 for pulpwood and sawtimber were collected from TimberMart-South (TMS, 2020b). Based on the geographic location, prices for TMS (TimberMart-South) region 2 was considered for FIA unit 1 to 3 and prices for TMS Region 1 was considered for Unit 4 and 5 (Table S3.6). All costs and prices were discounted using a 4% interest rate and the discounting year was the median of each planning period, such as year 3 for T1, year 8 for T2, etc.

3.2.3. Mathematical framework

From a social planner's perspective, we developed a linear spatial equilibrium model that maximizes profit for landowners and minimizes the cost of timber procurement and transportation to satisfy the demand of pulpmills, sawmills, and power plants in Georgia. All parameters and variables were defined in Table 3.2.

We developed three scenarios to fully understand the impact of additional bioenergy demand to replace coal:

a) **Baseline** - business as usual, where there is no coal replaced with biomass in the power plant;
b) **Scenario 1** - where 50% coal is replaced with pulpwood only, i.e., variable BIO includes SoftPT2 and HardPT2; and
c) **Scenario 2** - where 50% coal is replaced with pulpwood and logging residues both; i.e., variable BIO includes SoftPT2, SoftLR, HardPT2, and HardLR.

Table 3.2: Parameters/variables used in the model and their definitions

Parameters	**Definition**
$Acreage_{unit,forest,age}$	Acreage of forest type in each FIA unit
$Yield_{unit,forest,wood,timber,age}$	
YieldSoftPT	Yield of softwood poletimber varied by location, forest type, and stand age
YieldSoftST	Yield of softwood sawtimber varied by location, forest type, and stand age
YieldSoftLR	Yield of softwood logging residues varied by location, forest type, and stand age
YieldHardPT	Yield of hardwood poletimber varied by location, forest type, and stand age
YieldHardST	Yield of hardwood sawtimber varied by location, forest type, and stand age
YieldHardLR	Yield of hardwood logging residues varied by location, forest type, and stand age
$P_{time,unit,wood,timber}$	Price of timber, both softwood and hardwood, varied by location
$Cost_{time,age}$	Annual tax paid by the landowner
$Harvest_{time,unit}$	Harvesting cost per ton, varied by location
$TC1_{time,unit,unitP}$	Transportation cost of pulpwood from unit centers to pulp mills
$TC2_{time,unit,unitS}$	Transportation cost of sawtimber from unit centers to saw mills
$TC3_{time,unit,plant}$	Transportation cost of feedstock from unit centers to power plants
$OC_{time,timber}$	Opportunity cost of harvesting but not transporting timber
$DemandSoftPT_{unitP}$	Softwood pulpwood quantity demanded at FIA units
$DemandSoftST_{unitS}$	Softwood sawtimber quantity demanded at FIA units
$DemandHardPT_{unitP}$	Hardwood pulpwood quantity demanded at FIA units
$DemandHardST_{unitS}$	Hardwood sawtimber quantity demanded at FIA units
$DemandBio_{plant}$	Biomass, pulpwood and/or logging residues, demanded at the power plants

Variables	**Definition**
$AA_{time,unit,forest,age}$	Acres available in each forest type in each FIA unit
$AH_{time,unit,forest,age}$	Acres harvested from each forest type in each FIA unit
$AU_{time,unit,forest,age}$	Acres not harvested from each forest type in each FIA unit
$\sum_{uniP,unitS,plant} Q_{unit,forest,wood,timber,age}$	
a) $SoftPT_{unit,forest,wood,timber,age,unitP}$	Amount of softwood pulpwood transported from Unit to unitP
b) $SoftST_{unit,forest,wood,timber,age,unitS}$	Amount of softwood sawtimber transported from Unit to unitS
c) $HardPT_{unit,forest,wood,timber,age,unitS}$	Amount of hardwood pulpwood transported from Unit to unitP
d) $HardST_{unit,forest,wood,timber,age,unitS}$	Amount of hardwood sawtimber transported from Unit to unitS
e) $BIO_{unit,forest,wood,timber,age,plant}$	Amount of pulpwood and/or logging residues transported from each Unit to all power plants
e1) SoftPT2	Amount of softwood pulpwood transported from Unit to plant
e2) SoftLR	Amount of softwood logging residues transported from Unit to plant
e3) HardPT2	Amount of hardwood pulpwood transported from Unit to plant
e4) HardLR	Amount of hardwood logging residues transported from Unit to plant

The welfare maximizing objective function for all three scenarios was defined as –

$$\max \frac{1}{1.04^{time}} [\text{revenue - landrent - harvestcost - transcost – opcost}] \quad (3.2)$$

where,

$$\text{revenue} = \sum_{time,unit,forest,wood,timber,age,unitP,unitS,plant} [\text{Quantity}_{time,unit,forest,wood,timber,age}\ x\ \text{P}_{time,unit,forest,timber}] \quad (3.3)$$

$$\text{landrent} = \sum_{time,unit,forest,age} [\text{AH}_{time,unit,forest,age}\ x\ \text{Cost}_{time}] \quad (3.4)$$

$$\text{harvestcost} = \sum_{time,unit,forest,wood,timber,age} [\text{AH}_{time,unit,forest,age}\ x\ \text{Yield}_{unit,forest,wood,timber,age}\ x\ \text{Harvest}_{unit,time}] \quad (3.5)$$

$$\text{transcost} = \sum_{time,unit,forest,wood,timber,age,plant} [\text{TC1}_{time,unit,plant}\ x\ \text{BIO}_{time,unit,forest,wood,timber,plant}] + \sum_{time,unit,forest,wood,timber,unitP} [\text{TC2}_{time,unit,unitP}\ x\ (\text{SofTPT}_{time,unit,forest,wood,timber,unitP} + \text{HardPT}_{time,unit,forest,wood,timber,unitP})] + \sum_{time,unit,forest,wood,timber,unitS} [\text{TC3}_{time,unit,unitS}\ x\ (\text{SoftST}_{unit,forest,wood,timber,unitS} + \text{HardST}_{unit,forest,wood,timber,unitS})] \quad (3.6)$$

$$\text{opcost} = \sum_{time,unit,forest,wood,timber,age} [\text{OC}_{time,timber}\ x\ (\{\text{AH}_{time,unit,forest,age}\ x\ \text{Yield}_{unit,forest,wood,timber,age}\} - \sum_{unitP,unitS,plant} \text{Quantity}_{unit,forest,wood,timber,age})] \quad (3.7)$$

Equation (3.3) defined ‘revenue’ as the sum of revenue earned by the landowner by selling timber. Equation (3.4) defined ‘landrent’ as the sum of annual taxes paid by the landowner. Equation (3.5) defined ‘harvestcost’ as the sum of costs for harvesting timber. Equation (3.6) defined ‘transcost’as the sum of costs of transporting timber to sawmills, pulp mills, and power plants. In the Baseline scenario, the quantity for variable BIO is zero. Equation (3.7) defined ‘opcost’ as the sum of opportunity costs for harvesting but not transporting pulpwood and sawtimber. From this formulation, it can be predicted that the maximum welfare achieved by equation (3.2) could be negative since the welfare function contained cost of logging and transportation but did not include the revenue from final products such as lumber, paper, or electricity.

Constraints for the Baseline scenario were as follows –

$AH_{time,unit,forest,age} + AU_{time,unit,forest,age} = Acreage_{time,unit,forest,age}$ for every time, unit, forest, wood, age (3.8)

$AA_{time,unit,forest,A1} = \sum_{age} AH_{time-1,unit,forest,age}$ for every time, unit, forest (3.9)

$AA_{time,unit,forest,age} = AU_{time-1,unit,forest,age-1}$ for every time, unit, forest, age (3.10)

$AA_{time,unit,forest,age=A21} = AU_{time-1,unit,forest,age=A20} + AU_{time-1,unit,forest,age=A21}$ for every time, unit, forest, and wood (3.11)

$\sum_{unitP} SoftPT_{time,unit,forest,wood,timber,age,unitP} \leq AH_{time,unit,forest,age} \; x \; YieldSoftPT_{unit,forest,wood,timber,age}$ for every time, unit, forest, wood, timber, age (3.12)

$\sum_{unitS} HardPT_{time,unit,forest,wood,timber,age,unitS} \leq AH_{time,unit,forest,age} \; x \; YieldHardPT_{unit,forest,wood,timber,age}$ for every time, unit, forest, wood, timber, age (3.13)

$\sum_{unitP} SoftST_{time,unit,forest,wood,timber,age,unitP} \leq AH_{time,unit,forest,age} \; x \; YieldSoftST_{unit,forest,wood,timber,age}$ for every time, unit, forest, wood, timber, age (3.14)

$\sum_{unitS} HardST_{time,unit,forest,wood,timber,age,unitS} \leq AH_{time,unit,forest,age} \; x \; YieldHardST_{unit,forest,wood,timber,age}$ for every time, unit, forest, wood, timber, age (3.15)

$\sum_{unit,forest,\ wood,timber,age} SoftPT_{time,unit,forest,wood,timber,age,unitP} = DemandSoftPT_{unitP}$ for every t and unitP (3.16)

$\sum_{unit,forest,\ wood,timber,age} SoftST_{time,unit,forest,wood,timber,age,unitP} = DemandSoftST_{unitS}$ for every t and unitS (3.17)

$\sum_{unit,forest,\ wood,timber,age} HardPT_{time,unit,forest,wood,timber,age,unitP} = DemandHardPT_{unitP}$ for every t and unitP (3.18)

$\sum_{unit,forest,\ wood,timber,age} HardST_{time,unit,forest,wood,timber,age,unitS} = DemandHardST_{unitS}$ for every t and unitS (3.19)

$AH, AU, SoftPT, SoftST, HardPT, HardST \geq 0$ (3.20)

Equation (3.8) suggested that the land use stays the same, i.e., acres harvested and acres unharvested will equal total acreage in all forest types. Equation (3.9) suggested that acres harvested in time "t" will move to stand age class A1 in time "t+1", i.e., the area will be replanted and stand age will become zero in the next planning period. Equation (3.10) suggested that the stand age of acres not harvested in the planning period "t" will move to the next stand age class in "t+1". Equation (3.11) suggested that if any acres with stands aged A21 is not harvested, then the land will remain in age A21 since this is the last stand age class. Equations (3.12) to (3.15) suggested that the total quantity of timber transported to pulp mills and sawmills cannot exceed the total biomass harvested from the timberland. Equations (3.16) to (3.19) suggested that demand at pulp mills and sawmills must be satisfied. Equation (3.20) was non-negativity constraints for acreage and the quantity of timber transported.

Scenario 1 included equations (3.8) to (3.11) and (2.14) to (3.20) as constraints. Additional constraints for Scenario 1 were as follows—

$$\sum_{unitP} SoftPT_{time,unit,forest,wood,timber,age,unitP} + \sum_{plant} SoftPT2_{time,unit,forest,wood,timber,age,plant} \leq AH_{time,unit,forest,wood,age} \; x \; YieldSoftPT_{unit,forest,wood,timber,age} \text{ for every time, unit, forest, wood, timber, age} \quad (3.21)$$

$$\sum_{unitP} HardPT_{time,unit,forest,wood,timber,age,unitP} + \sum_{plant} HardPT2_{time,unit,forest,wood,timber,age,plant} \leq AH_{time,unit,forest,wood,age} \; x \; YieldHardPT_{unit,forest,wood,timber,age} \text{ for every time, unit, forest, wood, timber, age} \quad (3.22)$$

$$\sum_{unit,forest,wood,timber,age} BIO_{time,unit,forest,wood,timber,age,plant} = Demand_{plant} \text{ for every t and plant} \quad (3.23)$$

$$SoftPT2, HardPT2 \geq 0 \quad (3.24)$$

Equations (3.21) and (3.22) suggests that total quantity of softwood pulpwood and hardwood pulpwood transported to the pulp mills and the power plants cannot exceed the total softwood pulpwood and hardwood pulpwood produced, respectively. Equation (3.23) suggested that power plant demand for biomass must be satisfied. Equation (3.24) was the non-negativity constraint for softwood and hardwood pulpwood transported to the power plants.

In addition to equations (3.8) to (3.11) and (3.14) to (3.24), Scenario 2 included equation (3.25) to (3.27) as constraints to include logging residues —

$$\sum_{plant} SoftLR_{time,unit,forest,wood,timber,age,plant} \leq AH_{time,unit,forest,wood,age}\ x\ YieldSoftLR_{unit,forest,wood,timber,age} \text{ for every time, unit, forest, wood, timber, age} \quad (3.25)$$

$$\sum_{plant} HardLR_{time,unit,forest,wood,timber,age,plant} \leq AH_{time,unit,forest,wood,age}\ x\ YieldHardLR_{unit,forest,wood,timber,age} \text{ for every time, unit, forest, wood, timber, age} \quad (3.26)$$

$$SoftLR, HardLR \geq 0 \quad (3.27)$$

Equation (3.25) suggested that the total quantity of softwood logging residues transported cannot exceed total logging residues generated; equation (3.26) suggested the same for hardwood. Equation (3.27) was the non-negativity constraint for softwood and hardwood logging residues transported to the power plant. After procuring the primary results from GAMS, we estimated timber production using the following equation–

$$Production = AH\ x\ Yield \quad (3.28)$$

where AH was the acres harvested from each forest type, and Yield was the total quantity of timber available on the harvested timberland—pulpwood and sawtimber in the Baseline scenario and Scenario 1 along with logging residues in Scenario 2. Preparation of results and graphing was performed in MS Excel and OriginPro Version 2019b (Originlab Corporation, 2019).

3.2.4. Carbon dynamics

3.2.4.1. Carbon in stand

Carbon in stand (CS, tons of C) was calculated using the following equation –

$$CS = Acreage \; x \; Yield \; x \; CGB \quad (3.29)$$

To calculate CS before the planning horizon, 'Acreage' was the total acres of timberland, all five forest types, reported by FIA in 2018 (US Forest Service, 2020a). To calculate CS throughout the planning horizon, 'Acreage' was the number of acres that remained unharvested after fulfilling all timber demand in every planning period. 'Yield' was the total green biomass, ton $acre^{-1}$ available on respective timberland. 'CGB' was the C content in green biomass, 25%. Change in CS before and after the planning horizon was calculated by subtracting CS before the planning horizon from CS at T10.

3.2.4.2. Carbon savings with biopower

We calculated the total electricity from wood, E (MWh), using the following equation –

$$E = T \; x \; Bark \; x \; (1 - MC) \; x \; CV \; x \; CE \; x \; TL \quad (3.30)$$

where, T is the amount of pulpwood or logging residues, in tons, transported to the power plant; Bark was the ratio of timber without bark, 93%; MC is the moisture content of the feedstock, 55%; CV is the calorific value of the torrefied feedstock, 10902.85 Btu lb^{-1} (Phanphanich & Mani, 2011);

CE is the conversion efficiency of 3071 MMBtu power plant, 0.43 (Bridgwater, Toft, & Brammer, 2002); TL is the transmission loss of electricity, 7% (US EIA, 2018b).

We calculated the total carbon savings, TCS (lb), using the following equation –

$$TCS = (E \; x \; CC) - (C_{HARVESTING} + C_{TRANSPORT} + C_{CHIPPING} + C_{DRYING} + C_{TORREFACTION} + C_{BURN}) \quad (3.31)$$

where CC is the carbon emission of coal-based electricity, 754.67 lb CO_2e $MMBTU^{-1}$ (US EIA, 2018a). Therefore, ($E \; x \; CC$) is the avoided carbon emission via coal replacement; $C_{HARVESTING}$ is the carbon emission from harvesting operation of timber, 13.01 lb CO_2e ton^{-1} of green wood (Masum, Dwivedi, & Anderson, 2020), $C_{TRANSPORTATION}$ was the carbon emission from biomass transportation from FIA unit center to the power plant, 0.45 lb CO_2e ton^{-1} $mile^{-1}$ (US EPA, 2018); $C_{CHIPPING}$ is the carbon emission from chipping, 9.72 lb CO_2e ton^{-1} (PRé Consultants, 2013); and C_{DRYING} was the GHG emissions related to the drying operation, 16.76 lb CO_2e ton^{-1} of dried biomass (Haque & Somerville, 2013); $C_{TORREFACTION}$ was the GHG emission from converting green biomass into torrefied biomass 303.27 lb CO_2e ton^{-1} of green biomass, calculated from Adams et al. (Adams, Shirley, & McManus, 2015); $C_{BURNING}$ was the non-biogenic carbon emission from the electricity production process in the power plant, 68.81 lb CO_2e ton^{-1} (WDNR, 2010). The amounts were converted to and reported in million tons of C.

3.2.5 Sensitivity analysis

For our sensitivity analysis, we considered varying percentages of coal replaced with biomass in the coal-based power plants. We replaced 10% to 100% coal in power plants using (i) pulpwood only and (ii) using both pulpwood and logging residues. We reported acres harvested, change in stand carbon, carbon avoided via coal replacement, and net carbon changes under these scenarios.

3.3. Results & Discussion

A globally optimal solution for the welfare was obtained for the entire planning horizon of 50 years at -$0.69 billion, -$8.78 billion, and -$7.71 billion for the Baseline Scenario, Scenario 1, and Scenario 2, respectively. It took 15960, 23553, and 26950 iterations in GAMS in the Baseline Scenario, Scenario 1, and Scenario 2, respectively. Negative welfare was expected as the model included cost for timber or biomass procurement but the revenue generated from the finished products such as paper or lumber was not included. The highest welfare was achieved for the Baseline scenario.

3.3.1. Timber Yield

Pulpwood availability was highest in planted softwood forest type in all Units in early age classes (Figure 3.3). Since there were almost no planted softwood stands aged over 55 as they were harvested, pulpwood from natural softwood exceeded in older age classes in Unit 4 and 5. For the same reason, sawtimber availability from planted softwood flattened down beyond age class 51-55. In Unit 1 and 2, sawtimber availability from natural softwood forest was almost equal in early age classes and exceeded beyond age 25. It was not readily intuitive as planted softwood tends to have higher sawtimber availability in practice. However, there were several reasons why natural softwood had higher sawtimber compared to planted softwood. First, FIA attributes stand age based on the most representative trees in that particular stand (US Forest Service, 2018). However, in that stand, there exist other trees that are not representative of that stand. These trees can be older and add to the sawtimber availability. This is especially true for natural stands as planted stands tend to have the same age for all trees. Second, natural softwood stands were fully stocked with 100% canopy cover while planted stands did not (Rosson, 2020).

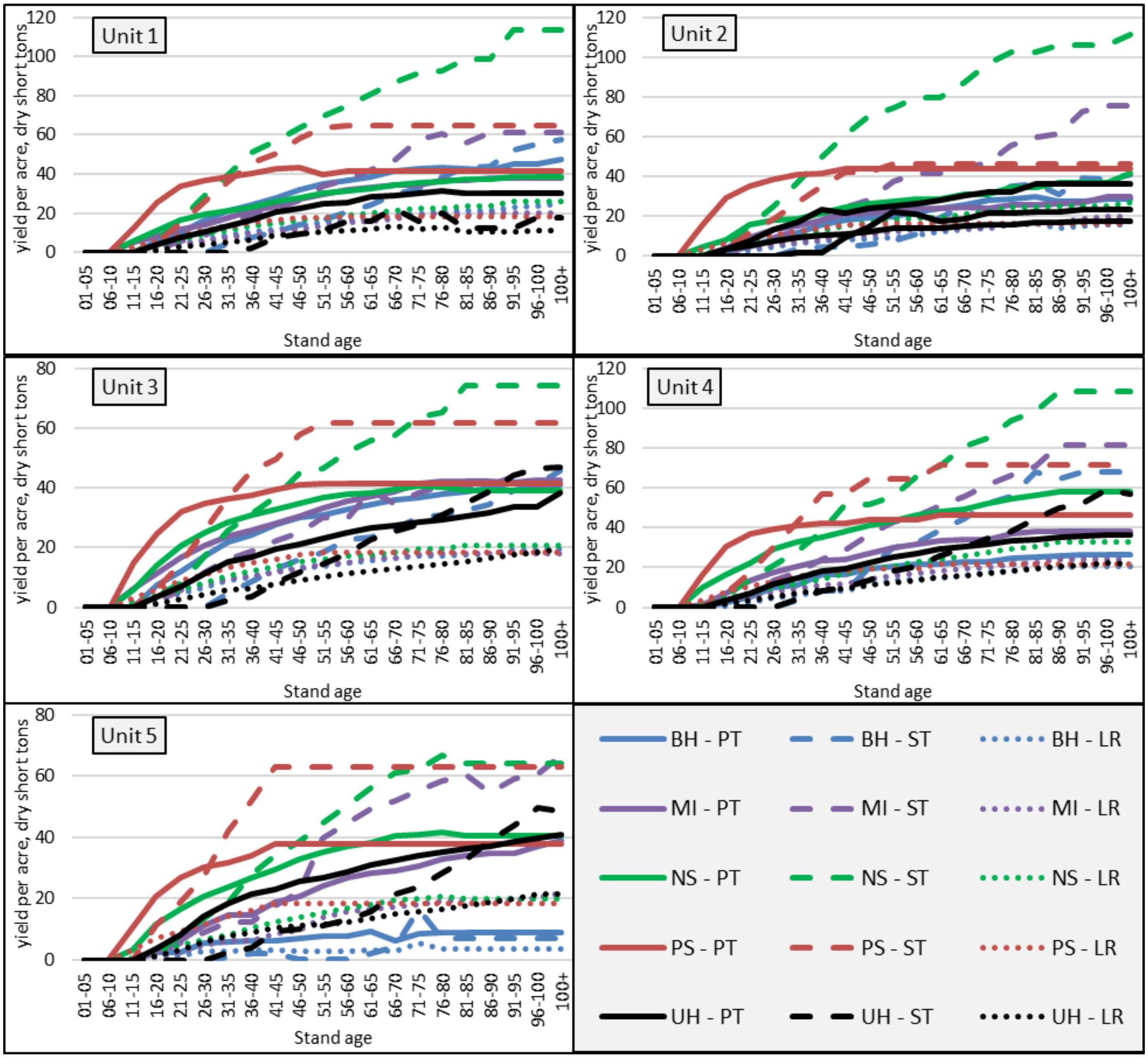

Figure 3.3: Timber availability in different forest type in FIA unit of Georgia

Therefore, it did not mean that natural softwood grows more quickly compared to planted softwood. It just meant that, in this snapshot of a scenario, natural softwood contained more sawtimber and will not provide higher sawtimber compared to planted softwood in a similar time scale. This is consistent with Kira's law of constant final yield, which states that the maximum carrying capacity of a site is independent of densities and that maximum volumes are independent of densities as long as space is fully occupied (Kira, Ogawa, & Sakazaki, 1953). In other words, if planted softwood stands were fully occupied, the yield situation would have been different. Third, Unit 1 and Unit 2 are known as the 'longleaf belt' where the interest of longleaf pine restoration introduced and planted more longleaf pine rather than loblolly pine (Rosson, 2020). As longleaf pine generally has lower sawtimber availability compared to loblolly pine, planting more longleaf in the planted stands can lower the total sawtimber availability. Other yield estimates presented no surprises.

3.3.2. Land use

3.3.2.1. Acres Harvested

Approximately 320, 816, and 551 thousand acres of land were annually harvested on an average in Baseline, Scenario 1, and Scenario 2, respectively (Figure 3.4). In Baseline and Scenario 2, average annual harvested acreage was consistent. However, the added pressure of fulfilling biomass demand in the power plants by pulpwood only started to show its impact from the 8^{th} planning period as harvested acreage increased.

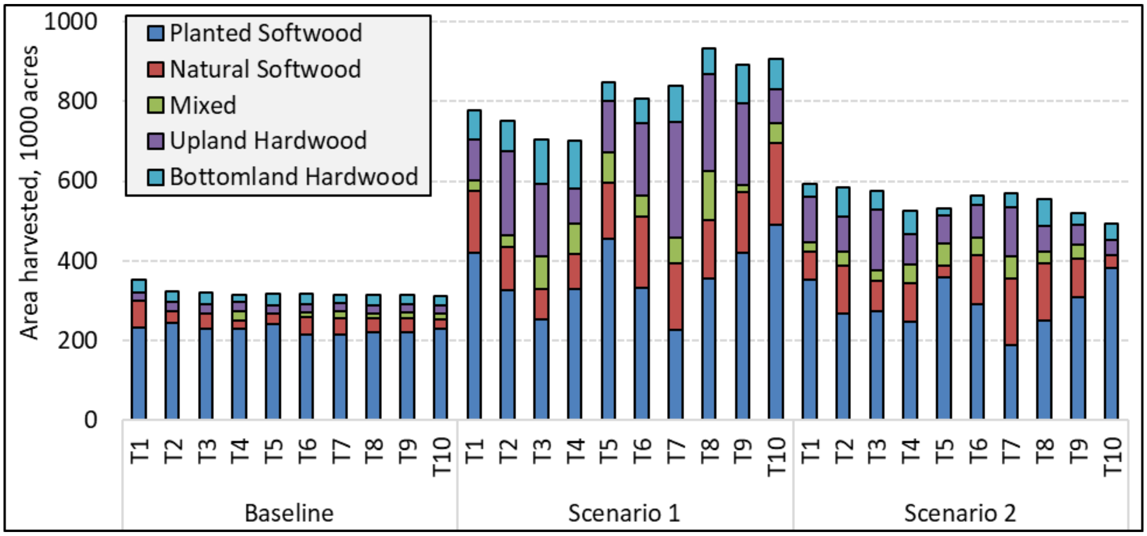

Figure 3.4: Area of forest types harvested in all three scenarios

3.3.2.1.1. Baseline

In the Baseline scenario, the highest and lowest amount of annual acreage was harvested in the first planning period (352 thousand acres) and tenth planning period (312 thousand acres), respectively (Figure 3.5). Planted softwood comprised 71% on an average, at least 66% to a maximum of 76%, of all forestland harvested through all planning periods (Figure S3.1). Most of these planted softwood forests were in Unit 1 (about 40%), and Unit 3 (about 35%) as demand was higher in those units. Additionally, these units are larger in area. No mixed forest was harvested in T1, T2, T3, and T5. All the mixed forests harvested in other time periods were in Unit 3, about 14 thousand acres annually. No Bottomland hardwood was harvested from Unit 2, Unit 4, and Unit 5 in any time period except about 5000 acres annually in T1.

Only about 46 thousand acres, across all forest types, were annually harvested from Unit 4 and 5 combined due to lower demand and higher harvesting cost. In all planning periods, bottomland hardwood harvested acreages were higher compared to upland hardwood, except in the fourth planning period. On average, across planning periods, 25 and 21 thousand acres of bottomland hardwood and upland hardwood were harvested annually. Most of the harvested bottomland hardwood acres were in Unit 1 and Unit 3. The reason for harvesting more from these units was similar to softwood, the demand for hardwood pulpwood and sawtimber were higher in Unit 1 and Unit 3.

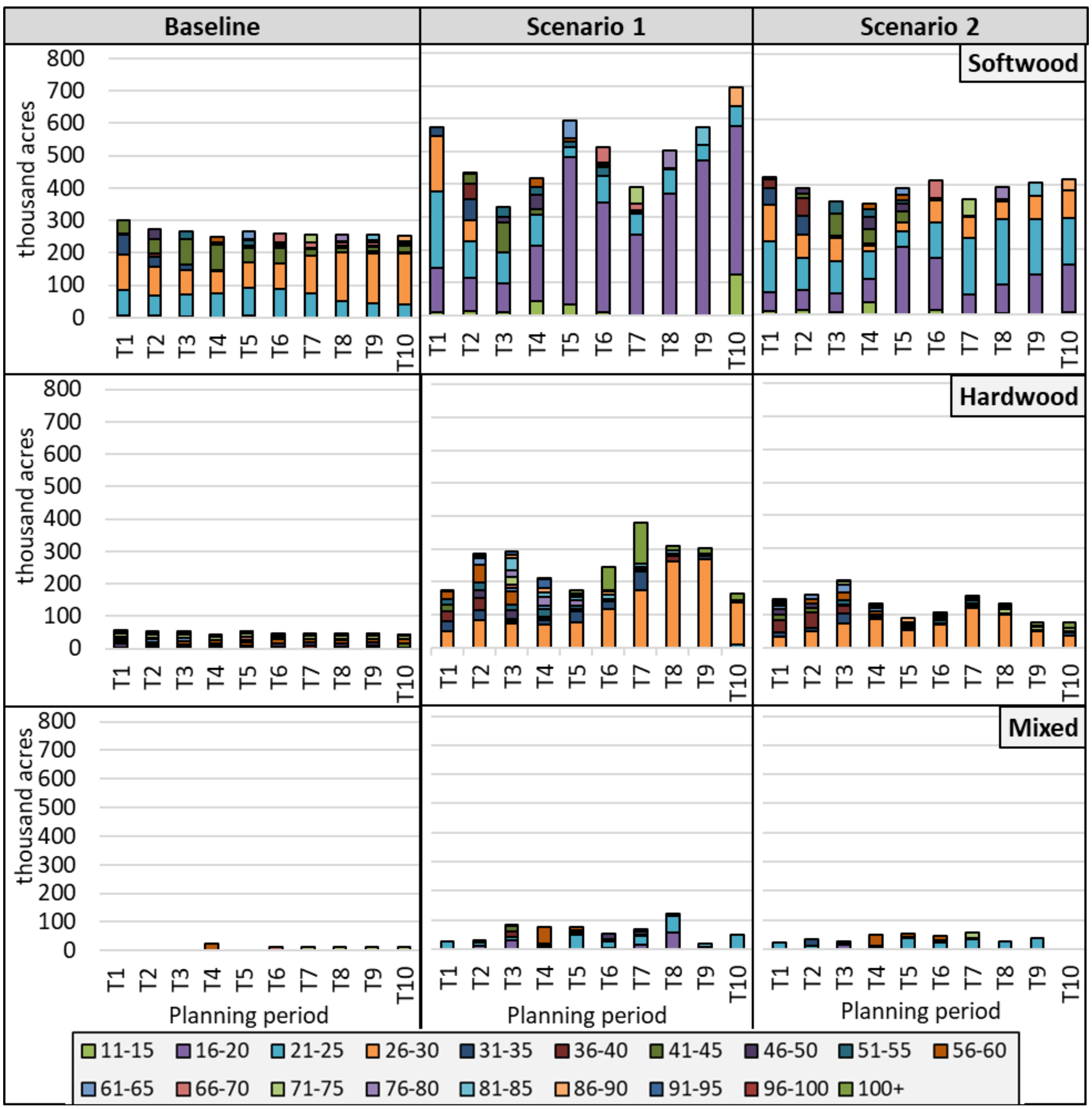

Figure 3.5: Stand age characteristics of annual average harvested acreage

Most of the softwood stands harvested aged either between 21 and 30 or between 41 and 45 years. It is reasonable to assume that younger trees were primarily harvested to satisfy pulpwood demand and older trees for sawtimber demand. In the first six planning periods, from T1 to T6, about 60% of softwood forests harvested were aged between 21 and 30 years, and about 21% were aged between 41 and 45 years. However, in the last four planning periods, 78% of the harvested softwood forests were aged between 21 and 30 years, and stands with 41 to 45 year old trees fell to 7%. No hardwood aged under 25 years was harvested in any period and harvest under 35 years old hardwoods were minimal. On average, across all periods, 21% hardwood stands harvested was between 56 and 60 years old.

Our total harvested acreage estimates for the Baseline scenario closely followed the historical trend (Figure 3.6). It was understandable as our Baseline scenario was the business-as-usual scenario where no bioenergy was used to replace coal in the power plants. The five-year average of the historical harvested area was 297 thousand acres, where our 50-year average showed 320 thousand acres. However, in our estimate, planted softwood harvest was higher, and upland hardwood harvest was lower compared to the historical data. This is primarily because in this model, Georgia is a closed system with no interstate or international transport. For example, TPO data reported approximately three times export than an import for hardwood pulpwood, and as those were absent in our model, hardwood harvest went lower than the historical average (US Forest Service, 2019).

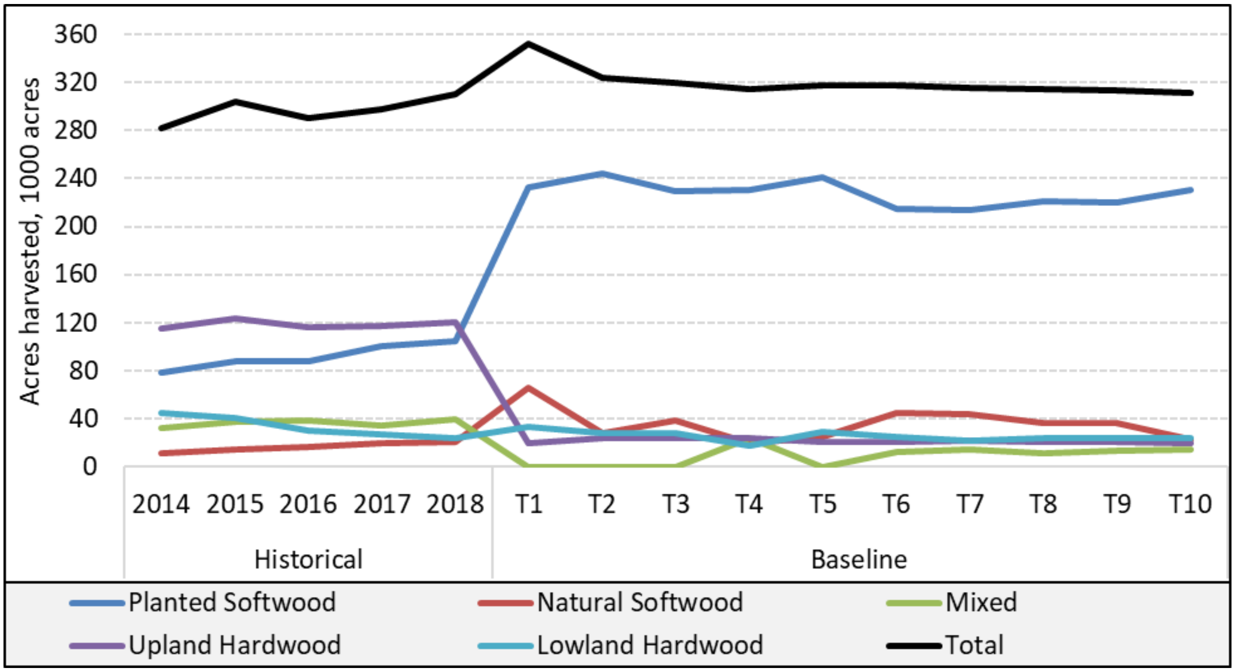

Figure 3.6: Historical trend (US Forest Service, 2020b) and Baseline projections of acres harvested in Georgia

3.3.2.1.2. Scenario 1

In the presence of additional pulpwood demand for bioenergy in the power plant, 778 thousand acres were harvested annually in T1, about 426 thousand acres higher compared to the Baseline scenario. The highest quantity of land harvested in Scenario 1 was in the eighth planning period, about 932 thousand acres annually. After that, in T9 and T10, about 900 thousand acres were harvested annually. On average, across planning periods, 61% of forest harvested was softwood, followed by 31% hardwood, and the remaining 8% was a mixed forest. Similar to Baseline, planted softwood harvest was the highest among all forest types, approximately 44% averaged across the planning periods (Figure S3.2). Most of the harvested softwood came from stands between 16 and 20 years old, especially after the fourth planning period. Compared to the Baseline scenario, softwood stands were harvested earlier. This makes logical sense because pulpwood availability is higher in the earlier stand ages compared to the older stands. Therefore, harvesting earlier provides revenue sooner and more rotations are possible within the same time frame with shorter rotations when market has additional demand. While harvesting forestland in higher quantity and from younger stands make sense as demand for pulpwood increased by 17.5 million tons annually, it was worrisome from the sustainability perspective because harvesting a million acres annually may lead to depleting stock in the forest. We discussed more this in the sensitivity analysis section (section 3.3.6).

Similar to the Baseline scenario, most softwood stands harvested were in Unit 1 and 3. However, unlike the Baseline scenario, upland hardwood was harvested more compared to bottomland hardwood, and more upland hardwood was harvested from northern units, i.e., Units 3 to 5. Whereas in Baseline, only 15 thousand acres of hardwood were harvested annually from Units 1 to 3 combined, it was about 29 thousand acres in Scenario 1. This is explained by the location of the power plants in Units 3, 4, and 5 and their additional pulpwood demand. Annual average hardwood stands harvested were 253 thousand acres, about 206 thousand acres higher compared to the Baseline scenario. Among hardwoods, upland hardwood stands (172 thousand acres annually) were harvested more compared to bottomland hardwood (82 thousand acres annually). The highest amount of upland hardwood (289 thousand acres) and bottomland hardwood (121 thousand acres) acres harvested were in the seventh and fourth planning periods, respectively. During the first four periods, approximately 29% of hardwood stands harvested were between 26 and 30 years old that increased to 46% in T5 through T7, then increased again to almost 84% in T8 through T10. It signals the fact that forests were getting younger due to the pressure of high extraneous demand from the power plant.

Mixed forest played a larger role in Scenario 1 compared to the Baseline. Whereas only 9 thousand acres of mixed forest were harvested annually in the Baseline, it increased by 567% to 60 thousand acres in Scenario 1. Harvest from the mixed forest was the highest in the eighth planning period, about 120 thousand acres annually.

3.3.2.1.3. Scenario 2

On average, across planning periods, 551 thousand acres of forestland were harvested annually in Scenario 2. This estimate was 231 thousand acres higher than Baseline due to the additional bioenergy demand in the power plant. However, Scenario 2 estimate was 265 thousand acres lower as logging residues were considered for satisfying bioenergy demand alongside pulpwood. On average, across all periods, approximately 387, 128, and 36 thousand acres of softwood, hardwood, and mixed forests were harvested annually in Georgia across all planning periods. The highest softwood (423 thousand acres), hardwood (200 thousand acres), and mixed (57 thousand acres) forest harvest were in the first, third, and seventh planning periods, respectively.

On average, from T1 through T9, 30% of softwood harvested was between 26 and 30 years old. Younger softwood aged between 16 and 20 years old were harvested only at 15% (62 thousand acres annually) during the first four planning period. However, in the final six periods, their share rose up to 31% (131 thousand acres annually). These two stand age classes, combined, comprised 54% of all softwood harvested acres across periods.

Similar to Baseline and Scenario 1, planted softwood accounted for the highest acres harvested, ranged from 33% of all harvested acreage in T7 (189 thousand acres annually) to 78% in T10 (381 thousand acres annually) (Figure S3.3). In T7 and T8, when planted softwood harvested acreage was low compared to the other periods, 33% and 45% respectively, natural softwood filled up the gap comprising 30% and 26%, respectively, of all harvested acreage in these periods. In contrast, it was about 15% in other periods. Due to similar reasons as Scenario 1, location of power plants, most upland hardwood harvested acreages were in the upper half of the state, i.e., Unit 3 to 5, and bottomland hardwood stands harvested were in Unit 3.

3.3.2.2. Acres unharvested

3.3.2.2.1. Baseline

Across all the five units, approximately 22 million acres remained unharvested in each planning period (Figure 3.7). Approximately 2.12 million acres of softwood was in the 40+ year age class at the beginning of the planning horizon. Out of those, 0.9 million acres of softwood (42%) kept growing and remained unharvested by the end of the planning horizon. Planted softwood and natural softwood aged 40+ before the planning horizon increased by 160% (0.2 to 0.52 million acres) and 18% (1.92 to 2.26 million acres). Hardwood had 0.27 million acres of land in 100+ years stand age classes in the beginning, which became 3.9 million acres after T10, a 1344% increase (Figure S3.4). Upland hardwood and bottomland hardwood aged 100+ before the planning horizon increased by 1477% (0.18 to 2.84 million acres) and 1111% (0.09 to 1.09 million acres). About 75% of mixed forests aged 40+ at the beginning (0.9 out of 1.2 million acres) became 90-year-old stands.

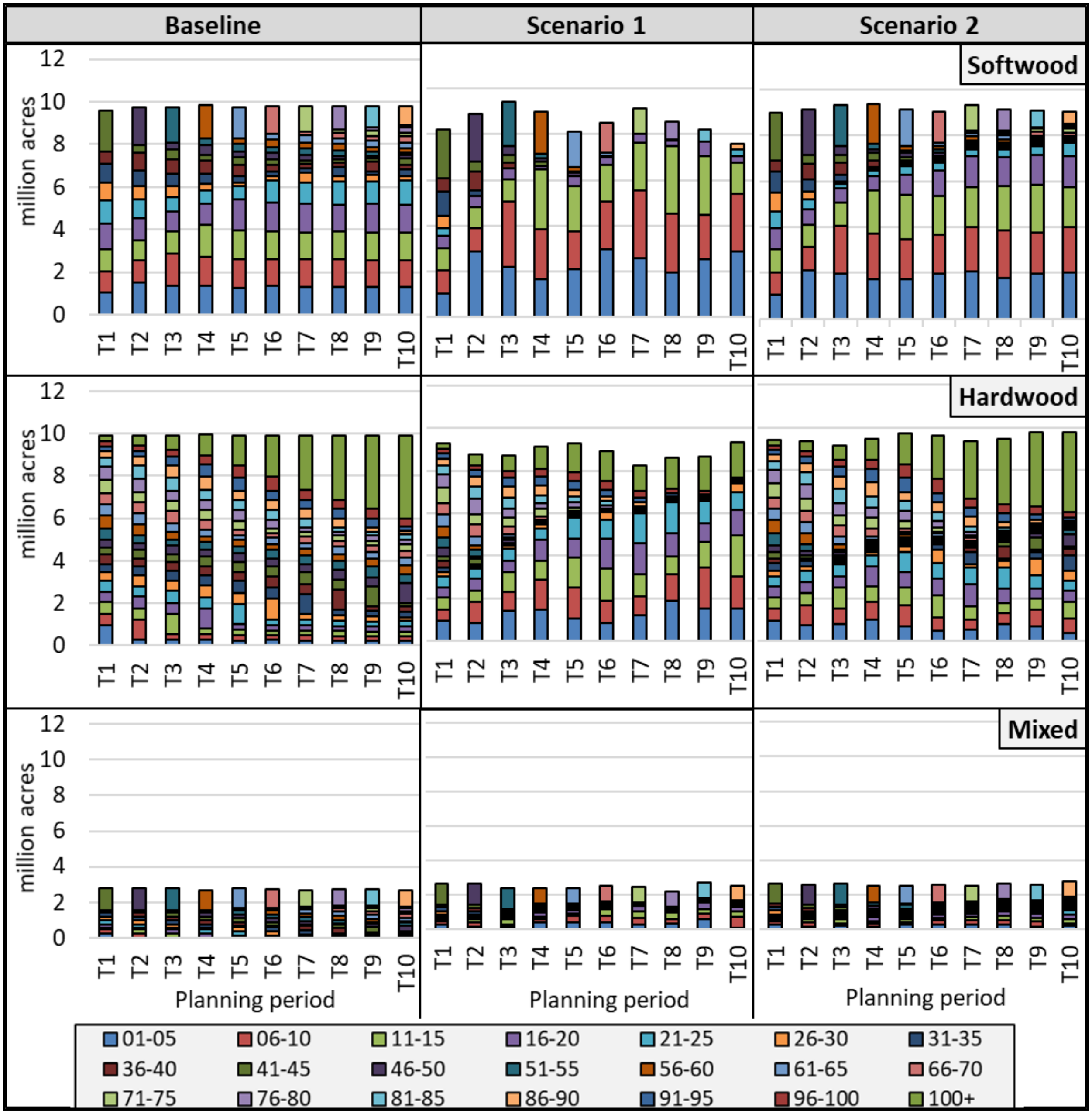

Figure 3.7: Stand age characteristics of acres remained unharvested in each planning period

3.3.2.2.2. Scenario 1

Approximately 20 million acres remained unharvested in T1 to T3 of Scenario 1, which was 2 million acres fewer than the Baseline scenario (Figure 3.7). Unharvested acreage decreased in T4 through T6 to 18.5 million acres. By the end of the planning horizon or at the end of T10, 17.8

million acres remained unharvested. Out of those 17.8 million acres, 13 million acres were in younger stands less than 15 years old with no sawtimber availability. Softwood unharvested acreage starts to decline from T8 as more and more softwood stands were harvested to keep up with the additional bioenergy demand. Softwood stands less than 15 years old, comprised about 3.1 million acres before the planning horizon, and increased by 116% (to 6.7 million acres) by T10. Upland hardwood stands younger than 15 years increased by 168%, from 1.38 to 3.7 million acres, before and after the planning horizon (Figure S3.5). From this result, it can be predicted that there may not be enough biomass for a few additional planning periods if pulpwood only is continued to satisfy power plant demand. However, upland hardwood and bottomland hardwood stands aged 100+ years increased by 233% (from 0.18 to 0.6 million acres) and 1089% (from 0.09 to 1.07 million acres), respectively, between before and after the planning horizon.

3.3.2.2.3. Scenario 2

Approximately 21.3 million acres remained unharvested in Scenario 2 when both pulpwood and logging residues were used to satisfy power plant demand. After 50 years of the planning horizon, upland hardwood and bottomland hardwood stands aged 100+ years increased by 1267% (from 0.18 to 2.46 million acres) and 1344% (from 0.09 to 1.3 million acres), respectively. Planted softwood and natural softwood aged 15 years and younger increased by 46% (from 2.54 to 3.72 million acres) and 313% (from 0.52 to 2.15 million acres), respectively (Figure S3.6). No major change was observed in mixed forest stands as they kept growing. More trees in the younger stands, in both Scenario 1 and 2, was a direct effect of additional bioenergy demand in the power plant. As older stands are harvested to meet the additional demand, forest age was reduced. It is indicative of lower carbon stock in the stands in Scenario 1 and 2 at the end of the planning horizon, which we discussed in section 3.3.5.1.

3.3.3. Timber production

3.3.3.1. Baseline

As per Baseline demand, approximately 1.14 billion tons of pulpwood and 0.99 billion tons of sawtimber were produced over the 50 years of the planning horizon (Figure 3.8). Among the total requirement of softwood pulpwood (0.97 billion tons), 86% came from planted softwood stands. Natural softwood provided 12%, and the remaining 2% came from the mixed forest. About 72% of softwood sawtimber requirement was fulfilled by planted softwood, 26% by natural softwood, and 2% by mixed. Consistent with the acres harvested results (section 3.3.2.1), softwood primarily came from Unit 1 and Unit 3. Unit 1 provided 43% and 40% of softwood pulpwood and sawtimber requirement, respectively, while Unit 3 provided 33% and 32% of these requirements, respectively.

The total hardwood pulpwood requirement was 170 million tons, and 55% of it came from bottomland hardwood forest as the remaining 77 million tons came from upland hardwood (34%) and mixed forest (11%). About 73% (67 million tons) of hardwood sawtimber came from bottomland hardwood. Unit 3 contributed the highest share of hardwood pulpwood (38% of total), which mostly came from bottomland hardwood (28% of total). However, Unit 1 produced the highest share of hardwood sawtimber (40% of total) with upland hardwood (32%) and mixed stands (8%). Unit 1 also produced the highest share of softwood pulpwood, 43% or 422 million tons, out of which 393 million tons came from planted softwood.

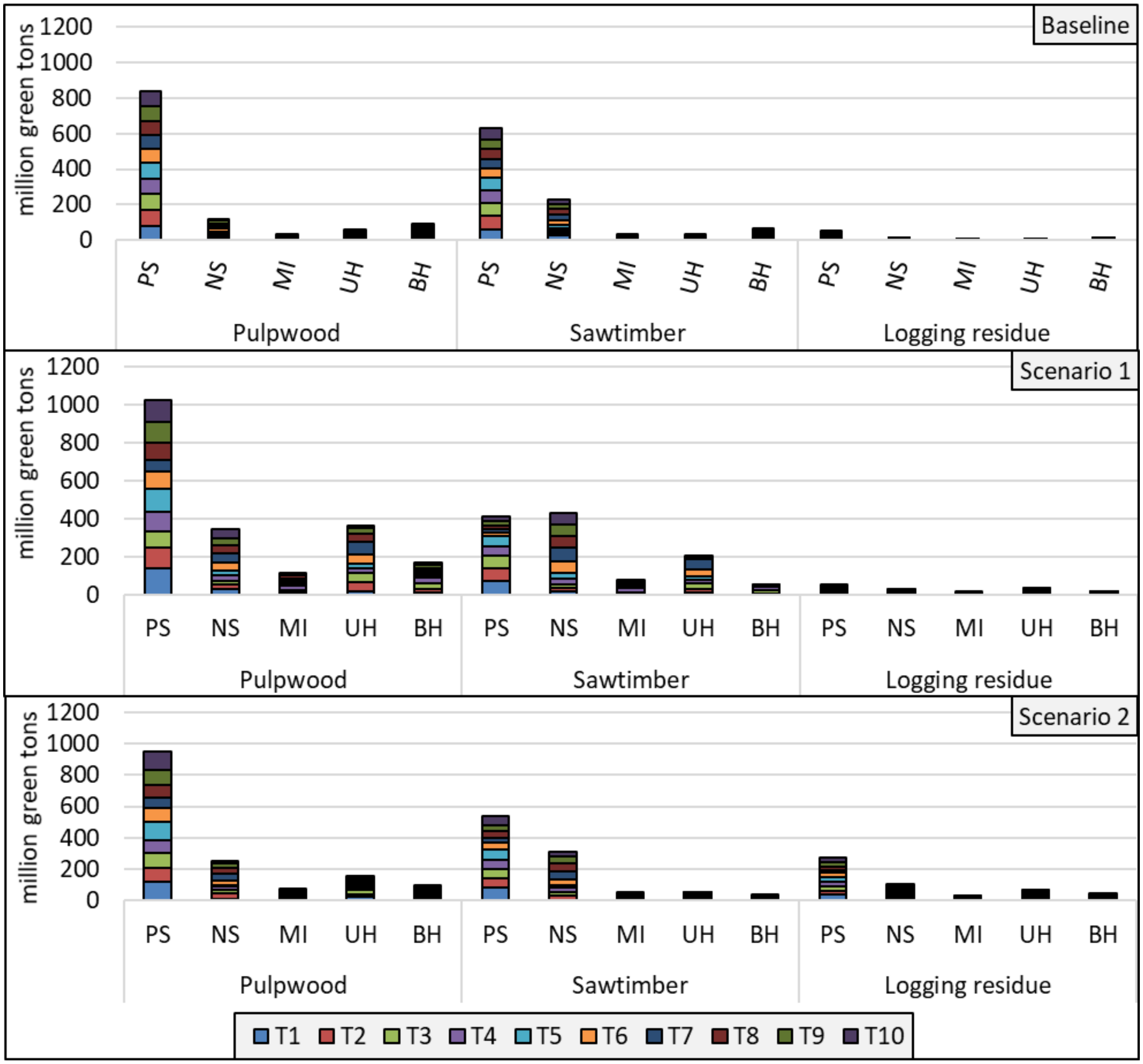

Figure 3.8: Total timber production in every planning period

The way our model was designed, with a penalty for harvesting but not transporting, it is understandable that the model would try to eradicate any excess timber. However, it was surprising to observe that no pulpwood or sawtimber was wasted in any planning period of the Baseline scenario, given that there was a strict constraint of meeting both demands. We assumed that one timber type would be wasted to completely satisfy the other timber demand, but that did not happen in the Baseline scenario. However, since logging residues were not collected, about 8 million tons of logging residues were left on the logging site annually.

3.3.3.2. Scenario 1

Approximately 2.02 billion tons of pulpwood and 1.18 billion tons of sawtimber was produced during 50 years in Scenario 1 (Figure 3.8). About 72% of the softwood pulpwood demand was met by planted softwood (1.03 billion tons), 24% by natural softwood (344 million tons), and the remaining 4% by mixed stands (57 million tons). Similar to the Baseline scenario, Unit 3 was the top producer of all timber categories combined, supplying the highest quantity of softwood pulpwood (37%) and the second-highest quantity of softwood sawtimber (31%), and the highest quantity of hardwood pulpwood (39%) and hardwood sawtimber (41%). Unit 1 supplied the highest quantity of softwood sawtimber (38% or 336 million tons) and the second-highest quantity of softwood pulpwood (36% or 519 million tons). In contrast to the Baseline scenario, the majority (62%) of total hardwood pulpwood production came from upland hardwood. As mentioned in the acres harvested section (section 3.3.2.1), more upland hardwood was harvested in Scenario 1 as Unit 3, 4, and 5 are closer to the power plants, and these units are rich in upland hardwood.

During the first planning period, about 0.8 million tons of sawtimber was produced extraneously, which increased to 2.8 million tons in T2 and 8.8 million tons in T3. Annual sawtimber waste decreased to 6.8 and 2.2 million tons in T4 and T5, respectively, and then increased again to 6.3 and 10.5 million tons in T6 and T7, respectively. No sawtimber was wasted in T8, T9, and T10. Since the pulpwood requirement was much higher compared to sawtimber, and we optimized for a market-clearing model where demands must be met, this type of sawtimber overflow makes sense mathematically. In other words, the model had to procure enough pulpwood to satisfy both traditional pulpwood demand and bioenergy demand at the power plant; excess sawtimber was produced but not transported anywhere. In a real-world scenario, this sawtimber would be exported outside the study area to satisfy demand elsewhere. Additionally, about 14 million tons of logging residues were left on the field annually.

3.3.3.3. Scenario 2

About 1.54, 0.99, and 0.53 billion tons of pulpwood, sawtimber, and logging residues, respectively, were produced in Scenario 2 (Figure 3.8). Out of 3.06 billion tons of total timber, 2.44 billion tons were from softwood stands, 0.47 billion tons were produced in hardwood stands, and 0.15 billion tons came from mixed stands. No pulpwood or sawtimber was wasted in this scenario, but approximately 5 million tons of logging residues were wasted in seven planning periods. In the sixth to eight planning periods, no logging residues were wasted. Wastage of logging residues was expected as it had no other usage other than being used in the power plants, and there were only three power plants in this model with a total annual bioenergy demand of 17.5 million tons. Our model had the option to use both pulpwood and logging residues to replace coal. The model was selected to collect logging residues from nearby harvest locations and then chose to supplement the remaining with pulpwood instead of going to distant locations to collect logging residues. This was because while logging residues is cheaper than pulpwood, using pulpwood from nearby locations was cheaper compared to increased transportation costs for harvesting from distant locations. In addition, since pulpwood and sawtimber had opportunity costs of harvesting but not transporting attached, the model selected to collect pulpwood if the benefit from that outweighed incurring increased transportation cost. It is essential to mention here that other scenarios do not include logging residues at all and the assumption was that all logging residues were discarded.

Compared to the Baseline scenario, pulpwood production was 0.4 billion tons higher, all of which were used in power plants. Pulpwood production was highest in T1, about 167 million tons, out of which 53 million tons went to power plants. The lowest pulpwood production was observed in the seventh planning period, about 148.91 million tons, out of which 34.6 million tons were used to meet power plant demand. Unit 3 was the top producer for softwood as it produced approximately 38% (959 million tons) of all softwood timber, followed by Unit 1, producing 36% (895 million tons). Unit 3 supplied the highest share of hardwood timber, about 43% in each timber category, whereas Unit 1 produced 15% approximately.

For all these units, timber production in hardwood stands in all planning periods was comparatively stable with no noticeable variation. Production from planted softwood stands had a reverse relationship with production from natural softwood and mixed stands. For example, pulpwood supply from planted softwood decreased between T1 and T4, from 24 to 16 million tons annually, natural softwood and mixed stands filled up the gap producing 3 million tons in T1 to 11 million tons in T4.

3.3.4. Timber allocation

3.3.4.1. Timber allocation to traditional mills

3.3.4.1.1. Baseline

As per demand, 973 and 874 million tons of softwood pulpwood was transported to the pulp and sawmills of Georgia, respectively, over the 50 years (Figure 3.9). Other than a few exceptions, units mostly satisfied their own demand, which makes sense as transportation costs would increase otherwise. However, unit 4 supplied 13 million tons of softwood pulpwood to Unit 5, which was one-third of Unit 5's total demand. Unit 3 and Unit 5 provided 10% (2.2 million tons) and 1% (0.3 million tons) hardwood pulpwood demanded by Unit 4, respectively. Other than Unit 5 supplying 106 thousand tons of hardwood sawtimber to Unit 4, which was only 0.1% of Unit 4's hardwood sawtimber demand, there was no sawtimber exchange in this scenario. In addition, in the first two planning periods, there was no inter-unit exchange.

3.3.4.1.2. Scenario 1

Similar to Baseline, Unit 1 supplied 422 million tons of softwood pulpwood to its pulp mills, satisfying 100% of the softwood pulpwood demand (Figure 3.10). Unit 1 and 2 exported 97 and 72 million tons of timber to Unit 3, satisfying 30% and 22% of its demand, respectively. Unit 3 supplied 46.5 million tons of softwood pulpwood to Unit 4 over the 50 years—approximately 4 million tons in T2 and T6, about 5 million tons in T8 and T9, and Unit 4's entire softwood pulpwood demand (7.2 million tons) in T4, T5, and T7. The only significant movement in the hardwood pulpwood category was Unit 1, supplying 50 million tons (80% of total demand) to Unit 3 over the planning horizon.

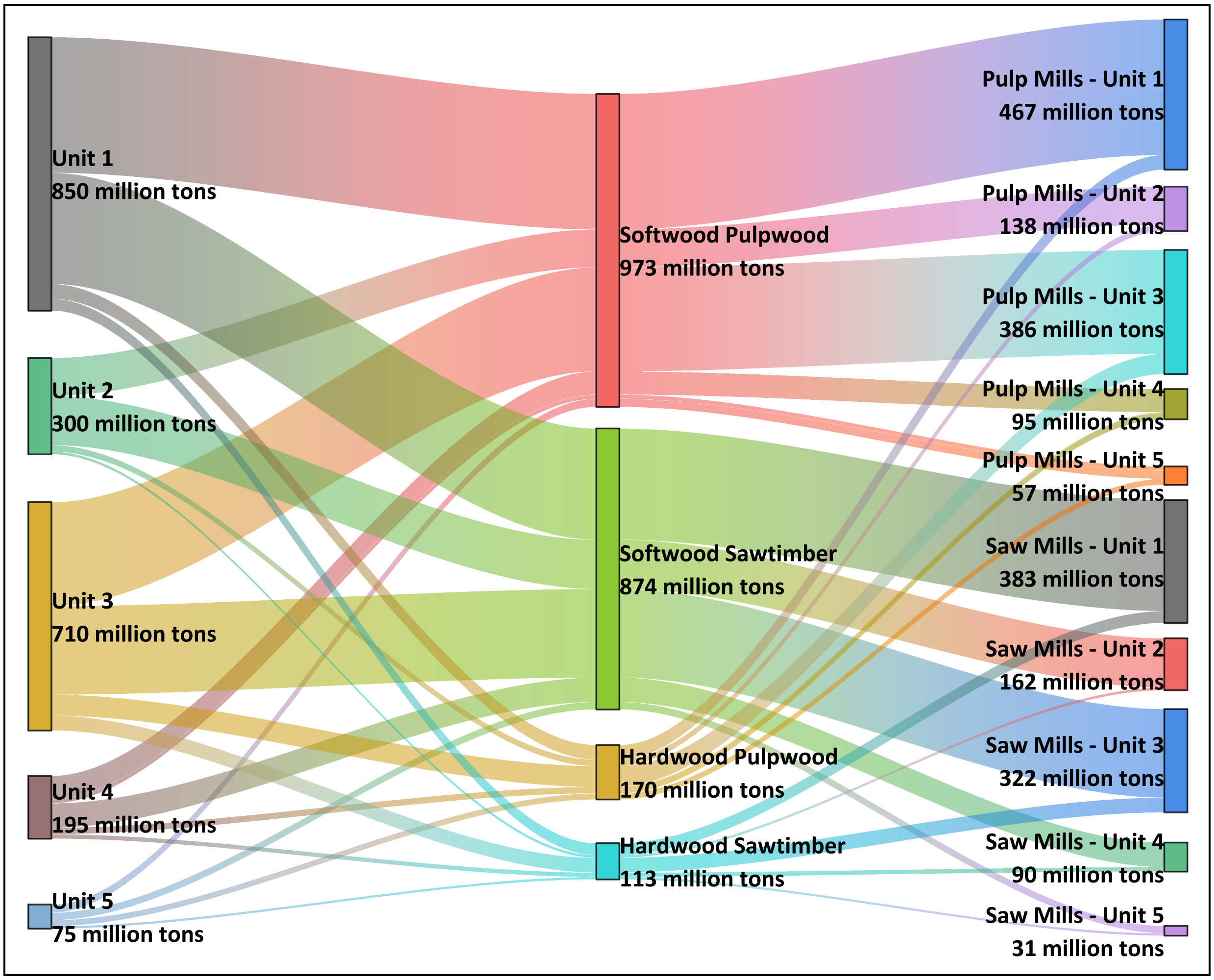

Figure 3.9: Total timber supply to the traditional mills over the entire planning horizon in the Baseline scenario

Unit 3 provided 30 million tons of softwood sawtimber to Unit 2 (19% of demand), and Unit 4 supplied 40 million tons of the same timber to Unit 3 (14% of demand). Unit 3 imported such large amounts of pulpwood from other units because it lacked the pulpwood required after initially satisfying demand in the power plant, especially the Scherer power plant, the largest coal power plant in Georgia, and its located in Unit 3. We discussed more this in section 3.3.4.2.

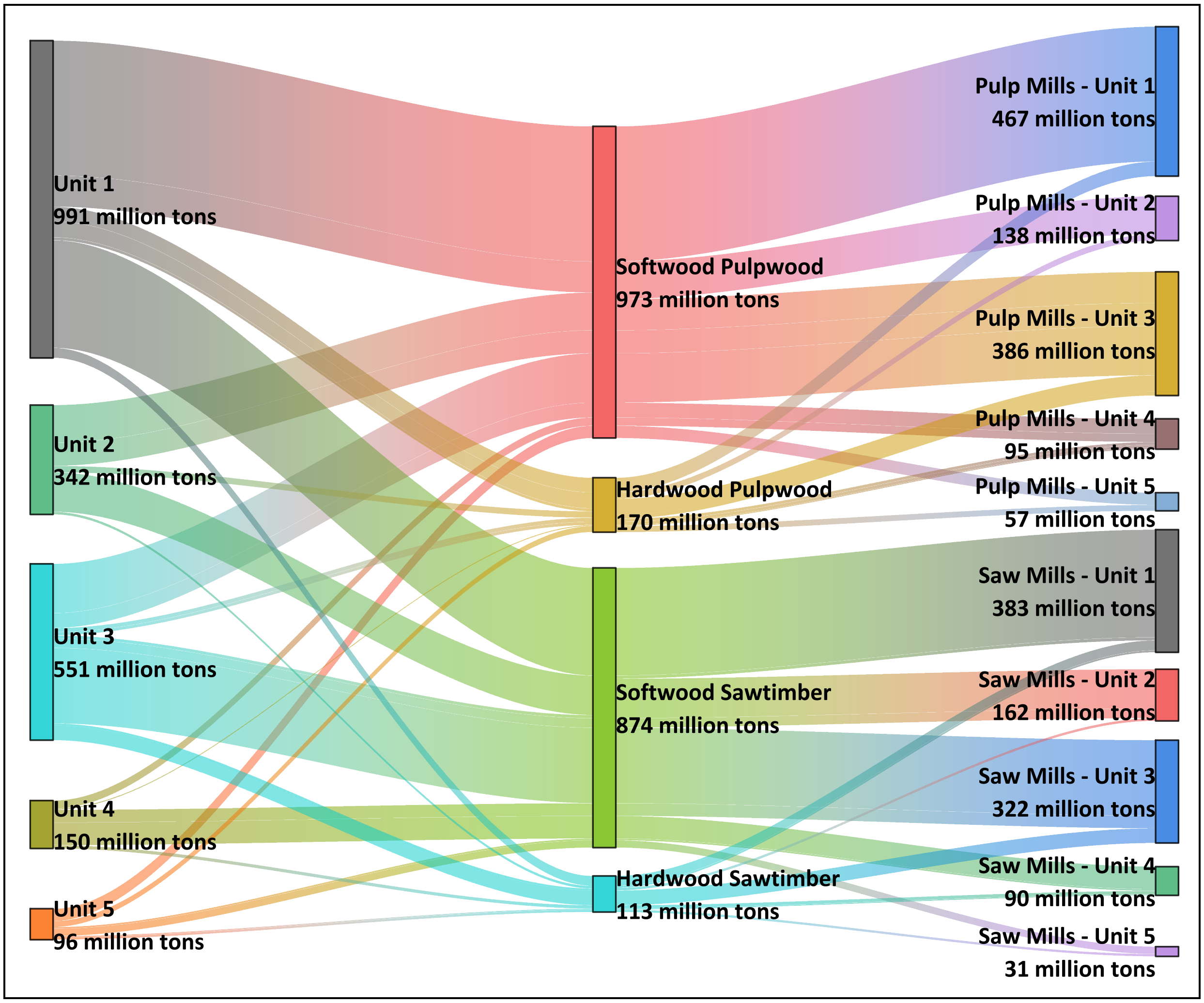

Figure 3.10: Total timber supply to the traditional mills over the entire planning horizon in Scenario 1

3.3.4.1.3. Scenario 2

Approximately 101, 54, 19, and 42 million tons of softwood pulpwood, softwood sawtimber, hardwood pulpwood, and hardwood sawtimber, respectively was transported between units and the remaining came from within the units (Figure 3.11). After satisfying its demand without any import for three periods, Unit 3 imported about 7 million tons of softwood pulpwood from T4 to T8 on average—about 31 million tons from Unit 2 and 5 million tons from Unit 1. The only inter-unit hardwood pulpwood movement occurred when Unit 3 supplied 19 million tons to Unit 4, satisfying 85% of its total requirement. Unlike Baseline and Scenario 1, there was quite a few hardwood sawtimber movement between units. Unit 3 exported 18 million tons to Unit 1 (47% of demand) and 1.9 million tons to Unit 2 (22% of demand). Unit 3 imported 12 million tons from Unit 4 (26% of demand). This higher sawtimber movement is probably due to an effort to minimize sawtimber wastage as only 0.16, 0.68, and 0.54 million tons of sawtimber was annually wasted in T2, T3, and T4, respectively. There was no excess sawtimber in any other period.

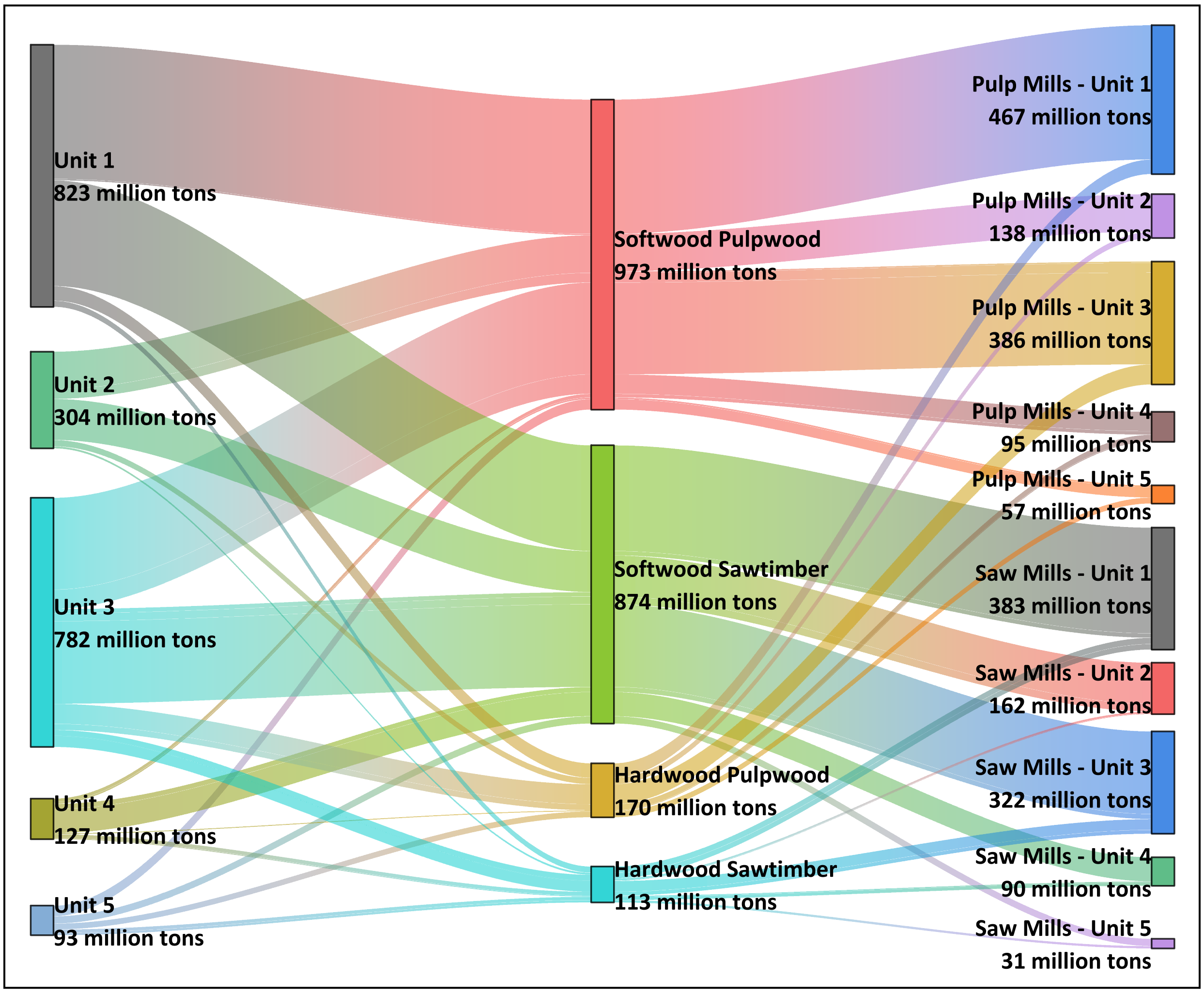

Figure 3.11: Total timber supply to the traditional mills over the entire planning horizon in Scenario 2

3.3.4.2. Timber allocation to power plants

3.3.4.2.1. Scenario 1

According to the demand, about 875 million tons of pulpwood was transported to all three power plants in Georgia over the 50 years of the planning horizon (Figure 3.12).

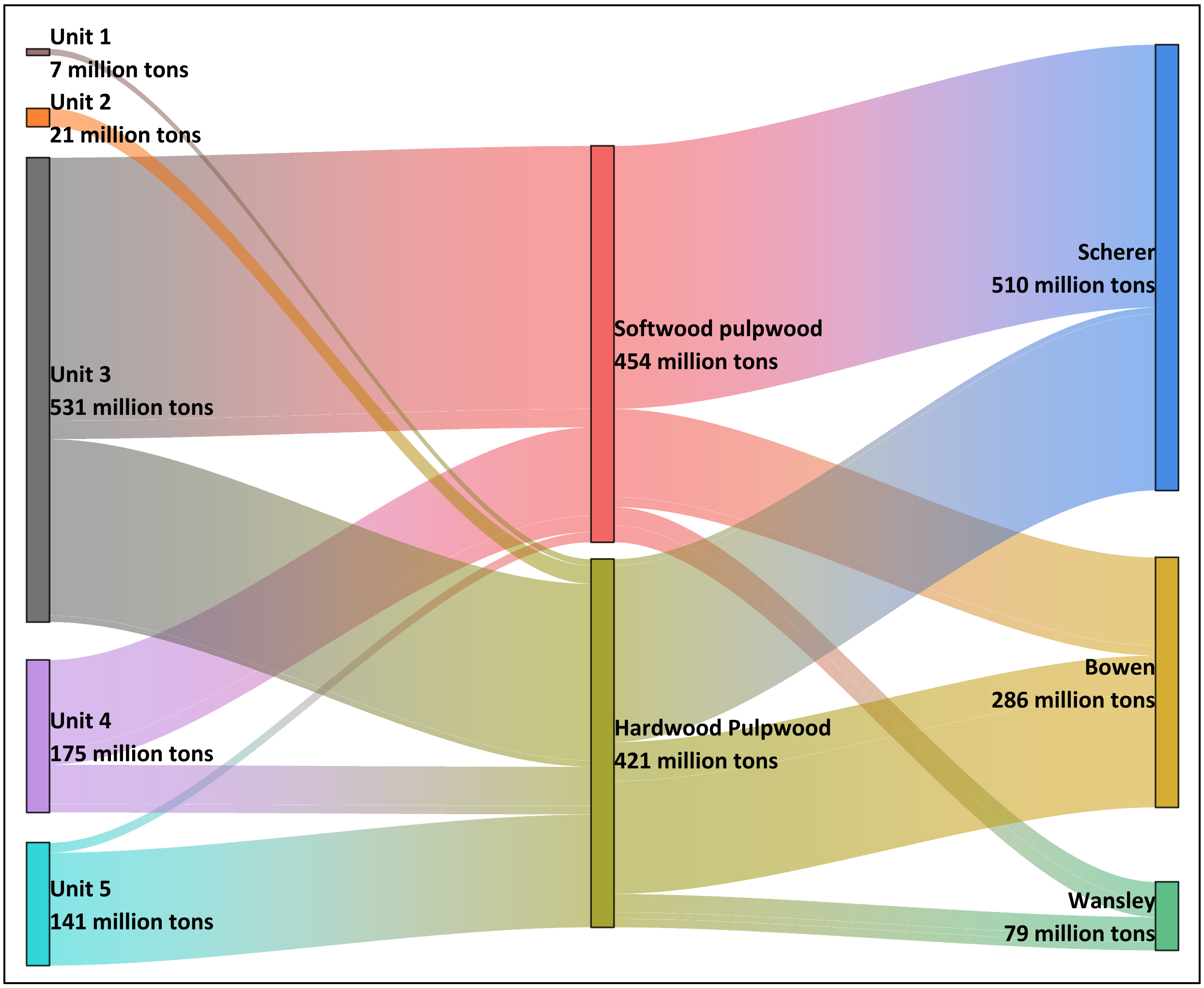

Figure 3.12: Pulpwood transported to the coal power plants in Georgia in Scenario 1

Unit 3 was the top supplier of bioenergy, which delivered 61% (531 million tons) of all pulpwood requirement—321 million tons of softwood and 210 million tons of hardwood. Plant Scherer received 301 million tons of softwood pulpwood, and all of it came from Unit 3. It also received

202 million tons of hardwood pulpwood from Unit 3. It only collected hardwood pulpwood from Unit 1 in T4, T6, and T7 to satisfy its demand. As Plant Scherer is located in Unit 3 and close to Unit 1 (Figure 3.1), these allocations make economic sense. The same argument was valid for Plant Bowen collecting pulpwood only from Unit 4 and Unit 5, 146 million tons, and 140 million tons, respectively. Plant Wansley received 40.3 and 38.3 million tons of softwood and hardwood pulpwood, respectively—softwood came from Unit 3 (21 million tons) and Unit 4 (19 million tons), and hardwood came from Unit 2 (21 million tons), Unit 3 (7.4 million tons), and Unit 4 (10 million tons).

3.3.4.2.2. Scenario 2

When both pulpwood and logging residues were used to replace coal in the power plants, approximately 55% (477 million tons) biomass was in the form of logging residues during the planning horizon (Figure 3.13).

Similar to Scenario 1, Unit 3 was the top supplier of bioenergy, providing 47% of the total biomass requirement—156 million tons of softwood pulpwood, 156 million tons of hardwood pulpwood, 148 million tons of softwood logging residues, and 52 million tons of hardwood logging residues. Plant Scherer received 153 million tons of pulpwood, and all of it came from Unit 3. Plant Bowen did not receive any logging residues from Unit 1, 2, and 3, while Plant Scherer did not receive any logging residues from Unit 4 and 5. Transportation distance has played the most critical role in these allocation decisions. Plant Wansley used only 6.7 million tons of pulpwood (8.5% of demand), and the remaining came from 58 and 14 million tons of softwood and hardwood logging residues, respectively.

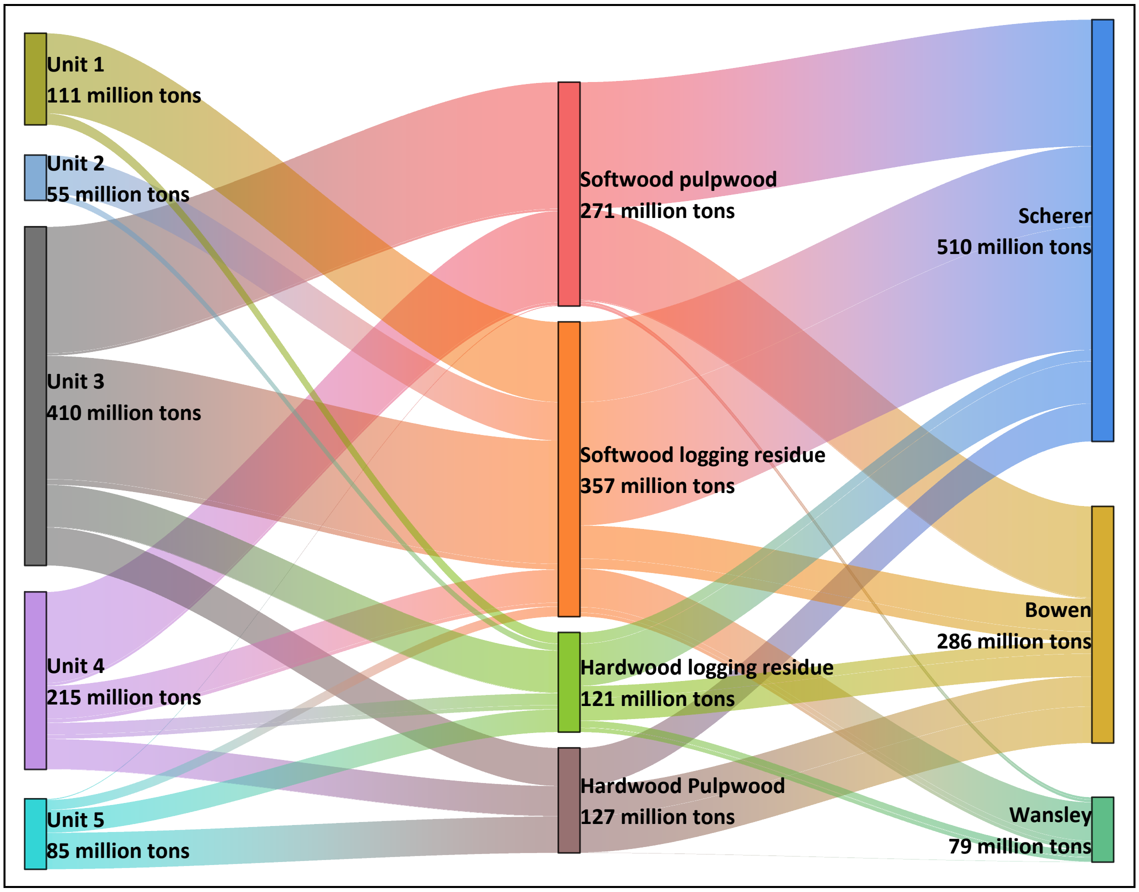

Figure 3.13: Pulpwood and logging residues transported to the coal power plants in Georgia in Scenario 2

3.3.5. Carbon dynamics

3.3.5.1. Carbon in stand

In total, 577 million tons C was present in the pulpwood, sawtimber, and logging residues combined in the forests of Georgia before the planning horizon started. Approximately 289, 238, and 50 million tons C were in softwood, hardwood, and mixed stands, respectively.

3.3.5.1.1. Baseline

Final aboveground C content in Georgia after the planning horizon was 759 million tons C, resulting in a net gain of 32% or 182 million tons C compared to the initial carbon in aboveground biomass (Figure 3.14). Carbon content increased in hardwood and mixed stands by 127 (54%) and 70 million tons (140%) C, respectively (Figure 3.15). However, the carbon in softwood stands decreased by 5.6% or 16 million tons C. Overall, carbon increase in aboveground biomass is consistent with the historical sequestration of carbon in these units (US Forest Service, 2020a).

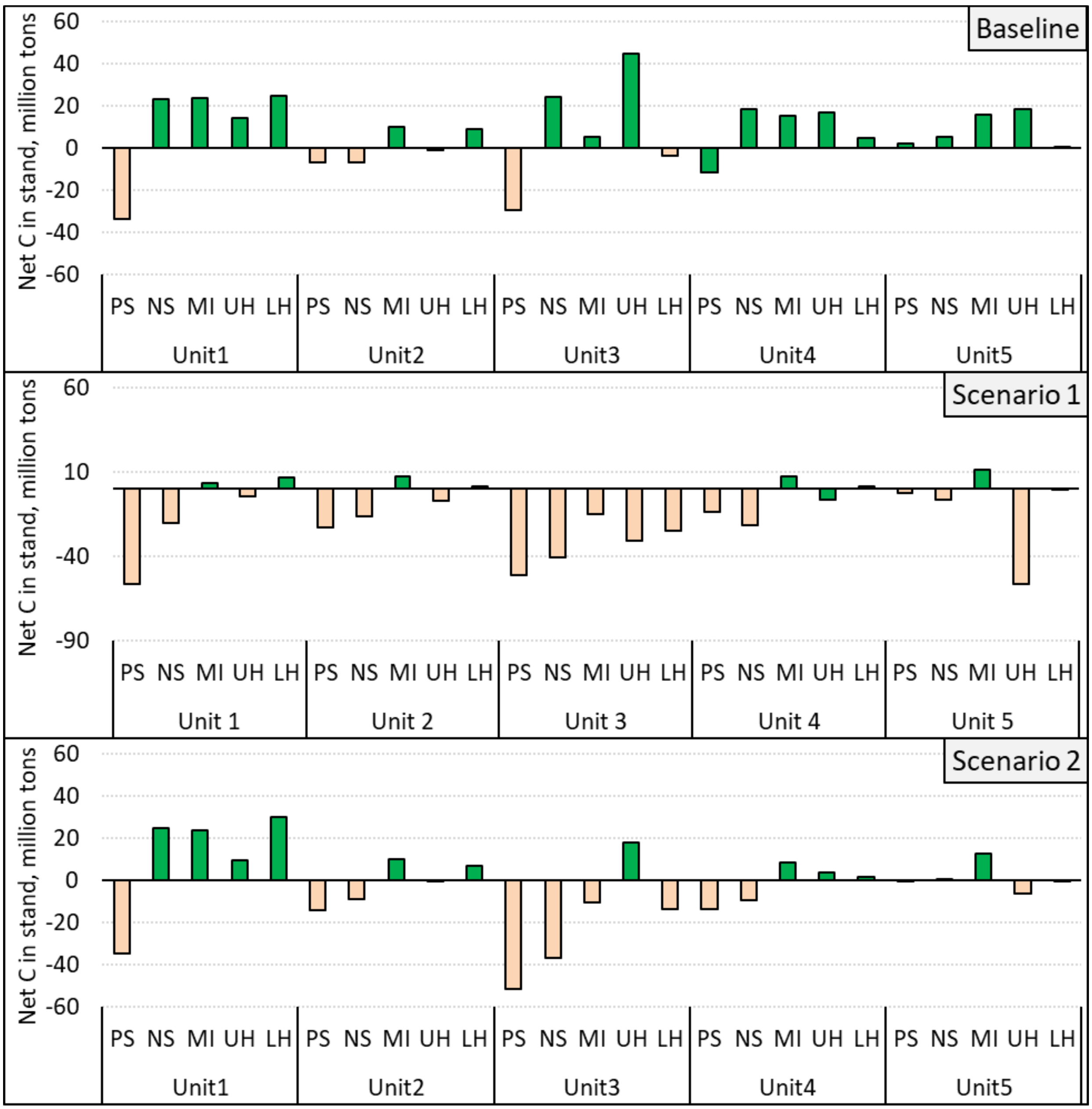

Figure 3.14: Net change in stand carbon after 50 years

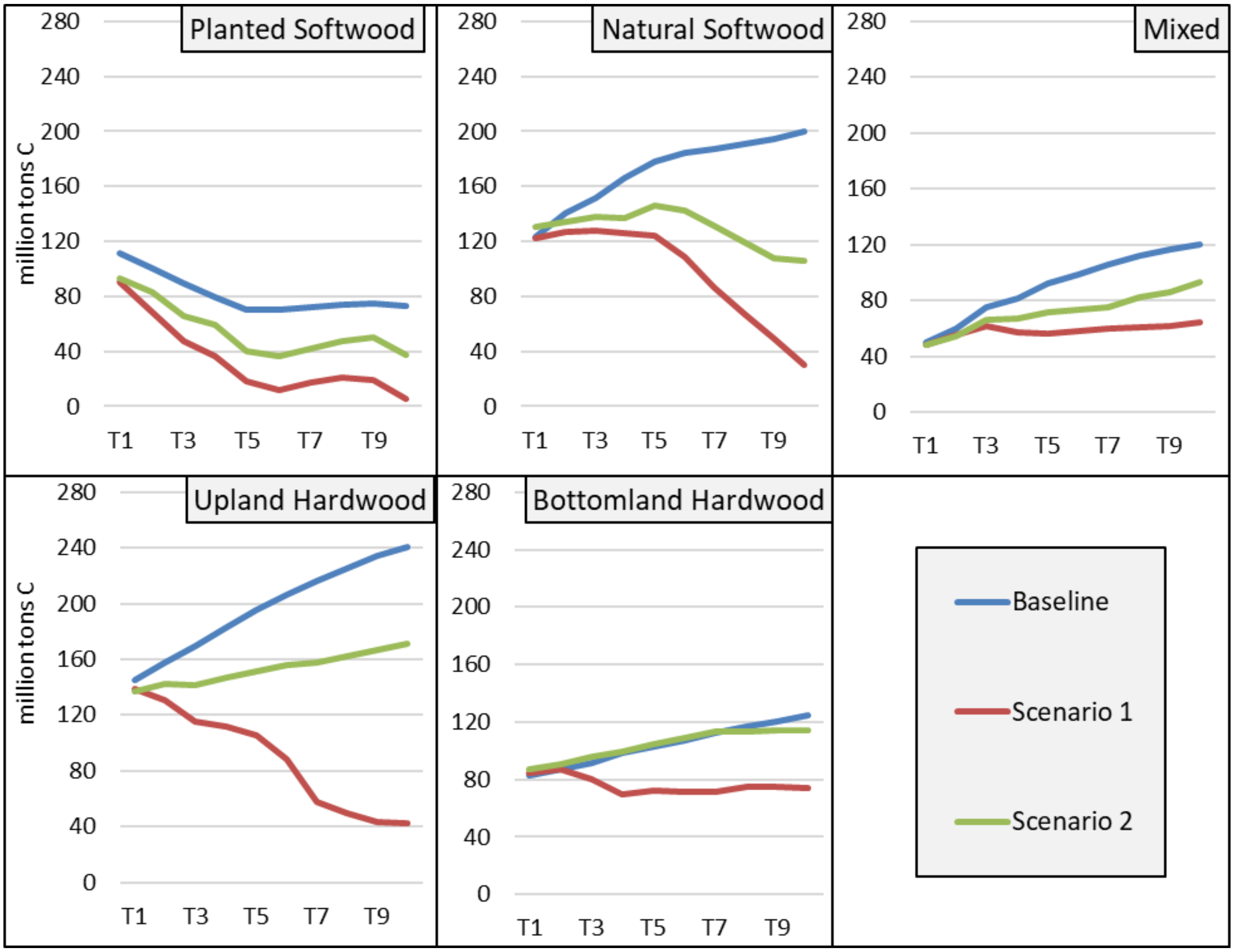

Figure 3.15: Stand carbon changes in all forest types of Georgia throughout the planning horizon

3.3.5.1.2. Scenario 1

Final aboveground carbon content after 50 years was 216 million tons C; about 36, 116, and 64 million tons C in softwood, hardwood, and mixed stands, respectively. Total C decrease in aboveground carbon was 251 million tons C or 44% compared to year 0 and 72% lower than the final C content in the Baseline scenario.

Carbon in aboveground biomass from planted softwood forest started with 153 million tons C before the planning horizon, decreased in every planning period, except in T7 and T8, before depleting to 11 million tons C in T10 (Figure 3.15). Carbon in natural softwood stands increased through T3 to 108 million tons C and gradually decreased to 25 million tons C in T10. Initial C in upland hardwood was 148 million tons C, which started gradually decreasing down to 50 million tons C in T8, then stabilized at around 42 million tons C in T9 and T10. Stand carbon in bottomland hardwood remained relatively stable at 73 million tons C from T4 through T10, about 19% lower than the carbon present initially. Carbon in aboveground biomass was higher only in mixed forest, by 3 million tons C compared to initial carbon.

3.3.5.1.3. Scenario 2

At the end of 50 years, the final aboveground carbon content in this scenario was about 523 million tons C. Aboveground C was about 54 million tons C (or 9%) lower compared to initial carbon and about 236 million tons C (or 31%) lower compared to final C content in Baseline scenario due to the additional harvest removal to satisfy power plant demand. It was about 307 million tons C higher than Scenario 1 because utilizing logging residues reduced the pressure on forest stock.

Planted softwood stands lost the highest amount of carbon, about 54 million tons C, in Georgia while mixed forest sequestered the highest carbon (43 million tons C). C in planted softwood decreased from 93 to 36 million tons C between T1 and T6, increased to 50 million tons C by T9 before dropping to 37 million tons C in T10. Carbon in natural softwood stands increased to 146 million tons C by T5, but gradually decreased through T10 to 106 million tons C. Both upland and bottomland hardwood kept sequestering carbon in all planning periods, and by the end of the planning horizon, C increased by 16% and 27%, respectively.

3.3.5.2. Avoided C emission and net C balance

Compared to scenarios 1 and 2, the Baseline scenario sequestered more carbon in aboveground biomass (Figure 3.16). However, there was no coal replacement in the Baseline scenario and, therefore, no avoided carbon emission from the power generation. Approximately 278 and 277 million tons of C was avoided via replacing coal with biomass for power generation in Scenario 1 and 2, respectively. Even though the same amount of coal was replaced in both scenarios 1 and 2, Scenario 1 avoided 1 million tons C more because it used pulpwood from a nearby location and reduced emission from transportation. In Scenario 2, the model could go longer distances to collect logging residues, which was cheaper compared to pulpwood. Scenario 2 was the best scenario in terms of carbon benefits as it lost less carbon in forest biomass than Scenario 1 and avoided carbon via coal replacement. In other words, utilizing logging residues and pulpwood both to replace 50% of coal (Scenario 2) is better from a total carbon benefit perspective compared to not replacing coal in the power plant (Baseline) or using pulpwood only to replace coal (Scenario 1).

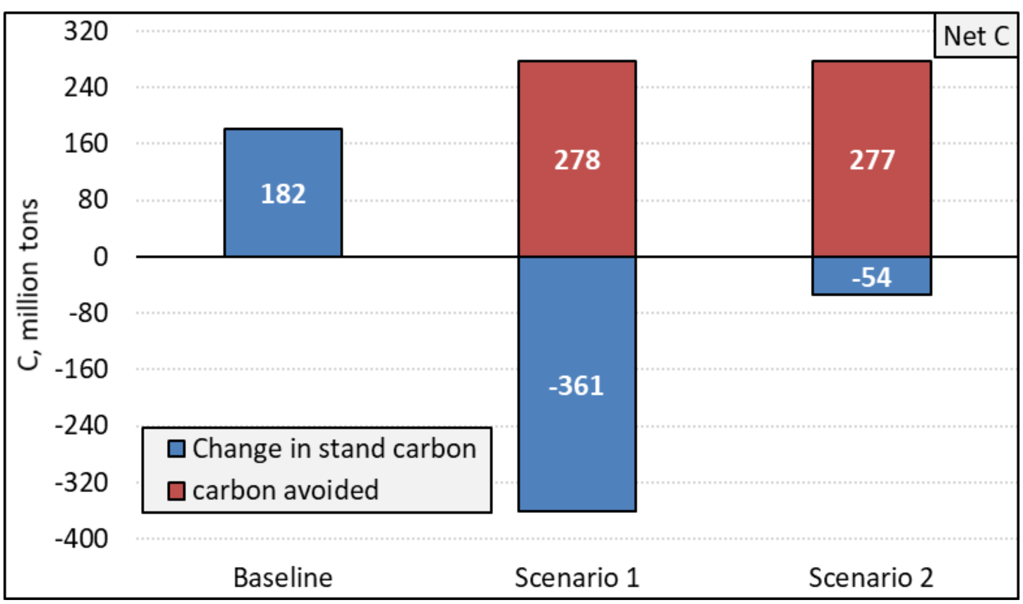

Figure 3.16: Net carbon change due to changes in stand carbon and carbon savings via coal replacement with biomass

In our estimates, 5.55 and 5.54 million tons C were avoided annually from the power generation in Scenario 1 and Scenario 2, respectively. EIA estimates that GHG emissions from using coal in the power sector of Georgia are 12 million tons annually (US EIA, 2020c). Our estimates were less than half of that as we only replaced 50% of coal in the power plants, and there were other emissions due to biomass harvesting, processing, and transportation. It is important to mention here that the biogenic carbon emissions from burning biomass were not included in this study. If biogenic emissions were added, results could have been substantially different, and there may not be any carbon savings via coal replacement.

3.3.6. Sensitivity analysis

The model provided optimal solutions for up to 70% coal replacement using pulpwood only (Table 3.3). The model was infeasible for 80% to 100% coal replaced by pulpwood as an increasing amount of forestland was harvested, and adequate pulpwood was not available for the ninth planning period. Using both pulpwood and logging residues, we got optimal solutions for up to 100% coal replacement in all planning periods. However, sensitivity analysis of acres harvested suggests that the model may not find enough biomass to satisfy power plant demand in the subsequent periods beyond the planning horizon, even with both pulpwood and logging residues.

Roughly 1.3 million acres would be harvested annually during the final three planning periods if 70% of coal were replaced by pulpwood only (Figure 3.17). This estimate was approximately three times the estimate of harvested acreage in Baseline. Even if the coal replacement percentage remained at 70%, it might become infeasible for a planning period beyond the planning horizon. In other words, it may not be sustainable. If logging residues are not used for coal replacement, then it is obvious that logging residues will be higher compared to when at least part of it is transported to the power plant (Figure 3.18). However, sawtimber wastage was higher as well since more forestland would be harvested for pulpwood to satisfy additional demand at the power plant, but produced sawtimber will be extraneous and need to be sold outside this market.

Table 3.3: Sensitivity analysis of net carbon* changes with various level of coal replacement

	Coal replacement	**Change in stand carbon**	**Carbon avoided**	**Net C**
		million tons C		
Coal replaced by pulpwood only	10%	82	56	138
	20%	-22	111	89
	30%	-138	167	29
	40%	-257	222	-35
	50%	-361	278	-83
	60%	-470	333	-137
	70%	-563	388	-175
	80%			
	90%	infeasible		
	100%			
Coal replaced by both pulpwood and logging residues	10%	185	56	241
	20%	124	111	235
	30%	42	167	209
	40%	-3	222	219
	50%	-54	277	222
	60%	-124	332	209
	70%	-197	388	191
	80%	-276	443	167
	90%	-346	499	152
	100%	-420	554	134

*Note – Net C may not add up due to rounding

Using pulpwood only to replace coal was the most beneficial from a carbon perspective when only 10% of coal was replaced (Table 3.3). However, even with a 10% replacement with pulpwood, carbon benefit was lower than the Baseline scenario (Figure 3.16). In other words, replacing no coal was better than replacing coal with pulpwood only. However, when both pulpwood and logging residues were used, carbon benefit exceeded the benefit in the Baseline scenario when

10% through 70% of coal was replaced. The maximum net carbon benefit was achieved when 10% of coal was replaced by both pulpwood and logging residues.

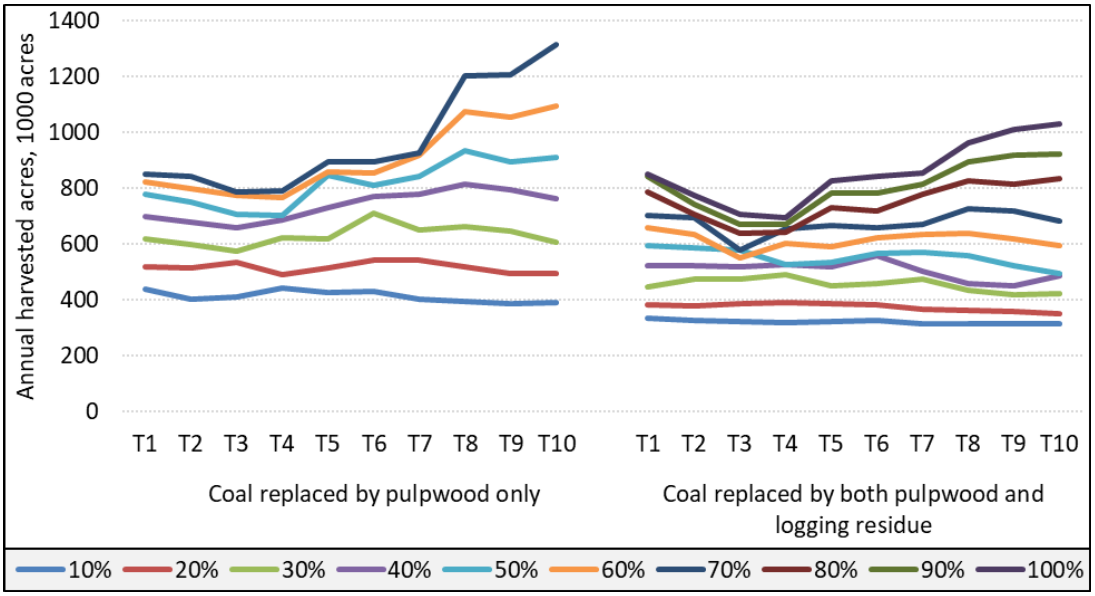

Figure 3.17: Annual average acres harvested under various percentages of coal replaced by biomass

3.4. Conclusion

In this study, we provided a comprehensive picture of the impact of timber sourcing and allocation for the next 50 years with and without coal replacement by biomass. We mathematically optimized for the least cost-effective ways to collect and allocate biomass to replace coal in the power plant along with satisfying traditional demand that would also maximize landowner's profit from their timberland. We also studied the impact on land use and associated carbon changes for such market shocks of additional demand. We showed that replacing 10% coal in the power plants of Georgia with both pulpwood and logging residues was the best option from carbon benefit perspectives due to the combined effect of changes in stand carbon and carbon avoided via coal replacement by biomass.

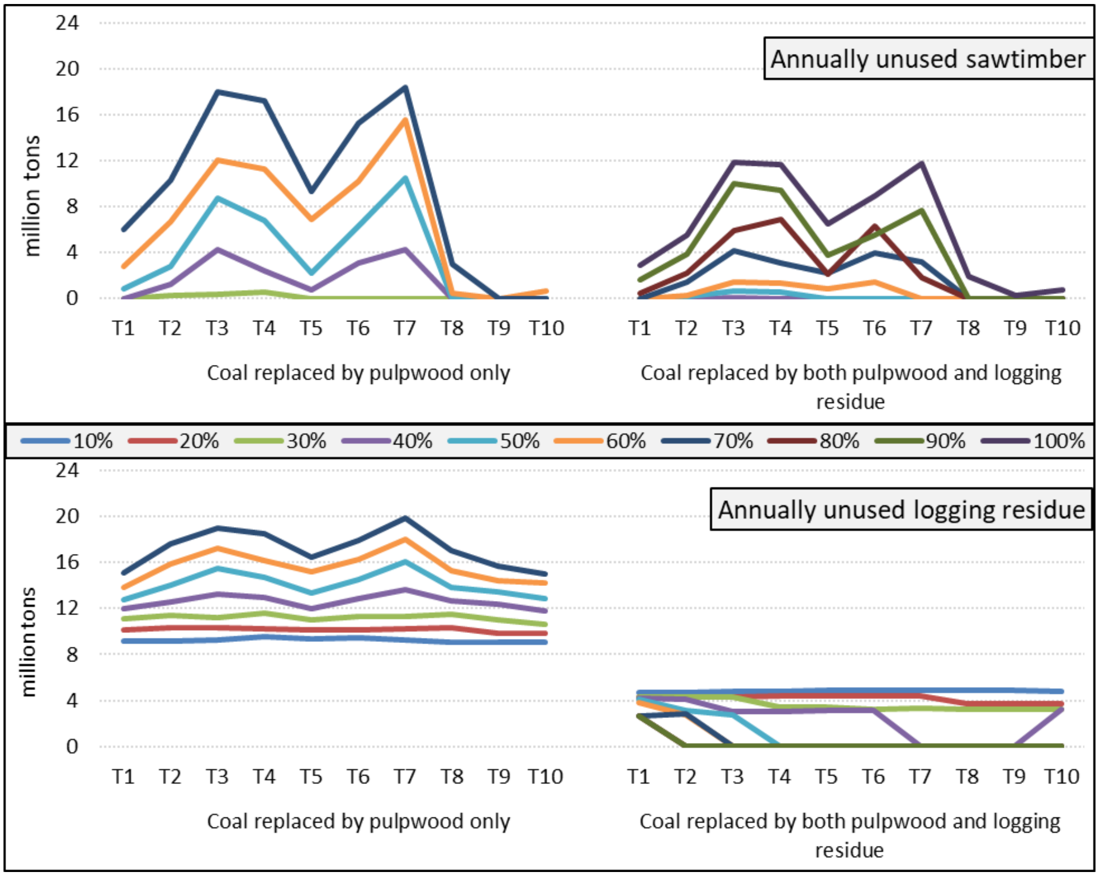

Figure 3.18: Annually unused sawtimber and logging residues with varying percentages of coal replacement

There are several limitations to the study. We considered Georgia as a closed system that satisfied its demand by harvesting biomass exclusively from within the state. This study can be expanded further by including neighboring states such as Alabama, Florida, North Carolina, South Carolina, and Tennessee. In addition, we did not include belowground carbon in our study. We considered poletimber from FIA inventory, and pulpwood demanded to be of equivalent size despite the fact that the diameter sizes were not an exact match. Quantity demanded was constant throughout the planning horizon as well, while it is safe to assume that demand will rise with an increase in the global population. To further increase the scope of this study, the option of land use conversion can be added where land can be used for another forest type when a stand is harvested. Furthermore, agricultural land, pastureland, and hayland can be added to the model. Additionally, a carbon emission minimization objective can be added to the objective function. In our study, we included an objective that reduces the cost of transportation distances for biomass collection and, therefore, distance and emission from transportation. However, the model went to distant locations to harvest logging residues as prices were low compared to pulpwood and sawtimber. Therefore, emissions may be minimum with carbon emission minimization in focus instead of profit maximization or cost minimization, even though that will affect economic sustainability. Along with these, biogenic carbon emission may be included in further analysis. Despite these limitations, this paper provides a reliable platform that will help regulate a sustainable supply chain of forest products in the southeastern US. This study reduced the knowledge gap regarding the combined effect of changing carbon in forest biomass and avoided carbon emission by using renewable biomass instead of coal. We expect that this article will help policymakers make an informed decision about using biomass to replace GHG intensive coal in the power sector.

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CHAPTER 3: SUPPORTING INFORMATION

Table S3.1: Timber demand (tons) in the study area (US Forest Service, 2020)

	Softwood pulpwood	Softwood sawtimber	Hardwood pulpwood	Hardwood sawtimber
GA unit 1	8,431,567	6,916,028	914,449	742,925
GA unit 2	2,360,518	3,064,658	399,835	166,693
GA unit 3	6,464,699	5,508,898	1,256,115	921,605
GA unit 4	1,443,720	1,522,828	450,745	276,395
GA unit 5	768,166	459,755	374,042	150,943

Table S3.2: Annual coal consumption in the power plants of Georgia (US EIA, 2020)

Power plants	Year	Coal consumed (tons)
Bowen	2019	4,515,728
Scherer	2019	8,049,620
Wansley	2018	1,239,529

Table S3.3: Discounted annual land rent for timberland

Stand age class	Discounted land rent ($)
T1	13.88
T2	33.66
T3	49.93
T4	63.30
T5	74.28
T6	83.32
T7	90.74
T8	96.84
T9	101.85
T10	105.98

Table S3.4: Distance (miles) between power plants and geographical centers of FIA units

	Bowen	Scherer	Wansley
Unit 1	229	131	203
Unit 2	205	123	161
Unit 3	120	23	93
Unit 4	49	54	55
Unit 5	40	114	88

Table S3.5: Distance (miles) between FIA units

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Unit 1	40	108	111	182	239
Unit 2	108	40	104	173	232
Unit 3	111	104	40	76	136
Unit 4	182	173	76	40	60
Unit 5	239	232	136	60	40

Table S3.6: Price* of timber ($) in Georgia (TMS, 2020)

	Softwood			Hardwood		
	Pulpwood	Sawtimber	Logging Residue	Pulpwood	Sawtimber	Logging Residue
Unit 1	12.74	25.25	1.5	9.71	32.15	1.5
Unit 2	12.74	25.25	1.5	9.71	32.15	1.5
Unit 3	12.74	25.25	1.5	9.71	32.15	1.5
Unit 4	9.16	22.07	1.5	8.53	33.62	1.5
Unit 5	9.16	22.07	1.5	8.53	33.62	1.5

*Note: Nominal price, needs to be discounted using the median year of planning periods, i.e., 3 for T1, 8 for T2, etc.

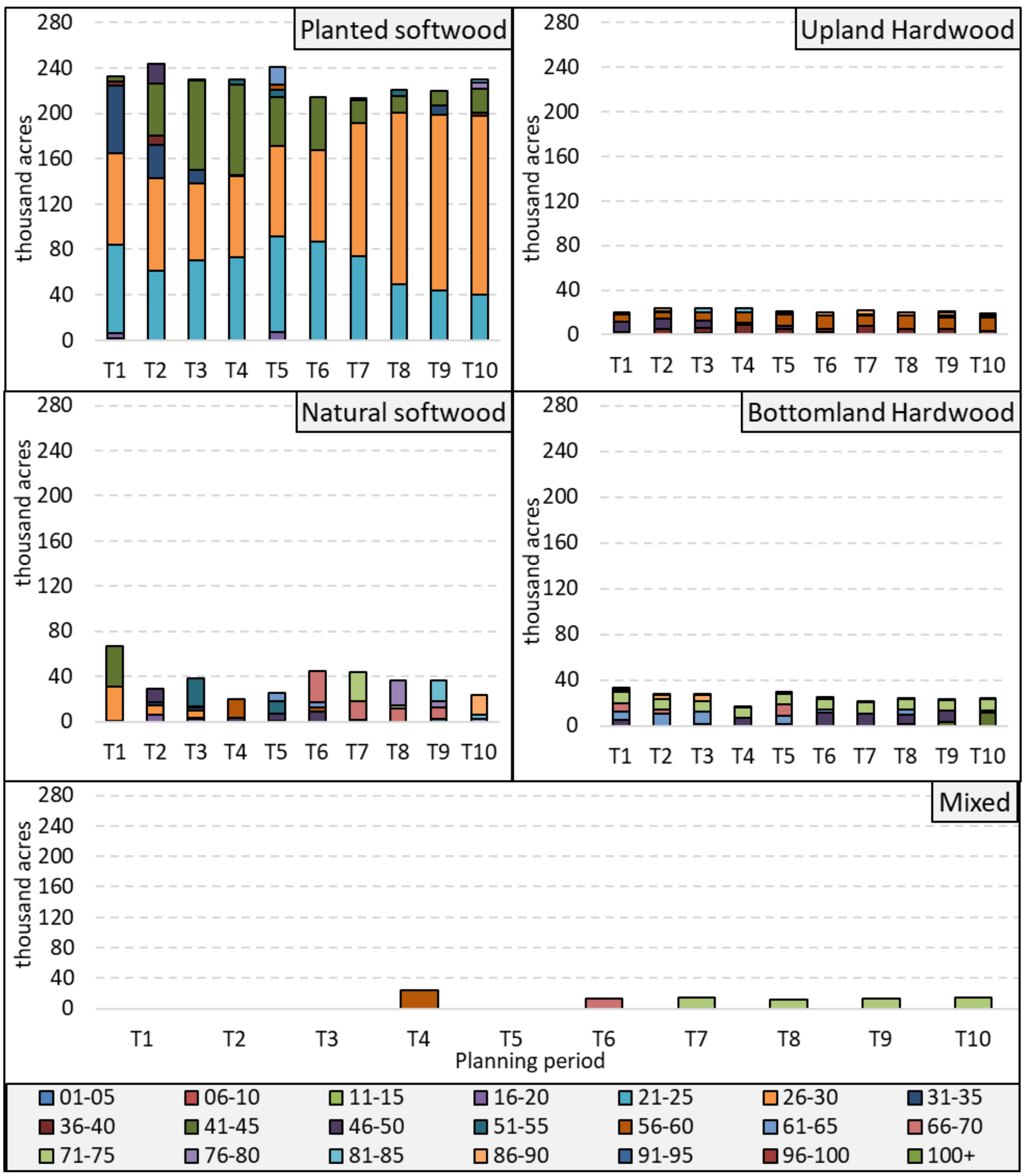

Figure S3.1: Stand age characteristics of annual average harvested acreage in the Baseline Scenario

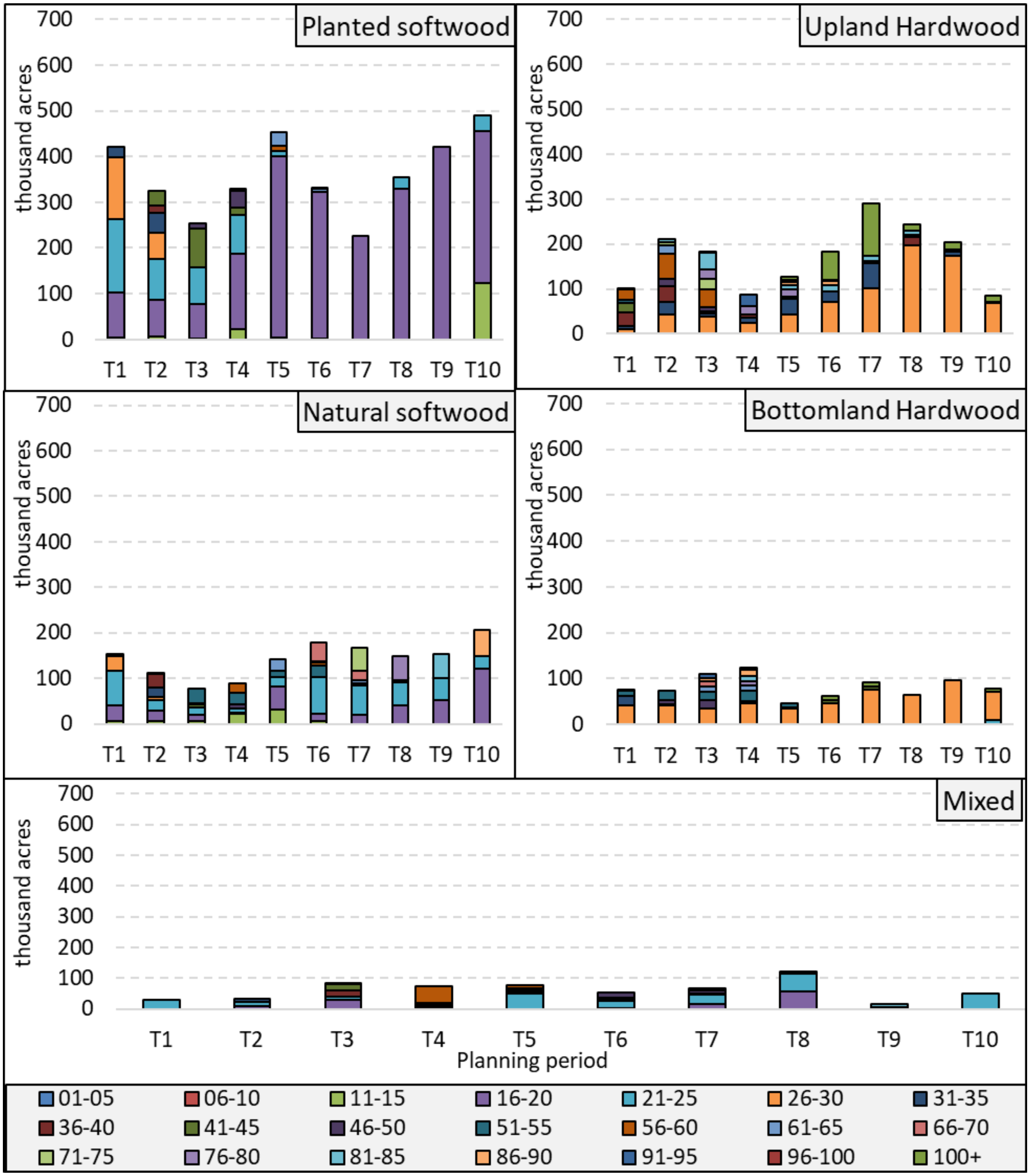

Figure S3.2: Stand age characteristics of annual average harvested acreage in Scenario 1

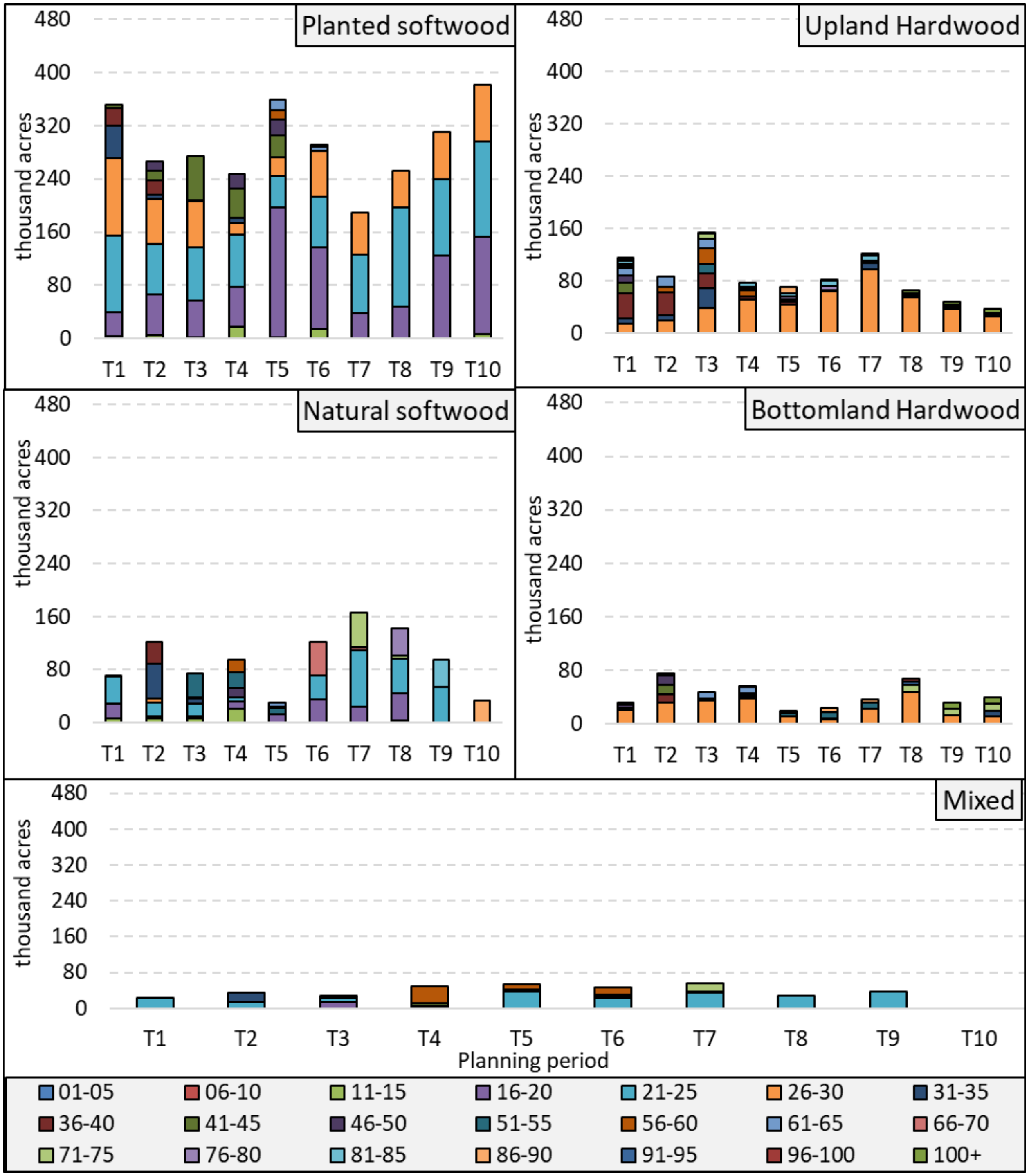

Figure S3.3: Stand age characteristics of annual average harvested acreage in scenario 2

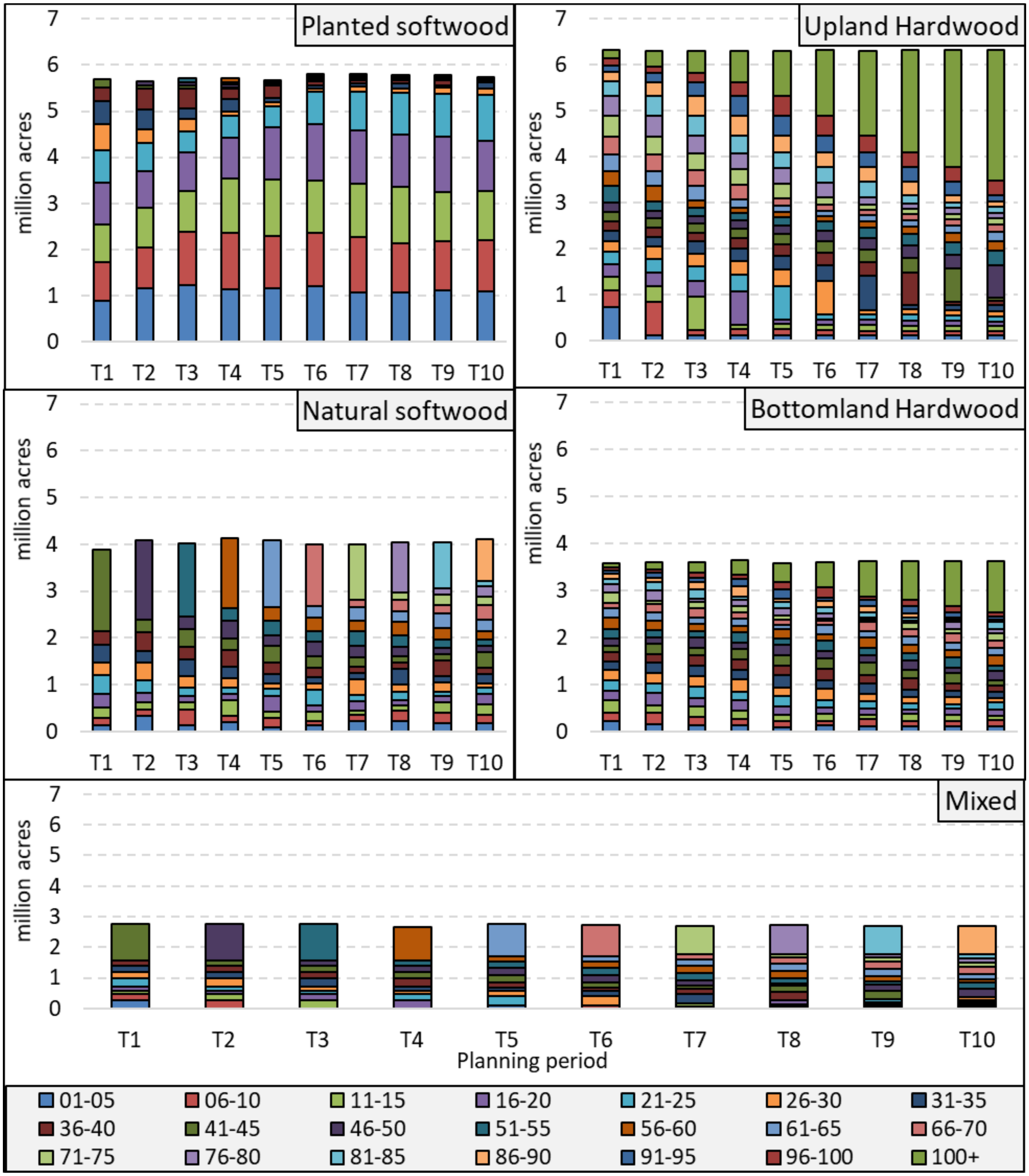

Figure S3.4: Stand age characteristics of annual average unharvested acreage in the baseline scenario

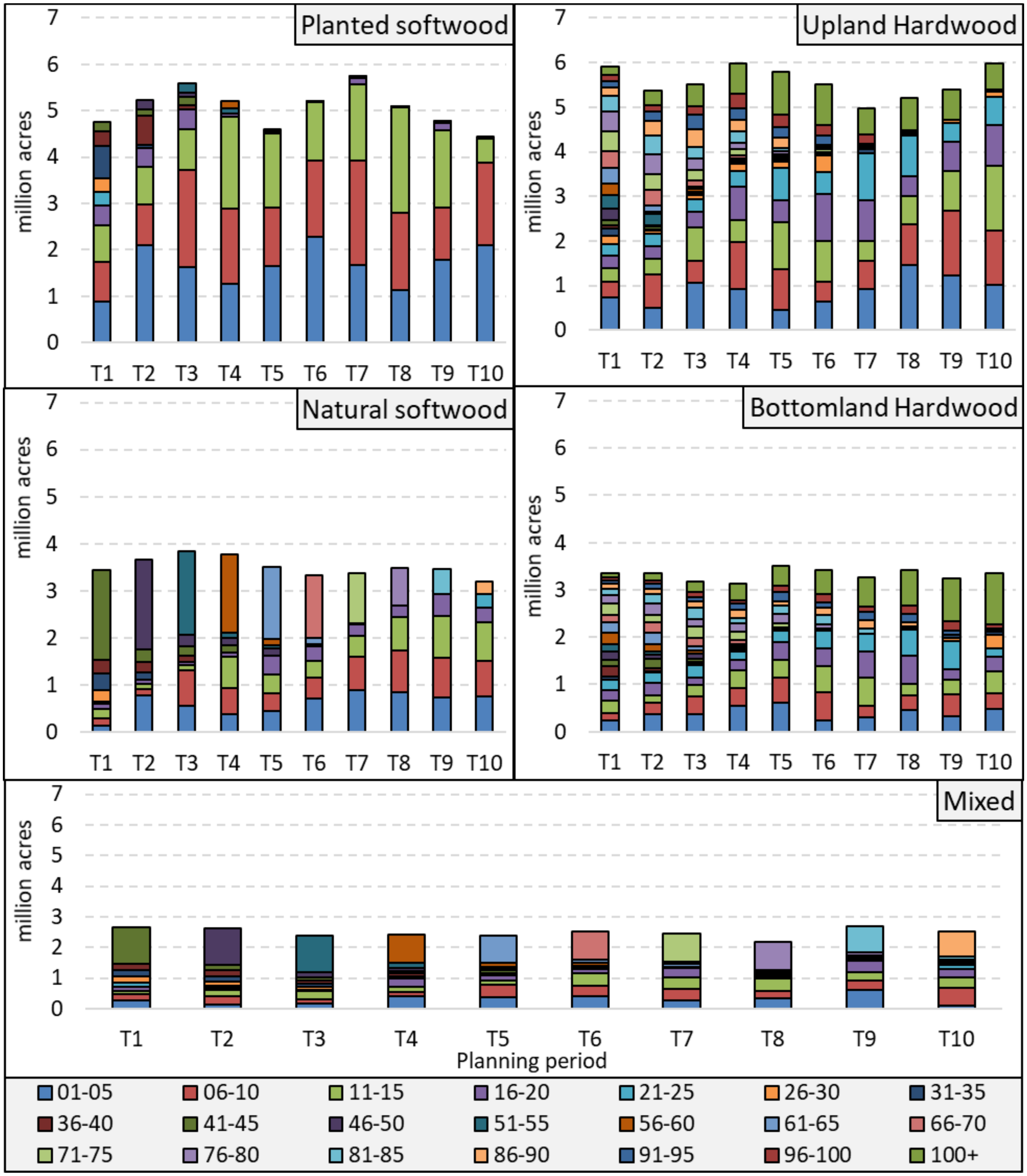

Figure S3.5: Stand age characteristics of annual average unharvested acreage in scenario 1

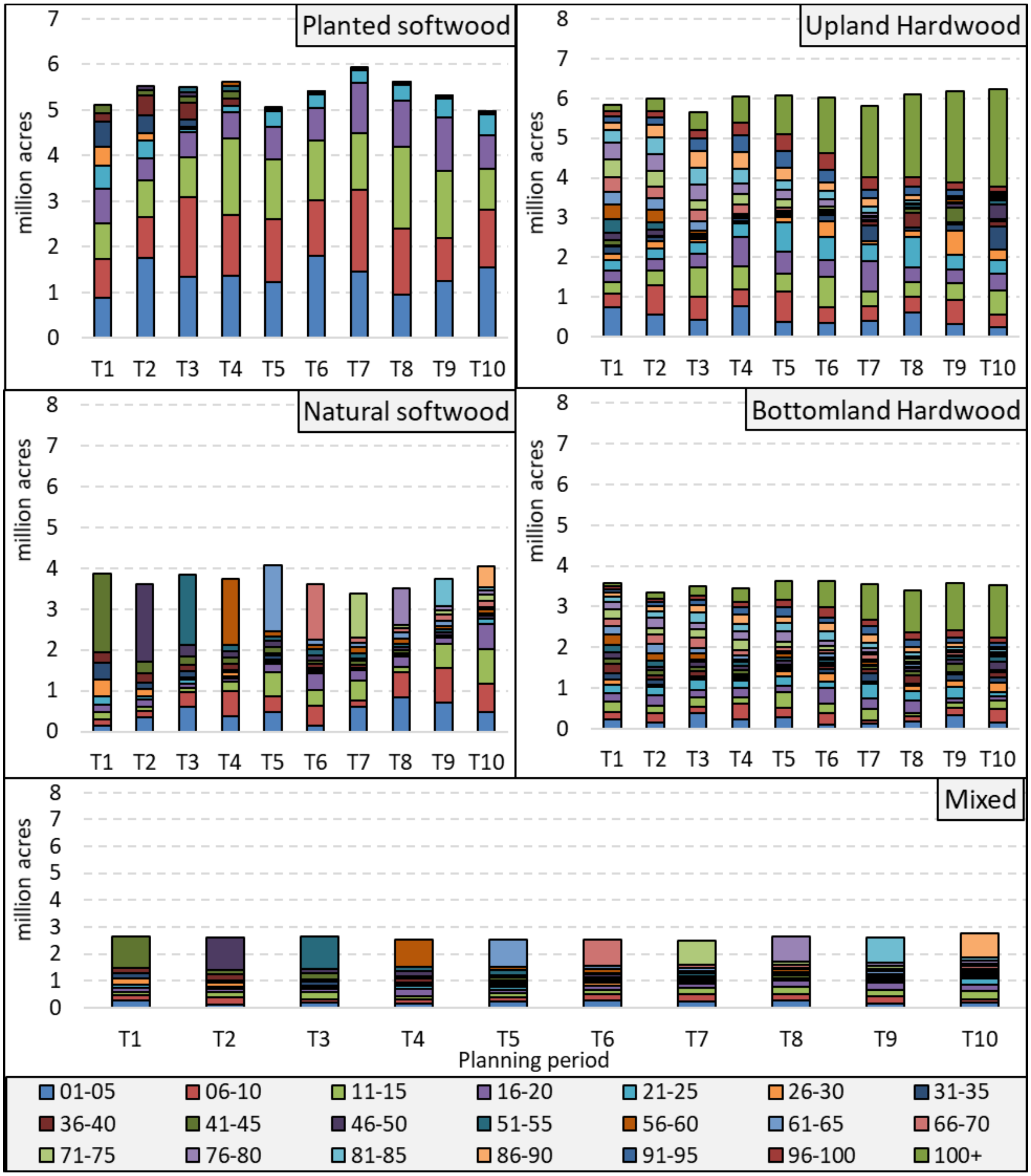

Figure S3.6: Stand age characteristics of annual average unharvested acreage in scenario 2

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CHAPTER 4: ANALYZING LAND USE CHANGE IMPACTS AND CARBON BENEFITS OF BIOPOWER GENERATION IN GEORGIA, UNITED STATES[3]

[3] Masum MFH and P Dwivedi. To be submitted to Environmental Science and Policy.

Abstract

Replacing coal in the power plant with biomass to reduce carbon emission and combat climate change can induce a multifaceted impact on land use changes. Using FIA unit level yield from forestland (planted softwood, natural softwood, upland hardwood, bottomland hardwood, and mixed forest) and grassland, we developed a market-clearing linear programming model spanning 50 years that satisfies both traditional timber demand in the pulp and sawmills and bioenergy (pulpwood, logging residues, and grass) demand to replace coal. We analyzed three scenarios: (i) Baseline - 100% traditional demand, no land use change, no coal replaced; (ii) Scenario 1 – 100% traditional demand, land use change allowed, 50% coal replaced with grass and pulpwood; and (iii) Scenario 2 - 100% traditional demand, land use change allowed, 50% coal replaced with grass, pulpwood, and logging residues. About 320, 522, and 618 thousand acres of forestland were annually harvested in Baseline, Scenario 1, and Scenario 2, respectively. Approximately 2.45 million acres of forestland was converted to grassland in Scenario 1 while forestland increased in Scenario 2 as 160 thousand acres of grassland was converted to forest. About 64% (564 million tons) of the overall bioenergy demand in the power plant was fulfilled with grasses in Scenario 1, while only 0.6% bioenergy demand was met by grass in Scenario 2. Sensitivity analysis suggested that replacing 100% coal with all three types of feedstocks, despite reducing the aboveground carbon in forest biomass, provided the highest carbon benefit when benefit from avoided carbon emission via coal replacement was accounted for with changes in the stand carbon.

Abbreviations

$	US dollars
C	carbon
CO_2e	carbon dioxide equivalent
lb	pounds

4.1. Introduction

Climate change has become one of the most concerning issues as the average global temperature increased by 1.8 ^oF since 1880 (NASA, 2020a). The current level of carbon dioxide, a major greenhouse gas responsible for global warming, in the atmosphere is 414 parts per million (NASA, 2020b). Reducing the usage of fossil fuel, which emits carbon dioxide in the atmosphere, is of prime importance to combat global warming. In 2018, about 33% of all energy-related CO_2 emission in the United States was due to electricity generation (US EIA, 2020a). Georgia, the third largest electricity generating and coal consuming state for power generation in the South Atlantic region, consumed about 265 trillion Btu of energy from coal and used about 14 million tons of coal in 2019 (US EIA, 2020b). Coal usage was responsible for approximately two-thirds of all carbon emissions from Georgia's power sector (US EIA, 2020c). Replacing coal with energy-rich torrefied biomass in the power plant can effectively reduce carbon dioxide emissions from Georgia's power sector.

In Georgia, woody biomass such as loblolly pine chips and perennial grasses such as bermudagrass were less GHG intensive renewable alternatives for power than coal (Masum, Dwivedi, & Anderson, 2020). Georgia has approximately 24 million acres of forestland, of which 13.8 million acres are softwood forest, and 10.2 million acres are hardwood forest. These forests can supply poletimber with diameter size between 5 to 9 inches for softwood or between 5 and 11 inches for hardwood, and logging residues with diameter size less than 5 inches to produce torrefied wood chips and replace coal (USDA, 2016). Sawtimber, with diameter size above 9 or 11 inches for softwood and hardwood, respectively, has more economical usage such as manufacturing plywood and furniture compared to being used as feedstock. Georgia also has about 1.3 million acres of pastureland and about 0.6 million acres of hayland (Brandeis & Hartsell, 2016; NASS, 2020). These lands can be used to grow bermudagrass, the most common perennial grass in Georgia, and make torrefied wood pellets and replace coal (Hancock, Hicks, Kichler, & Smith, 2020). These lands can also be converted into forestland to produce timber for power plants as pelletizing grass incurs an extra cost (Mani, Sokhansanj, Bi, & Turhollow, 2006; Pirraglia, Gonzalez, Saloni, & Denig, 2013; van der Stelt, Gerhauser, Kiel, & Ptasinski, 2011).

However, optimizing the supply chain to satisfy both traditional demands at the timber mills and power plant will be of prime importance due to several influencing factors such as current land use, choice of biomass, location-specific biomass yield, and distance between power plants and biomass source. Georgia's forest industry was worth USD $36 billion in 2018, which supported approximately 150 thousand jobs (GFC, 2019). Optimizing the supply chain for such a big industry makes economic sense. An optimized supply chain will optimize the total land harvested for biomass, decrease waste of biomass, and cut costs by reducing the transportation distance. Understanding where forest biomass will come from to meet the biopower demand is crucial as forest and SRWC (short rotation woody crops) biomass is predicted to initially supply up to half of the total biomass requirement (Latta, Baker, Beach, Rose, & McCarl, 2013). Determining the optimal amount of biomass used for energy that is realistic, based on the economic and environmental factors such as current pricing, yield, and traditional timber demand makes intuitive sense from the sustainability perspective (Vukašinović & Gordić, 2016). Since transportation directly relates to GHG emission, an optimization model that reduces the transportation distance will also reduce GHG emissions from transportation. Such an optimization model with a longer planning horizon can help understand what kind of forestland will be harvested over time if additional biomass demand to replace coal in the power plant continues. It will reveal stand age characteristics through time or show how the stand carbon will change before and after the planning period.

Linear programming models were used in the literature for bioenergy related environmental decisions where biomass transportation and collection costs were minimized, and energy sales and renewable energy certificates were maximized (Freppaz et al., 2004; Frombo, Minciardi, Robba, Rosso, & Sacile, 2009; Huang, Chen, & Fan, 2010). Models have also been developed to estimate land use changes, and it was found that forest area increases as demand for biomass increases; however, forest landscape moves from non-intensive to intensive management significantly (Costanza, Abt, McKerrow, & Collazo, 2017). In the absence of additional demand for wood pellets, urban areas and/or planted pine are projected to replace natural timberland (Duden et al., 2017). Harvesting wood for bioenergy can lead to increased carbon sequestration as a response to increased afforestation (Abt, Abt, & Galik, 2012). However, the highest biomass insertion may not provide the highest GHG reduction in the power sector (Murphy, Sosa, McDonnell, & Devlin, 2016). Since biomass production spans a longer horizon in time while biomass collection and transportation decisions are made in medium to short time horizons, there is a need to coordinate between these two horizons (Ekşioğlu, Acharya, Leightley, & Arora, 2009). Other cost minimization or profit/yield maximization studies, accounted for land allocation and scheduling in biomass harvesting subject to various forms of area restrictions, suggests that impact on land can be very significant if demand rises drastically (Constantino, Martins, & Borges, 2008; Goycoolea, Murray, Barahona, Epstein, & Weintraub, 2005; Khanna, Önal, Dhungana, & Wander, 2011; Kim, Wear, Coulston, & Li, 2018). In Georgia, approximately 35 million tons of green biomass would be required additionally, after satisfying the demand of currently existing pulp mills, in order to replace 100% coal (13.8 million tons) with torrefied biomass in the coal-fired power plants (US EIA, 2020b). To use biomass in coal-power plants, biomass needs to be torrefied as torrefied biomass has less moisture content and calorific value equivalent to sub-bituminous coal (Phanphanich & Mani, 2011).

To understand the significance of coal replacement with biomass, we developed a market-clearing optimization model with land use change expanding 50 years. We determined the optimal harvest location and biomass allocation while satisfying traditional timber demand in the pulp and sawmills and torrefied biomass demand in the coal-fired power plants of Georgia. We analyzed how the stand age pattern will change with and without Georgia's additional bioenergy demand and how the land will move from between forestland and grassland. We also estimated the changes in stand carbon and avoided carbon emission via coal replacement in the power plants. Given the size of the timber market, the productive nature of its land, and the need to reduce carbon emission from its power sector, this study answers critical questions related to the sustainability of forest resources in Georgia. With that overarching goal to evaluate the sustainability of biopower generation, the specific objectives of this study are –

i) Optimizing the timber sourcing location of biomass to satisfy demand at pulp mills, sawmills, and power plants in the presence of land use change.

ii) Optimizing the quantity of biomass transported from each biomass production region to demand points in the presence of land use change.

iii) Estimating changes in stand carbon and avoided carbon emission via replacing coal in the coal-fired power plants of Georgia with biomass in the presence of land use change.

4.2. Methodology

4.2.1. Study area

Georgia has five FIA (Forest Inventory and Analysis) units and 25.94 million acres (million acres) of forestland and grassland (Figure 4.1).

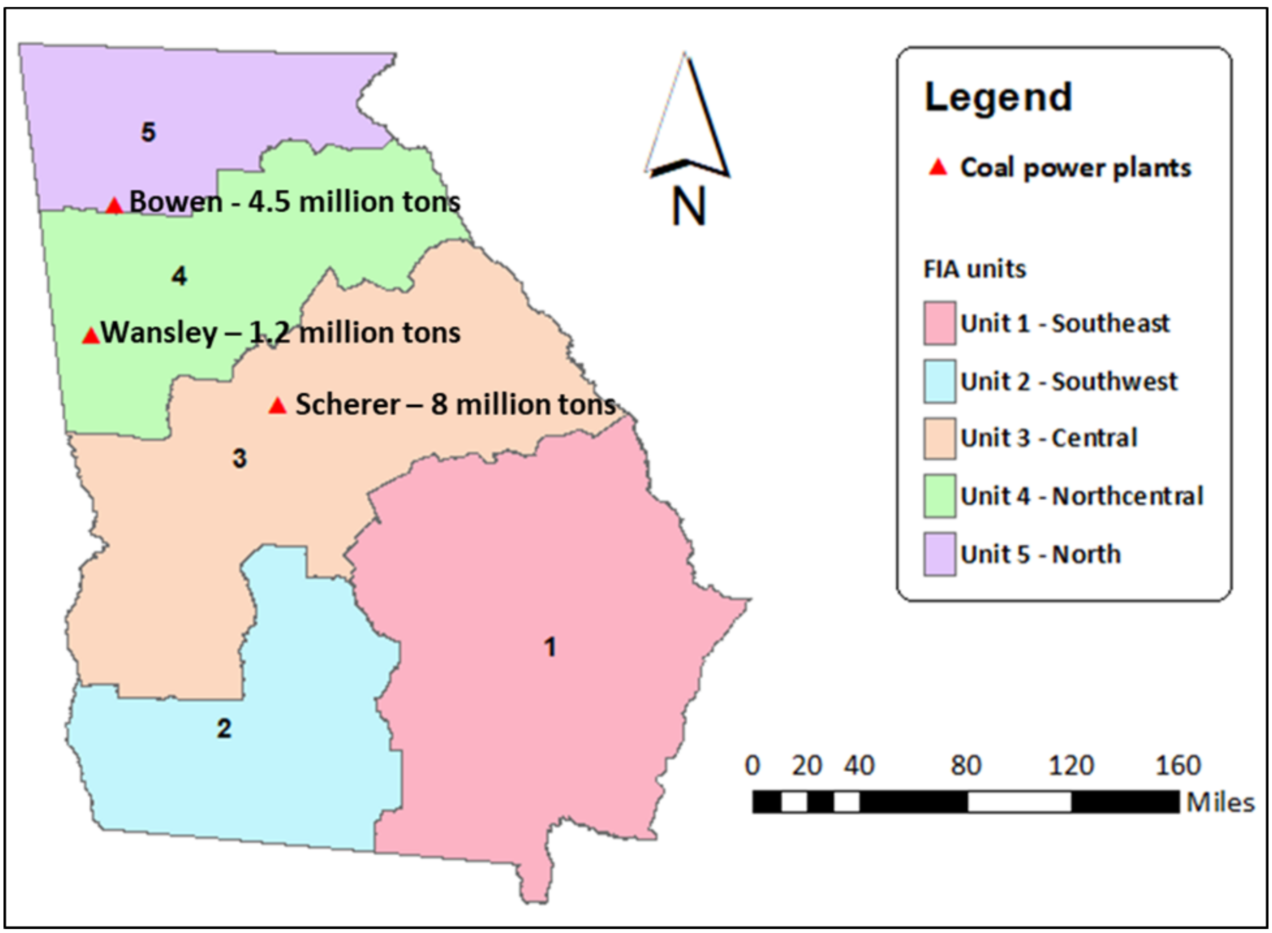

Figure 4.1: FIA units and coal power plants of Georgia

Forestland (24.01 million acres) consists of five forest types—planted softwood (6.86 million acres), natural softwood (4.22 million acres), upland hardwood (6.42), bottomland hardwood (3.73 million acres), and mixed stands (2.78 million acres). Unit 1 has the highest quantity of forestland, approximately 7.65 million acres, which was followed by Unit 3 (7.5 million acres). While Unit 1 and 3 are rich in softwood, Unit 4 and 5 are rich in hardwood. Grassland (1.93 million acres) consists of pastureland (1.33) and hayland (0.6 million acres). Three coal-firing power plants in Georgia are—Bowen, Scherer, and Wansley. Annual coal consumption of these plants are 4.52, 8.05, and 1.24 million tons, respectively (US EIA, 2020b).

4.2.2. Data

'Unit' was defined as the five FIA units, the supply node of biomass, and its alias 'un' was used as the demand nodes of pulpwood and sawtimber (Table 4.1).

Table 4.1: Data dimensions used in the model

Sets	Definition
Unit	FIA units in Georgia, timber supply region
Un	Alias of unit, used for demand nodes of un
Land	Land use types – planted softwood (PS), natural softwood (NS), upland hardwood (UH), bottomland hardwood (BH), mixed forest (MI), grassland (GR)
Ll	Alias of land, used for converted land
species	Species types—softwood, hardwood, and grass—available in different land use system
Crop	Crop types–poletimber (PT), sawtimber (ST), logging residues (LR), and bermudagrass (BE)—available under species
Age	Stand age class with 5-year interval, A1 to A21
Time	Planning period with 5 year interval, T1 to T10; total planning horizon – 50 years
Plant	Coal power plants in Georgia

'Land' was the land use included in the study—forestland and grassland. Subdivisions under forestland were planted softwood, natural softwood, upland hardwood, bottomland hardwood, and mixed forest. For grassland, we collected pastureland and hayland acreage information from NASS and combined them into a single category called ‘grassland’ (NASS, 2020). To reduce an extra dimension in the model, we kept all five forest types and grassland under the same set ‘land’. Land can change between any land use types except bottomland hardwood. Alias for ‘land’ was ‘ll’, which was used for converted land. ‘Species’ was the type of biomass produced in land—softwood, hardwood, and grass. Details on softwood and hardwood are discussed in Chapter 3. ‘Crop’ was the available product from ‘species’ type—poletimber, sawtimber, logging residues, and grass. Poletimber, sawtimber, and logging residues were available in the five forest types, and grass was available in the grassland. For grass, we considered bermudagrass (BE) as the most common forage species in Georgia. The availability of ‘crop’ varied based on land type, species type, and stand age classes declared as ‘age,’ with the interval of 5 years, starting from 0-5 (A1) to 100+ years (A21). ‘Time’ referred to ten planning periods T1 to T10, each with 5-year interval in the total planning horizon of 50 years; i.e., T1 referred to year 0 to 5, T2 referred to 6 to 10, etc. ‘Plant’ was coal-based power plants or the bioenergy demand node.

4.2.2.1. Supply and Demand

Growth and yield estimation procedure for poletimber, sawtimber, and logging residues were from five forest types were described in Chapter 3 (section 3.2.2.1). For yield from grassland, county-wise total hay production and area harvested data for hayland were collected from NASS (NASS, 2020). County-wise data was converted into FIA unit-wise data by combining counties with their respective unit codes mentioned in the FIA user database (US Forest Service, 2018). Unit-wise yield was calculated by dividing total production in a unit with the respective acreage in the unit. Yield of hay was 2.76, 3.10, 2.59, 2.38, and 2.42 tons acre^{-1} year^{-1} in Unit 1 through 5, respectively.

Since there was no yield data for pastureland, we treated both hayland and pastureland with equal inputs and equal yields, and referred them together as grasslands for the remainder of the article. Demand for pulp mills, sawmills, and power plants were discussed in Chapter 3 (section 3.2.2.2).

4.2.2.2. Cost and prices

Beside the costs and prices mentioned in chapter 3 (section 3.2.2.3), costs related to land conversion, fertilization, herbicide application, and irrigation and price of grass was included in this study. To change land use from grassland to forestland, herbicide application cost was assumed to be \$100 acre^{-1}. Forestland to grassland conversion cost was assumed to be \$3000 acre^{-1}, which includes stump removal, uprooting, and herbicide application. Fertilization rate for producing grass was 200 lb N, 60 lb P, 200 lb K, and 1000 lb lime per acre at the rate \$0.42 lb^{1}, \$0.39 lb^{1}, \$0.28 lb^{1}, and \$0.02 lb^{1}, respectively (CAES, 2020b; Knight, 2017). The additional cost of irrigation, herbicide and insecticide management, fuel, and equipment was \$250 acre^{-1} year^{-1} (CAES, 2020a; Knight, 2017). Therefore, the total cost for grass production becomes \$403 acre^{-1}. This cost was 57% lower than the cost estimate provided by the College of Agricultural and Environmental Sciences (CAES), University of Georgia, but our production estimates were 75% lower as well (CAES, 2020a). Harvesting cost for poletimber, sawtimber, and logging residues were \$11.67 ton^{-1} for Unit 1 to Unit 3 and \$12.9 ton^{-1} for Unit 4 and Unit 5 (TMS, 2020). Harvesting cost for grasses was \$6 ton^{-1} (CAES, 2020a). Timber products were chipped at a rate of \$6.5 ton^{-1} (USDOE, 2011). As grasses need to be pelletized to use in power plant, pelletization cost was included for pellets made from grass, \$40 ton^{-1}. The price of grass was collected from NASS, \$84 ton^{-1} (NASS, 2020). If grasses are not used in the power plant, then it can be sold at the same price at an assumed transportation distance of 100 miles at a rate of \$0.15 ton^{-1} mile^{-1}.

We used this transportation distance to omit unfair advantage to grass derived from having no maximum limit on production and since other products have transportation distances. Similar to chapter 3, these costs were discounted with a 4% interest rate using the median year of each planning period.

4.2.3. Mathematical framework

From a social planner's perspective, we developed a linear optimization model with land use changes that maximizes profit for landowners and minimizes the cost of biomass procurement and transportation to satisfy the demand of pulp mills, sawmills, and power plants in Georgia. Parameters and variables were defined in Table 4.2.

Our primary decision variables were area harvested, area converted, the quantity of crops procured from harvest locations, and biomass allocation to demand nodes. Since this was a market-clearing model, we added constraints that demand in all three demand nodes must be satisfied. Prices were considered exogenous for this study. We used the CPLEX solver in GAMS (General Algebraic Modeling System), version 31.2, to optimize this model (GAMS Development Corp., 2020).

We developed three scenarios to fully understand the impact of land use change in the presence of additional bioenergy demand to replace coal:

a) **Baseline** - business as usual, where there is no coal replaced with biomass in the power plant, grassland is not included, and no land use change;
b) **Scenario 1** - where 50% of coal is replaced with pulpwood and grass-pellets only, i.e., variable BIO includes SoftPT2, HardPT2, and GrassBE2; and

Table 4.2: Parameters/variables used in the mathematical model

Parameters	Definition
$Acreage_{unit,land,age}$	Acreage of land type in each FIA unit
$Yield_{unit,land,species,crop,age}$	
YieldSoftPT	Yield of softwood poletimber varied by location, land type, and stand age
YieldSoftST	Yield of softwood sawtimber varied by location, land type, and stand age
YieldSoftLR	Yield of softwood logging residues varied by location, land type, and stand age
YieldHardPT	Yield of hardwood poletimber varied by location, land type, and stand age
YieldHardST	Yield of hardwood sawtimber varied by location, land type, and stand age
YieldHardLR	Yield of hardwood logging residues varied by location, land type, and stand age
YieldGrass	Yield of grass varied by location and land type
$P_{time,unit,species,crop}$	Price of crops
$Cost_{time,age}$	Annual tax paid by the landowner
$Fercost_{land,time}$	Fertilizer cost for grass production
$Concost_{land,ll,time}$	Conversion cost between land types
$Harvest_{time,unit,land}$	Harvesting cost per ton, varied by location and land use type
$TC1_{time,unit,un}$	Transportation cost of timber from unit centers to pulp or sawmills
$TC2_{time,unit,plant}$	Transportation cost of feedstock from unit centers to power plants
$OC_{time,crop}$	Opportunity cost of harvesting but not transporting crop
$DemandSoftPT_{un}$	Softwood pulpwood quantity demanded at FIA unit
$DemandSoftST_{un}$	Softwood sawtimber quantity demanded at FIA unit
$DemandHardPT_{un}$	Hardwood pulpwood quantity demanded at FIA unit
$DemandHardST_{un}$	Hardwood sawtimber quantity demanded at FIA unit
$DemandBio_{plant}$	Biomass demanded at Plants
Variables	**Definition**
$AA_{time,unit,land,age}$	Acres available in each land type in each FIA unit
$AH_{time,unit,land,age}$	Acres harvested from each land type in each FIA unit
$AU_{time,unit,land,age}$	Acres not harvested from each land type in each FIA unit
$AC_{time,unit,land,age,ll}$	Acres converted to a different land type after harvesting
$ANC_{time,unit,land,age,ll}$	Acres remained in the same land type
$\sum_{un,plant} Q_{unit,land,species,crop,age}$	
a) $SoftPT_{unit,land,species,crop,age,un}$	Amount of softwood pulpwood transported from Unit to un
b) $SoftST_{unit,land,species,crop,age,un}$	Amount of softwood sawtimber transported from Unit to un
c) $HardPT_{unit,land,species,crop,age,un}$	Amount of hardwood pulpwood transported from Unit to un
d) $HardST_{unit,land,species,crop,age,un}$	Amount of hardwood sawtimber transported from Unit to un
e) $GrassBE_{unit,land,species,crop,age,un}$	Amount of bermudagrass transported from Unit to un
e) $BIO_{unit,land,species,crop,age,plant}$	Amount of pulpwood, logging residues, and/or bermudagrass transported from each Unit to all power plants
e1) SoftPT2	Amount of softwood pulpwood transported from Unit to Plant
e2) SoftLR	Amount of softwood logging residues transported from Unit to Plant
e3) HardPT2	Amount of hardwood pulpwood transported from Unit to Plant
e4) HardLR	Amount of hardwood logging residues transported from Unit to Plant
e5) GrassBE2	Amount of bermudagrass transported from Unit to Plant

c) **Scenario 2** - where 50% coal is replaced with pulpwood, logging residues, and grass-pellets; i.e., variable BIO includes SoftPT2, SoftLR, HardPT2, HardLR, and GrassBE2.

The welfare maximizing objective function was defined as –

$$\max \frac{1}{1.04^{time}} [\text{revenue - tax - convert - fertilizer - harvest - trans - opcost - pellet}] \quad (4.1)$$

where,

$$\text{revenue} = \sum_{time,unit,land,species,crop,age,un,plant} [Q_{time,unit,land,species,crop,age} \ x \ P_{time,unit,land,crop}] \quad (4.2)$$

$$\text{tax} = \sum_{time,unit,land,age} [AH_{time,unit,land,age} \ x \ Cost_{time}] \quad (4.3)$$

$$\text{convert} = \sum_{time,unit,land,age,ll} [AC_{time,unit,land,age,ll} \ x \ Concost_{land,ll,time}] \quad (4.4)$$

$$\text{fertilizer} = \sum_{time,unit,land,age} [AA_{time,unit,land\ ,age} \ x \ Fercost_{land,time}] \quad (4.5)$$

$$\text{harvest} = \sum_{time,unit,land,species,crop,age} [AH_{time,unit,land\ ,age} \ x \ Yield_{unit,land,species,crop,age} \ x \ Harvest_{unit,time}] \quad (4.6)$$

$$\text{trans} = \sum_{time,unit,\ land,species,crop,un} [TC2_{time,unit,un} \ x \ (SofTPT_{time,unit,land,species,crop,un} + HardPT_{time,unit,land,species,crop,un} + SoftST_{unit,land,species,crop,unitS} + HardST_{unit,land,species,crop,un})] + \sum_{time,unit,land,species,crop,plant} [TC1_{time,unit,plant} \ x \ BIO_{time,unit,land,species,crop,plant}] \quad (4.7)$$

$$\text{opcost} = \sum_{time,unit,land,species,crop,age} [OC_{time,crop} \ x \ (\{AH_{time,unit,land,age} \ x \ Yield_{unit,\ land,species,crop,age}\} - \sum_{un,plant} Quantity_{unit,land,species,crop,age})] \quad (4.8)$$

$$\text{pellet} = \sum_{time,unit,land,species,crop,age,plant} [GrassBE2_{time,unit,land,species,crop,age,plant} * Pelletization_{crop,time}] \quad (4.9)$$

Equation (4.2) defined ‘revenue’ as the sum of revenue earned by the landowner by selling biomass. Equation (4.3) defined ‘tax’ as the sum of annual taxes paid by the landowner. Equation (4.4) defined ‘convert’ as the total cost of converting land use from one land type to another. As mentioned before (section 4.2.2), bottomland hardwood was not allowed to change. Equation (4.5) defined ‘fertilizer’ as the total cost of fertilizing bermudagrass. Equation (4.6) defined ‘harvest’ as the sum of costs for harvesting biomass. Equation (4.7) defined ‘trans’ as the sum of costs of transporting biomass. In the Baseline scenario, the quantity for variable BIO is zero. Equation (4.8) defined ‘opcost’ as the sum of opportunity costs for harvesting but not transporting pulpwood and sawtimber—further details on which are presented in chapter 3, section 3.2.2.3. Equation (4.9) defined ‘pellet’ as the total cost of pelletizing bermudagrass in order to use in power plants. For the Baseline scenario, constraints (4.5), (4.6), and (4.9) were not included as the Baseline included no land use change and no grassland. From this formulation, it can be predicted that the maximum welfare achieved by equation (4.1) could be negative since the welfare function contained the cost of logging and transportation but did not include the revenue from final products such as lumber, paper, or electricity.

Constraints for the Baseline scenario were as follows –

$AH_{time,unit,land\ ,age} + AU_{time,unit,land\ ,age} = Acreage_{time,unit,land\ ,age}$ for every time, unit, land, species, age (4.10)

$AA_{time,unit,forest,A1} = \sum_{age} AH_{time-1,unit,forest,age}$ for every time, unit, forest (4.11)

$AA_{time,unit,land,age} = AU_{time-1,unit,land,age-1}$ for every time, unit, land, age (4.12)

$AA_{time,unit,land,age=A21} = AU_{time-1,unit,land,age=A20} + AU_{time-1,unit,land,age=A21}$ for every time, unit, land, and species (4.13)

$\sum_{un} SoftPT_{time,unit,land,species,crop,age,un} \leq AH_{time,unit,land,age}\ x\ YieldSoftPT_{unit,land,species,crop,age}$ for every time, unit, land, species, crop, age (4.14)

$\sum_{un} HardPT_{time,unit,land,species,crop,age,un} \leq AH_{time,unit,land,age}\ x\ YieldHardPT_{unit,land,species,crop,age}$ for every time, unit, land, species, crop, age (4.15)

$\sum_{un} SoftST_{time,unit,land,species,crop,age,un} \leq AH_{time,unit,land,age}\ x\ YieldSoftST_{unit,land,species,crop,age}$ for every time, unit, land, species, crop, age (4.16)

$\sum_{un}$ $HardST_{time,unit,land,species,crop,age,un} \leq AH_{time,unit,land,age}$ x $YieldHardST_{unit,land,species,crop,age}$ for every time, unit, land, species, crop, age (4.17)

$\sum_{unit,land, species,crop,age}$ $SoftPT_{time,unit,land,species,crop,age,un} = DemandSoftPT_{un}$ for every t and un (4.18)

$\sum_{unit,land, species,crop,age}$ $SoftST_{time,unit,land,species,crop,age,un} = DemandSoftST_{un}$ for every t and un (4.19)

$\sum_{unit,land, species,crop,age}$ $HardPT_{time,unit,land,species,crop,age,un} = DemandHardPT_{un}$ for every t and un (4.20)

$\sum_{unit,land, species,crop,age}$ $HardST_{time,unit,land,species,crop,age,un} = DemandHardST_{un}$ for every t and un (4.21)

AH, AU, SoftPT, SoftST, HardPT, HardST ≥ 0 (4.22)

Equation (4.10) ensured that the total land quantity stays the same, i.e., acres harvested and acres unharvested will equal total acreage in all land types. Equation (4.11) ensured that acres harvested in time "t" would move to stand age class A1 in time "t+1", i.e., the area will be replanted and stand age will become zero in the next planning period. Equation (4.12) ensured that the stand age of acres not harvested in the planning period "t" will move to the next stand age class in "t+1". Equation (4.13) ensured that if any acres with stands aged A21 is not harvested, then the land will remain in age A21 since this is the last stand age class. Equation (4.14) to (4.17) ensured that the total quantity of timber transported to pulp mills and sawmills could not exceed the total biomass harvested from the timberland. Equation (4.18) to (4.19) ensured that demand at pulp mills and sawmills must be satisfied. Equation (4.22) was non-negativity constraints for acreage and the quantity of timber transported.

Constraints for Scenario 1 included equations (4.10), (4.13), and (4.16)-(4.22). Additional constraints for Scenario 1 were as follows –

$AH_{time,unit,land,A1} = \sum_{ff} AC_{time+1,unit,land,age,ff} + ANC_{time+1,unit,land,age}$ for every unit, land, and age (4.23)

$AA_{time,unit,land,A1} = \sum_{age} AH_{time-1,unit,land,age} - \sum_{age,ll} AC_{time,unit,land,age,ll} + \sum_{ll,age} AC_{time,unit,ll,age,land}$ for every unit and land (4.24)

$\sum_{un} SoftPT_{time,unit,land,species,crop,age,un} + \sum_{plant} SoftPT2_{time,unit,land,species,crop,age,plant} \leq AH_{time,unit,land,species,age}$ x $YieldSoftPT_{unit,land,species,crop,age}$ for every time, unit, land, species, crop, age (4.25)

$\sum_{un} HardPT_{time,unit,land,species,crop,age,un} + \sum_{plant} HardPT2_{time,unit,land,species,crop,age,plant} \leq AH_{time,unit,land,species,age}$ x $YieldHardPT_{unit,land,species,crop,age}$ for every time, unit, land, species, crop, age (4.26)

$\sum_{un} GrassBE_{time,unit,land,species,crop,age,un} + \sum_{plant} GrassBE2_{time,unit,land,species,crop,age,un} \leq AH_{time,unit,land,age}$ x $YieldGrass_{unit,land,species,crop,age}$ for every time, unit, land, species, crop, age (4.27)

$\sum_{unit,land,species,crop,age} BIO_{time,unit,land,species,crop,age,plant} = Demand_{plant}$ for every t and plant (4.28)

SoftPT2, HardPT2, GrassBE, GrassBE2 ≥ 0 (4.29)

Equation (4.23) ensured that if an acre is harvested, it can either be converted to different land use or remain in the same land use. Equation (4.24) ensured that total land availability in a particular land use included the land moving into the same land use and excluded the land moving out of it. Equation (4.25) and (4.26) ensured that the total quantity of softwood pulpwood and hardwood pulpwood transported to the pulp mills and the power plants could not exceed the total softwood pulpwood and hardwood pulpwood produced, respectively. Equation (4.27) suggested that total grass transported to the power plant and/or sold at the demand node 100 miles away could not exceed the total production. Equation (4.28) ensured that power plant demand for biomass must be satisfied. Equation (4.29) was the non-negativity constraints for grass transported for sale for profit, and softwood pulpwood, hardwood pulpwood, and grass transported to power plants.

In addition to all the constraints related to Scenario 1, Scenario 2 included equation (4.30) and (4.31) as constraints to include logging residues —

$\sum_{un}$ $SoftLR_{time,unit,land,species,crop,age,plant} \leq AH_{time,unit,land,species,age} \; x \; YieldSoftLR_{unit,land,species,crop,age}$ for every time, unit, land, species, crop, age (4.30)

$\sum_{un}$ $HardLR_{time,unit,land,species,crop,age,plant} \leq AH_{time,unit,land,species,age} \; x \; YieldHardLR_{unit,land,species,crop,age}$ for every time, unit, land, species, crop, age (4.31)

$SoftLR, HardLR \geq 0$ (4.32)

Equation (4.30) ensured that the total quantity of softwood logging residues transported could not exceed the total logging residues generated; equation (4.31) ensured the same for hardwood. Equation (4.32) was the non-negativity constraint for softwood and hardwood logging residues transported to power plants. After running the model in GAMS, the preparation of results and graphing was performed in MS Excel and OriginPro Version 2019b (Originlab Corporation, 2019).

4.2.4. Carbon dynamics

The estimation procedure for carbon in stand and carbon savings with biopower was discussed in Chapter 3, section 3.2.4.1, and 3.2.4.2. Besides that, in total carbon savings, we included carbon emission from pelletizing grasses, 311.4 lb CO_2e ton^{-1} (Dwivedi, Bailis, Bush, & Marinescu, 2011). We only reported carbon changes in the forestland, not in the grassland, as harvest occurs every year, and aboveground biomass after harvest from grassland is negligible (Md Farhad H Masum, Mehmood, Pelkki, & Liechty, 2020).

4.2.5 Sensitivity analysis

We replaced coal in power plants in a 10% increment, from 10% to 100%, using (i) pulpwood and grasses only, and (ii) pulpwood, logging residues, and grasses. In other words, these are extensions of Scenario 1 and Scenario 2 with varying levels of coal replacement. We reported acres harvested and acres available as grassland throughout the planning period. We also reported total change in stand carbon, carbon avoided via coal replacement, and net carbon changes under these scenarios. Additionally, we reported what percentage of coal demand was satisfied by grass pellets.

4.3. Results and Discussion

A globally optimal solution for the welfare was obtained for the entire planning horizon of 50 years at -$0.69 billion, 1.6 billion, and -$5.2 billion for Baseline, Scenario 1, and Scenario 2, respectively. Negative welfare was expected as the model included cost for timber or biomass procurement but the revenue generated from the finished products such as paper or lumber was not included. However, positive welfare was achieved for Scenario 1 since there was no constraint on how much grass can be produced and sold. Timber yield from forestland was discussed in Chapter 3, section 3.3.1.

4.3.1. Acres harvested

In Baseline, where no grassland is included, and no coal is replaced in the power plant, about 320 thousand acres of forestland were harvested annually (Figure 4.2). Baseline estimates of total area harvested were on par with the historical data, details on which were discussed in Chapter 3, section 3.3.2.1.1.

4.3.1.1. Scenario 1

When pulpwood and grasses replaced coal, the annual average forestland harvest increased to 522 thousand acres, 202 thousand acres higher than Baseline. Total forestland harvested had a decreasing trend during the first five planning periods, from 1107 thousand acres in T1 to 444 thousand acres in T5, and then stabilized around 400 thousand acres during the last two planning periods.

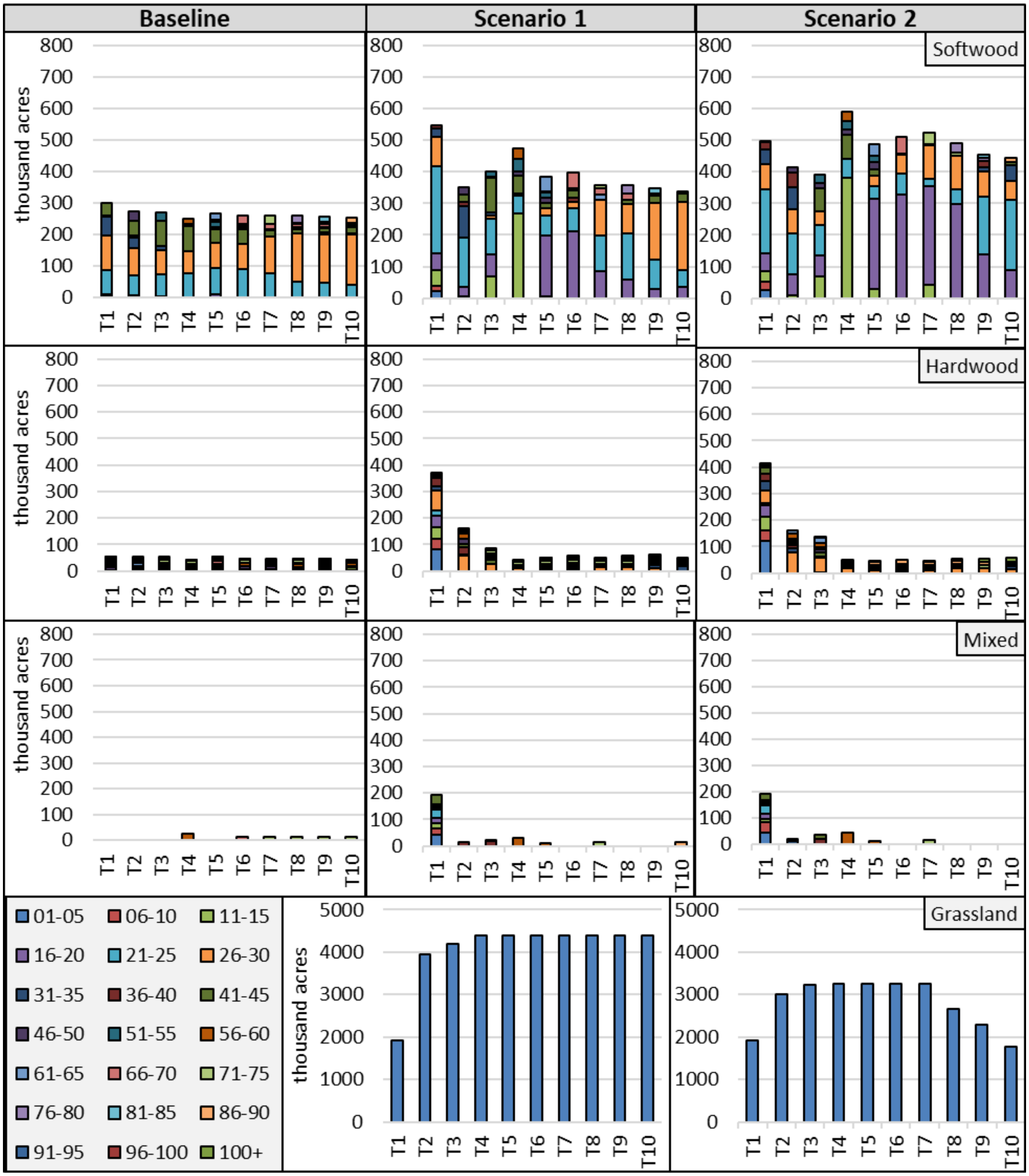

Figure 4.2: Stand age characteristics of area* harvested throughout the planning horizon
*Note: Upper bound for grassland is different from forestlands

Among forestland harvested areas, 80% was softwood, 16% was hardwood, and the remaining 4% was mixed stands on an average across the planning horizon. Planted softwood harvested acreage accounted for 31% (341 thousand acres) of total harvested acreage in T1, increased to 48% (251 thousand acres), and 59% (298 thousand acres) in T2 and T3, and stabilized around 83% in the last four planning periods. The highest natural softwood was harvested acreage was in T3, 20% (101 thousand acres) of the total. The highest mixed (191 thousand acres) and upland hardwood (339 thousand acres) forest harvested was in T1, which was 17% and 31% of the total in T1, respectively. Respectively, about 67 and 122 thousand acres from mixed and upland hardwood forest was harvested from stands under 10 years old to convert into other land use, which we discussed more in the next section (section 4.3.2). Most softwoods came from stand aged between 21 and 25 years old, except in T5 to T7 where harvested softwood stands were primarily 16 to 20 years old. In T6, about 60% of planted softwood stands harvested was aged between 16 and 20 years. In T4, about 67% (267 thousand acres) planted softwood harvested was 11 to 15 years old.

All available grasslands were harvested annually, as there was no fixed demand associated with grass in the model, and revenue will be lost if grassland is not harvested every year. In T1, 1.93 million acres of grassland were available and was harvested. Both available and harvested acres increased to about 3.9 million acres in T2 and stabilized at 4.4 million acres for the rest of the planning horizon.

4.3.1.2. Scenario 2

When both pulpwood and logging residues from forestland and grass from grassland was used to replace coal, the annual average forestland harvested was 618 thousand acres. More forestland was harvested compared to Baseline because of the higher bioenergy demand. It was higher compared to Scenario 1 because land conversion to grassland was lower than Scenario 1. More discussion about the land conversion was presented in the next section (section 4.3.2). On average, across the planning horizon, 81% harvested forest acreage was softwood, 15% was hardwood, and 4% was mixed forest. Similar to Scenario 1, most harvested forestland acreage was planted softwood, approximately 72% across the planning horizon. Also, similar to Scenario 1, planted softwood harvested acreage increased through the planning periods. In the last six planning periods, 85% of harvested acreage was planted softwood. In T5 to T8, about 65% of planted softwood harvest was from 16 to 20-year-old stands. In T4, 381 thousand acres (73% of T4) with even younger stand age, between 11 to 15 years, were harvested. In general, hardwood stands harvested were aged between 26 to 30 years. However, about 214 thousand acres of younger upland hardwood stands, under 15 years old, where there is no pulpwood or sawtimber were harvested in T1, primarily for conversion to another land use. The same was true for mixed stands under 10 years old. About 97 thousand acres of such stands were harvested for conversion. Similar to Scenario 1, all available grassland were harvested every year, which increased by 56% from T1 (1.93 million acres) to T2 (3.02 million acres) but decreased by 46% gradually between T7 (2.7 million acres) and T10 (2.27 million acres).

4.3.2. Acres available

After harvested, land use was allowed to change in Scenario 1 and Scenario 2, but not in Baseline (Figure 4.3). Therefore, in the Baseline scenario, the available land area under each land use remained the same throughout the planning horizon.

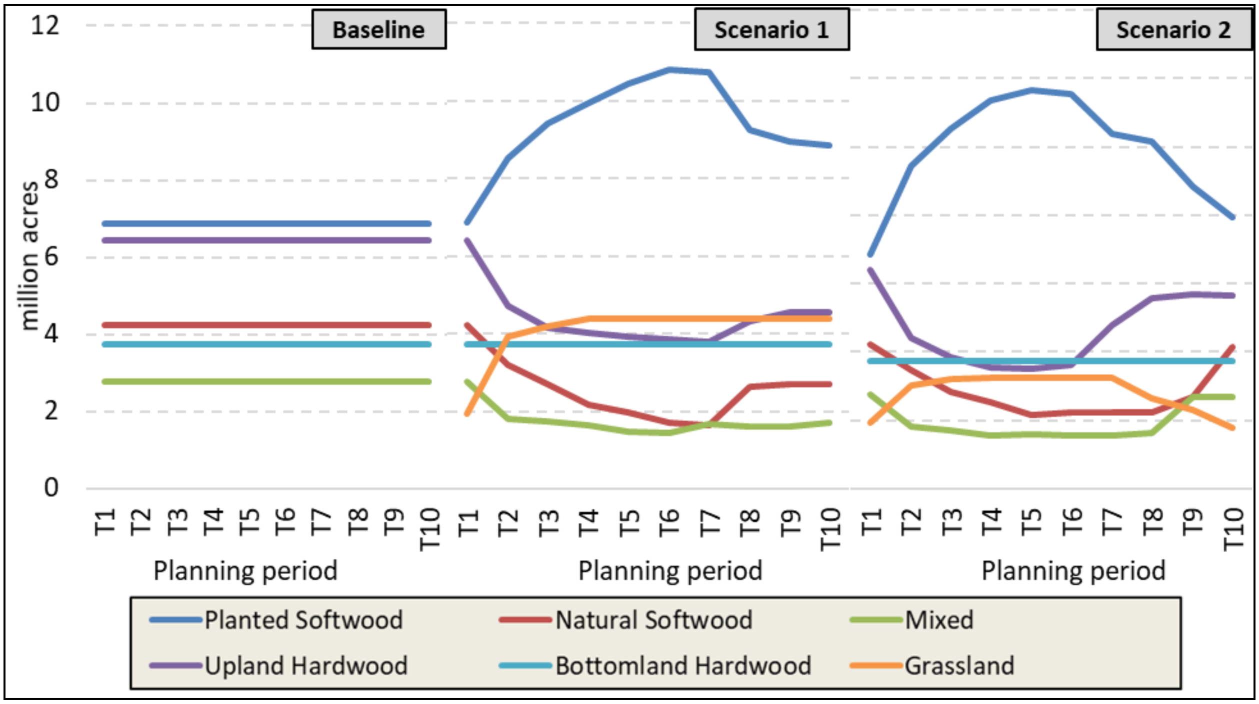

Figure 4.3: Acres available in different land use throughout the planning horizon

4.3.2.1. Scenario 1

Natural softwood, upland hardwood, and mixed forest decreased by about 36%, 29%, and 38%, respectively, between before and after the planning horizon. Across these three forest types, 4.45 million acres of forestland were lost. These lands were allocated to planted softwood (1.99 million acres) and grassland (2.45 million acres), which led to a 29% and 127% increase in these land uses, respectively. Converting 2.45 million acres of forestland to grassland meant a 10% decrease in forestland. This is a direct impact of additional demand in the power plant since logging residues were not available for harvest, and there was more biomass yield per acre in grassland. For example, in Unit 1, an acre of planted softwood stands aged between 36 and 40 years can provide around 82 tons of pulpwood. On that acre, about 111 tons of grasses can be produced over the same period. This can reduce transportation cost for the power plants to harvest biomass from the nearer sites. Even though there was a large sum of cost ($3000 acre^{-1}) attached to forestland to grassland conversion, the benefit of reduced transportation cost over the remaining 40 to 45 years of planning horizon outweighed that. With one exception, all forestland to grassland conversion occurred in Unit 2 where grass yield was the highest among all units, timber demand was lower compared to the other units, and power plant Scherer was in close proximity. The only exception was 704 thousand acres of upland hardwood in Unit 3 converted to grassland in T2.

Acres available in different stand age classes is an excellent indicator to interpret stress on forestland. For example, at the end of the planning horizon, if more forestland is in the younger stands less than 10 years for softwood or 15 years in hardwood where there is no poletimber or sawtimber compared to the older stands, it is a sign of stress. From that, it can be predicted that demand for subsequent planning periods can be under threat. However, that was not the case in this scenario. Only 4.09 million acres of forestland were under 10 years old at T10, which is only about 1% higher compared to the initial acreage before the study began. Following the same logic, another good indicator for forest health is hardwood stands older than 100+ years. In T10, the final hardwood acreage available was 8.44 million acres, of which 4.04 (48%) was in stands aged between 100+ years (Figure 4.4), which was a 1396% increase in this stand age class compared to the initial acreage before the planning horizon. In upland and bottomland hardwood, this increase was about 1416% and 1355%, respectively.

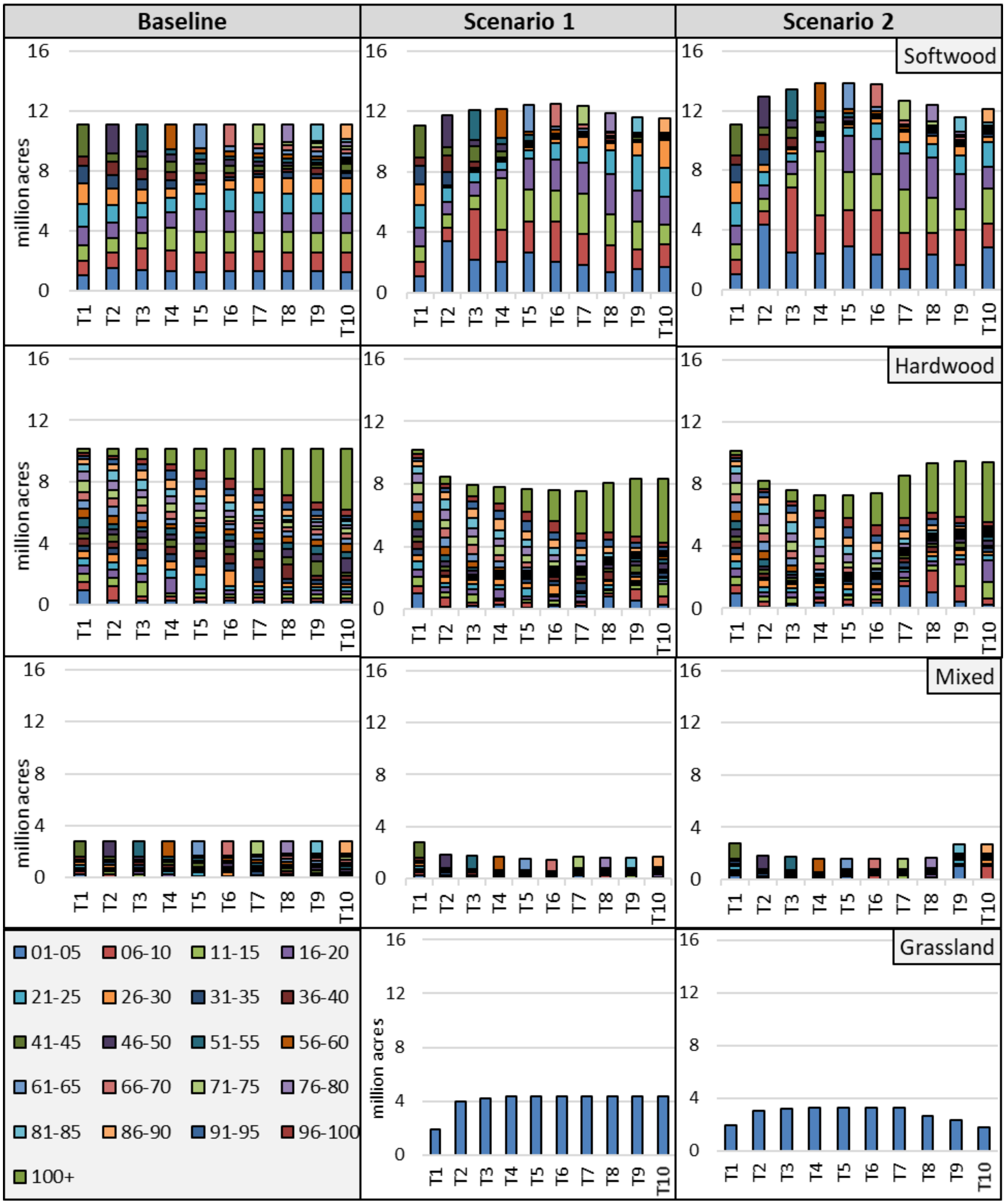

Figure 4.4: Stand age characteristics of area available in different land use throughout the planning horizon

Major land use change was observed during the beginning of the planning horizon (Figure 4.5). Between T1 and T2, 0.7 and 1 million acres of upland hardwood was converted to planted softwood and grassland, respectively. During the same transition, 526 thousand acres of planted softwood and 350 thousand acres of mixed forest was converted to grassland. Until T7, most major conversions were from other land use to planted softwood. Between T7 and T8, about 1 million acres of planted softwood was left to become natural softwood stands, and about 562 thousand acres of planted softwood was converted to upland hardwood.

4.3.2.2. Scenario 2

Forestland increased by 0.7% when logging residues from forestland was allowed to use in the power plants (Figure 4.3). Planted softwood area increased by 40% between T1 (6.86 million acres) and T10 (7.96 million acres). However, it was the highest in T6, approximately 11.7 million acres. Total grassland decreased by about 8% between T1 and T10, from 1.93 million acres to 1.77 million acres. However, it increased by 68% from T1 to T4 and remained relatively stable at about 3.3 million acres until T7, after which it decreased to 2.65, 2.3, and 1.77 million acres in T8, T9, and T10, respectively. In T10, the area of hardwood stands aged between 100+ years was about 3.86 million acres (Figure 4.4), which was a 1330% increase in this stand age class compared to the initial acreage before the planning horizon. In upland and bottomland hardwood, this increase was about 1283% and 1422%, respectively. The increase in this age class was higher for bottomland hardwood and lower for upland hardwood than Scenario 1.

Similar to Scenario 1, major land use conversions occurred during the first ten years of the planning horizon, and most subsequent changes were conversion to planted softwood from other land uses. However, between T8 and T9, about 1.06 million acres of planted softwood stands were converted to mixed stands, and 0.54 million acres were left to become natural softwood stands. Between T9 and T10, more (.89 million acres) planted softwood was left to become natural stands. In T8, 592 thousand acres of grassland were converted to upland hardwood. More grassland was converted to planted softwood in Unit 5 (355 thousand acres in T9) or natural softwood in Unit 3 (529 thousand acres in T10). Comparable to Scenario 1, all forestland to grassland conversion occurred in Unit 2. However, in total, forestland to grassland conversion was less in Scenario 2 compared to Scenario 1. This can be attributed to the presence of logging residues that reduced the transportation distance for all demand nodes to collect biomass—pulpwood for pulp mills, sawtimber for sawmills, and logging residues for power plants.

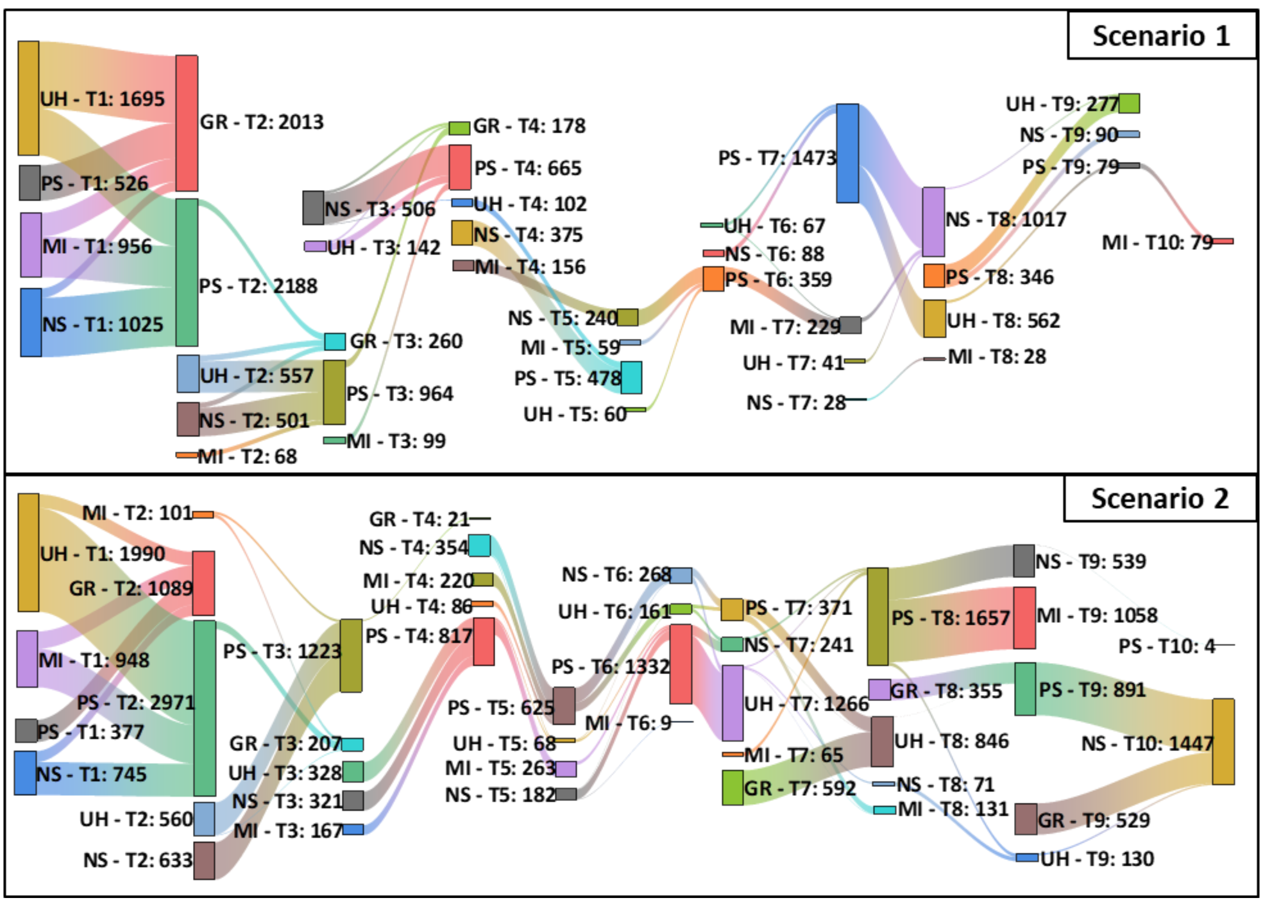

Figure 4.5: Area converted (thousand acres) to a different land use throughout the planning horizon

4.3.3. Biomass production

As demanded in the Baseline scenario, approximately 1.14 billion tons of pulpwood and 0.99 billion tons of sawtimber were produced over the 50 years of the planning horizon (Figure 4.6). There was no waste of pulpwood or sawtimber in Baseline. However, over 50 years, 417 million tons of logging residues were left on site. Further discussion on production in Baseline is available in Chapter 3, section 3.3.3.1.

4.3.3.1. Scenario 1

About 1.45 billion tons of pulpwood, 0.99 billion tons of sawtimber, and 0.56 billion tons of grass were produced when coal was replaced by pulpwood and grasses only. Pulpwood production estimates were about 36% (0.41 billion tons) higher compared to Baseline due to the additional demand in the power plant. Softwood and hardwood combined, about 72% pulpwood and 64% of total sawtimber came from planted softwood stands. About 85% of softwood pulpwood and 72% of softwood sawtimber production was from planted softwood. Unit 3 was the top producer of softwood pulpwood (481 million tons or 39%), while Unit 1 was the top producer of softwood sawtimber (346 million tons or 40%). Unit 1 and Unit 3, combined, produced about 75% of softwood pulpwood and 77% of softwood sawtimber each. Softwood pulpwood production from the planted forest was the lowest in T2 and T3, about 90 million tons in each period. Natural softwood filled up the gap by producing about 26 million tons in each of these periods. Among hardwood pulpwood production, about 49% (103 million tons), 38% (80 million tons), and 12% (26 million tons) came from bottomland hardwood, upland hardwood, and mixed stands, respectively. Unit 3 produced the highest hardwood pulpwood (40% or 84 million tons) and the highest hardwood sawtimber (37% or 42 million tons). While pulpwood and sawtimber production from upland hardwood stands had a decreasing trend (26 million tons in T1 to 5 million tons in T10), bottomland hardwood had an increasing trend (5 million tons in T1 to 18 million tons in T10). Grass production increased between T1 (25 million tons) and T4 (61 million tons) and remained stable through T10. These estimates reflect the acres available in grassland that peaked in T4 and remained the same through T10. About 492 million tons of logging residues were produced during the logging operation and left on site.

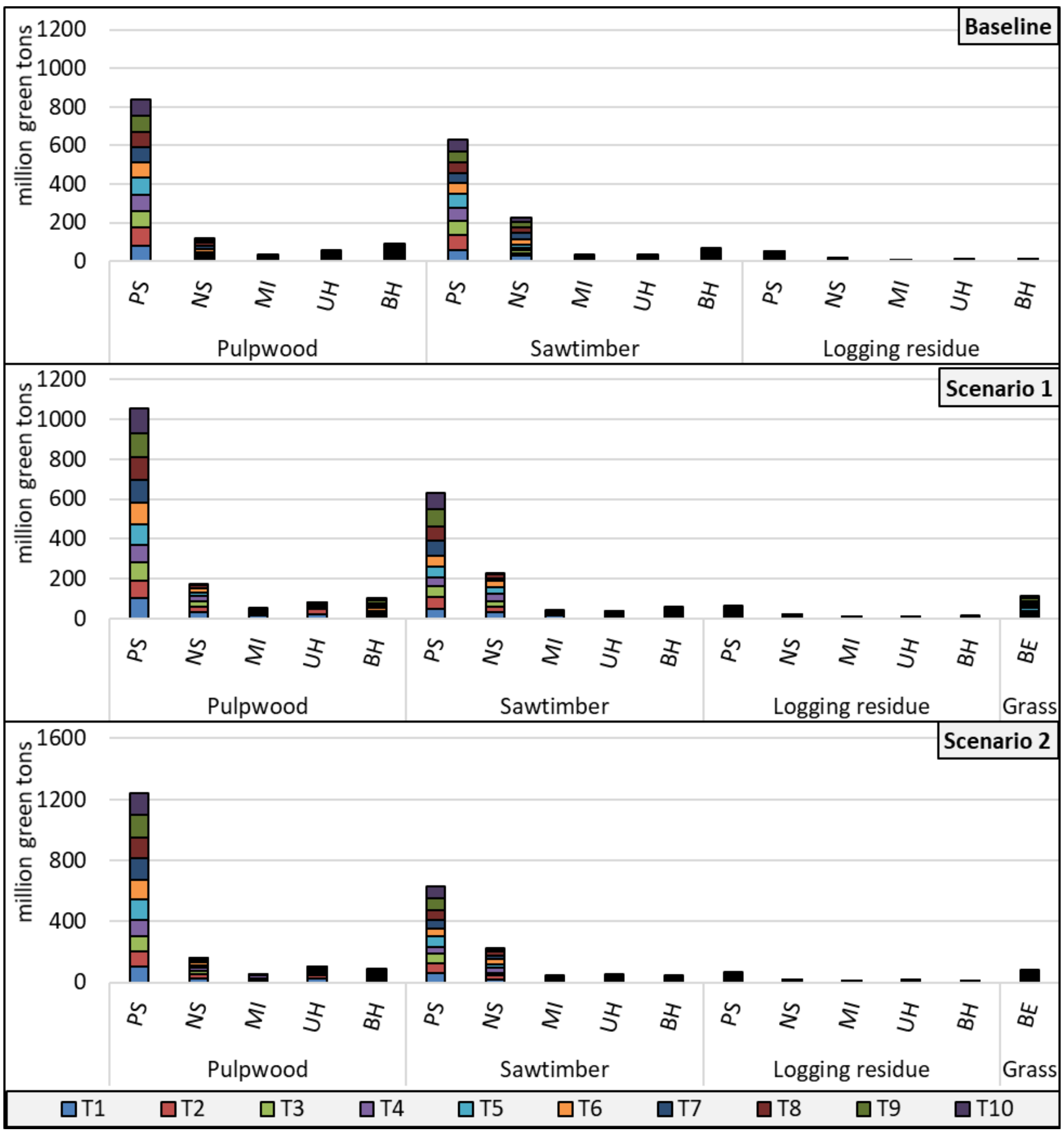

Figure 4.6: Biomass production throughout the planning horizon

4.3.3.2. Scenario 2

About 1.64 billion tons of pulpwood, 0.99 billion tons of sawtimber, 0.53 billion tons of logging residues, and 0.39 billion tons of grass was produced when coal was replaced by pulpwood, logging residues, and grasses. Total pulpwood production was about 43% higher compared to Baseline and 13% higher compared to Scenario 1. However, grass production was 30% lower compared to Scenario 1.

Softwood and hardwood combined, Planted softwood stands produced 75% and 64% of all pulpwood and sawtimber, respectively. This picture closely resembles Scenario 1. Also similar to Scenario 1, Unit 3 was the top producer of softwood pulpwood (619 million tons or 43%), hardwood pulpwood (92 million tons or 42%), and hardwood sawtimber (47 million tons or 41%), and Unit 1 was the top producer of softwood sawtimber (334 million tons or 38%). Pulpwood production from planted softwood had a general increasing trend throughout the planning horizon (106 million tons in T1 to 144 million tons in T10), while natural softwood had a decreasing trend (22 million tons in T1 to 5 million tons in T10). Grass production increased between T1 (25 million tons) and T4 (45 million tons) and remained stable through T7, then decreased in T8 (38 million tons), T9 (34 million tons), and T10 (27 million tons), resembling acre availability under grassland.

4.3.4. Biomass allocation

4.3.4.1. Timber allocation to traditional mills

In Baseline, units mostly satisfied their timber demand other than a few exceptions. Details are presented in Chapter 3, section 3.3.4.1.1.

4.3.4.1.1. Scenario 1

Similar to Baseline, Unit 1 supplied 100% (42 million tons) of its own annual softwood pulpwood demand in all planning periods in Scenario 1 (Figure 4.7). Unit 3 did the same for itself, except for the first planning period when it imported 59% (19 million tons) of its total annual demand. Over 50 years, the highest inter-unit transportation of softwood pulpwood was Unit 3, exporting 57 million tons to Unit 4 (79% of Unit 4 demand).

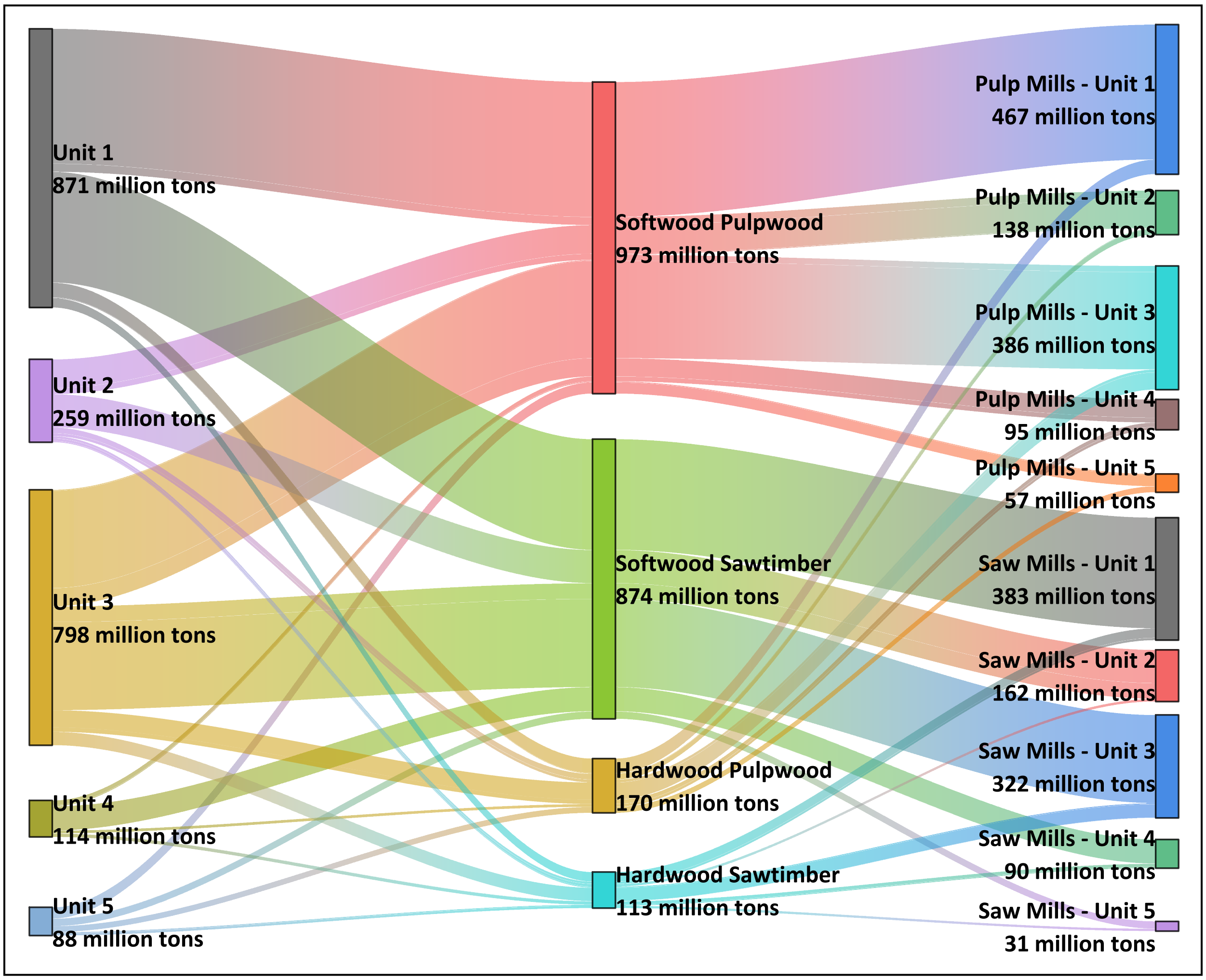

Figure 4.7: Total timber supply to traditional mills over the entire planning horizon in Scenario 1

For softwood sawtimber, other than Unit 3 exporting 49 million tons to Unit 2 (32% of demand), there was no major inter-unit transport. For hardwood pulpwood, two major timber exchanges were Unit 3 exporting 14 million tons to Unit 4 (61% of demand) and Unit 2 exporting 9.2 million tons to Unit 3 (15% of demand). Unit 1 and 5 did not import any hardwood in any planning period. For hardwood sawtimber, Unit 2 and 5 did not import any amount in any planning period. The highest inter-unit hardwood sawtimber transport was Unit 2, supplying about 7.3 million tons to Unit 1, most of which (6.2 million tons) occurred in T1 and T2. From T6 to T10, Unit 1 did not import any hardwood sawtimber. Overall, the inter-unit timber movement was higher in Scenario 1 compared to Baseline because of the additional demand in the power plant. Whereas 99% of all pulpwood demand and almost 100% sawtimber demand was fulfilled from within the unit in Baseline, 11% (108 million tons) of softwood pulpwood, 6% (50 million tons) of softwood sawtimber, 15% (25 million tons) of hardwood pulpwood, and 13% (15 million tons) of hardwood sawtimber moved inter-unit in Scenario 1.

4.3.4.1.2. Scenario 2

About 95% of total softwood pulpwood and softwood sawtimber demand, combined all units over 50 years, was satisfied from within the units (Figure 4.8). Similar to Scenario 1, Unit 1 satisfied 100% of their softwood pulpwood demand from within the unit. The highest inter-unit softwood pulpwood exchange was Unit 3, supplying 25 million tons to Unit 4 (35% of demand). While inter-unit hardwood pulpwood exchange was similar to Scenario 1 (12% or 20 million tons), hardwood sawtimber import-export was higher in Scenario 2. Approximately 36 million tons (32% of total) was exchanged between units over the planning horizon. Unit 1 was the top importer of hardwood sawtimber who imported 17.5 million tons (47% of demand) from Unit 2 and Unit 3. Similar to Scenario 1, inter-unit exchanges were higher in Scenario 2 compared to Baseline.

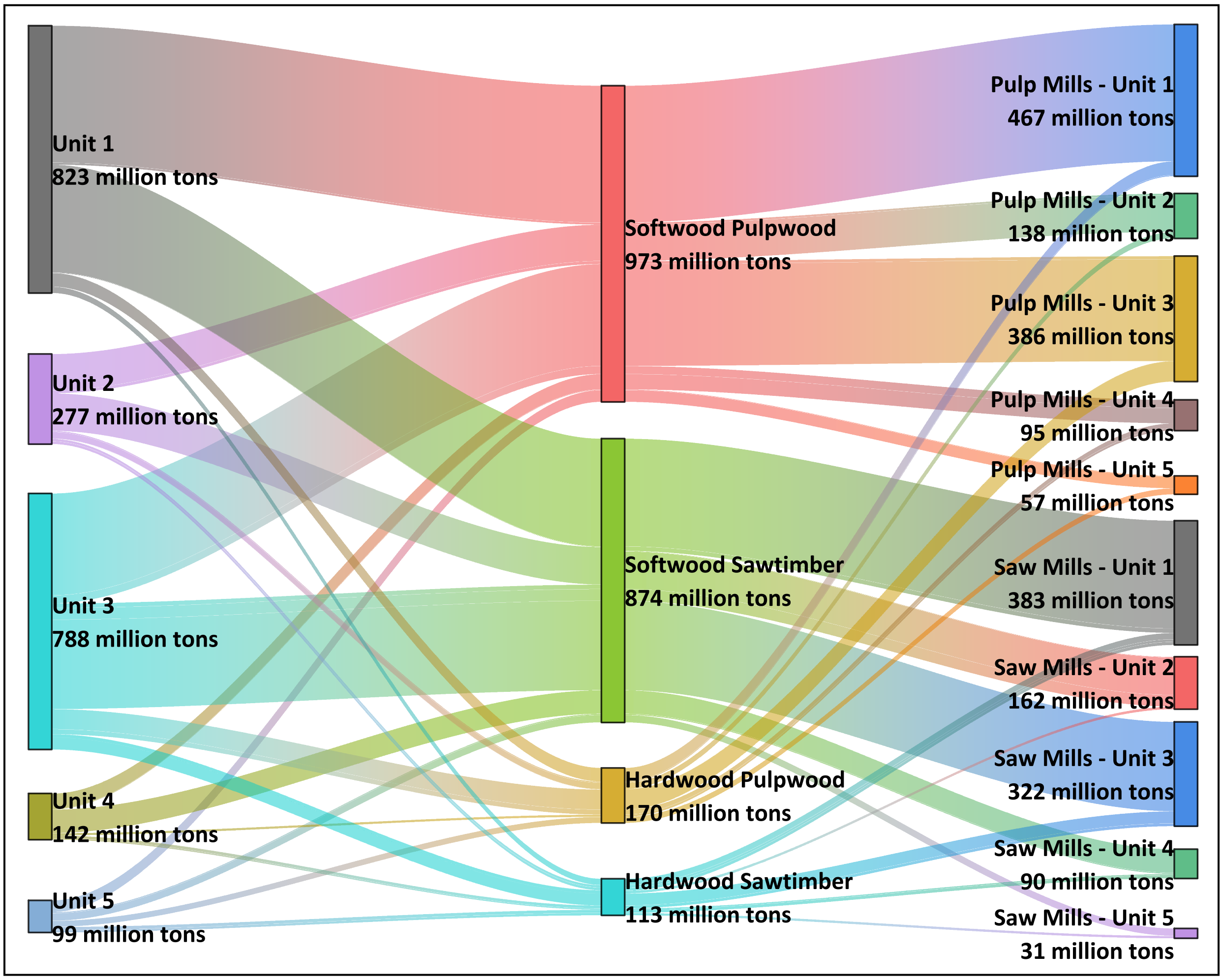

Figure 4.8: Total timber supply to traditional mills over the entire planning horizon in Scenario 2

4.3.4.2. Bioenergy allocation to power plants

Since there was no coal replacement with biomass in the Baseline scenario, no biomass was allocated to the power plants.

4.3.4.2.1. Scenario 1

We mentioned earlier that Unit 3 was the top producer of softwood pulpwood, producing 481 million tons over 50 years. However, the total softwood pulpwood supply from Unit 3 to pulp mills of all units combined (364 million tons) was lower compared to Unit 1 (447 million tons). The remaining 116 million tons produced in Unit 3 were transported to plant Scherer to replace coal (Figure 4.9).

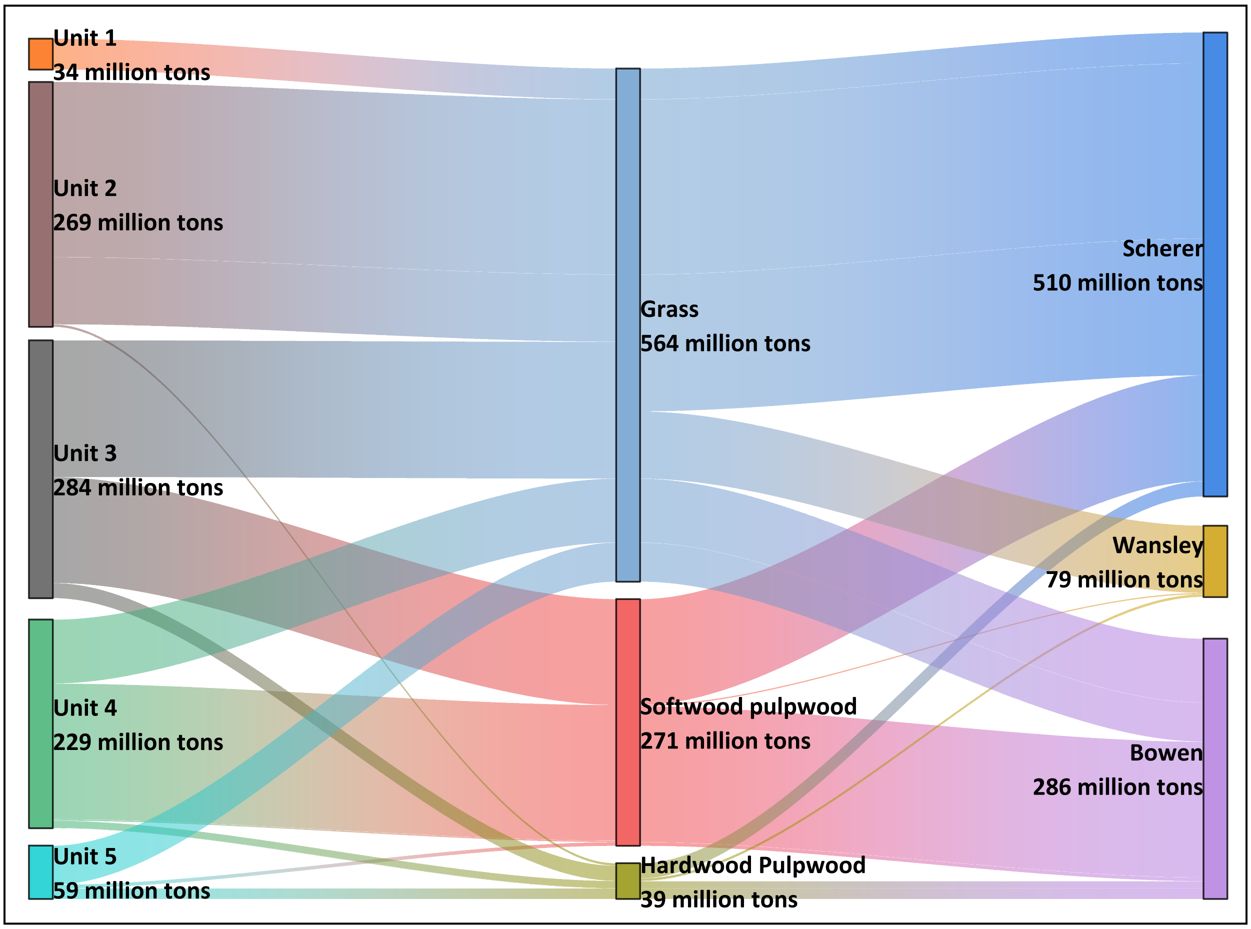

Figure 4.9 : Pulpwood and grass transported to coal power plants in Georgia in Scenario 1

Unit 3 also supplied about 17 million tons of hardwood pulpwood and 150 million tons of grasses to Scherer, which makes Unit 3 the largest supplier for Scherer satisfying 56% of its demand over

50 years. This is expected since Scherer is located in Unit 3. In total, Scherer replaced 74% of its coal with grasses and 26% with pulpwood. About 51% (193 million tons) of all the grasses received by plant Scherer came from Unit 2. Unit 2 also supplied the highest share of biomass demanded in Plant Wansley, mostly in the form of grasses (74 million tons). In total, only 6% (4.6 million tons) of biomass demand by Wansley was fulfilled by timber, the remaining 97% (74 million tons) came from grasses. Unlike Scherer and Wansley, plant Bowen got the highest share of the biomass from timber—60% or 173 million tons—of which 88% (153 million tons) was softwood pulpwood. In total, 64% (564 million tons) of the overall biomass demand in the power plant was fulfilled with grasses.

4.3.4.2.2. Scenario 2

In the presence of logging residues, only 5 million tons of grass (0.6% of total demand) was transported to the power plants during the entire planning horizon (Figure 4.10). Only plant Bowen received grass to replace coal and most of which occurred in T3 (4.3 million tons) and came from Unit 5, which was understandable given the location of Bowen. The highest share of biomass demand was met by softwood pulpwood, about 52% or 451 million tons, followed by softwood logging residues (33% or 293 million tons). The entire demand by plant Scherer, the largest coal-firing power plant in Georgia, was met by Unit 3—with about 276 million tons of softwood pulpwood, 182 million tons of softwood logging residues, 15 million tons of hardwood pulpwood, and 38 million tons of hardwood logging residues. Plant Bowen, located almost on the border of Unit 4 and Unit 5, received 205 million tons of biomass (72% of demand) from Unit 4 and 81 million tons (28% of demand) from Unit 5. Using more pulpwood (502 million tons) compared to logging residues (386 million tons) made sense as welfare was increased if more pulpwood was sold. Even though revenue would be higher if more grass was sold compared to pulpwood or logging residues, but transportation distance and cost would increase along with the cost of converting forestland to grassland.

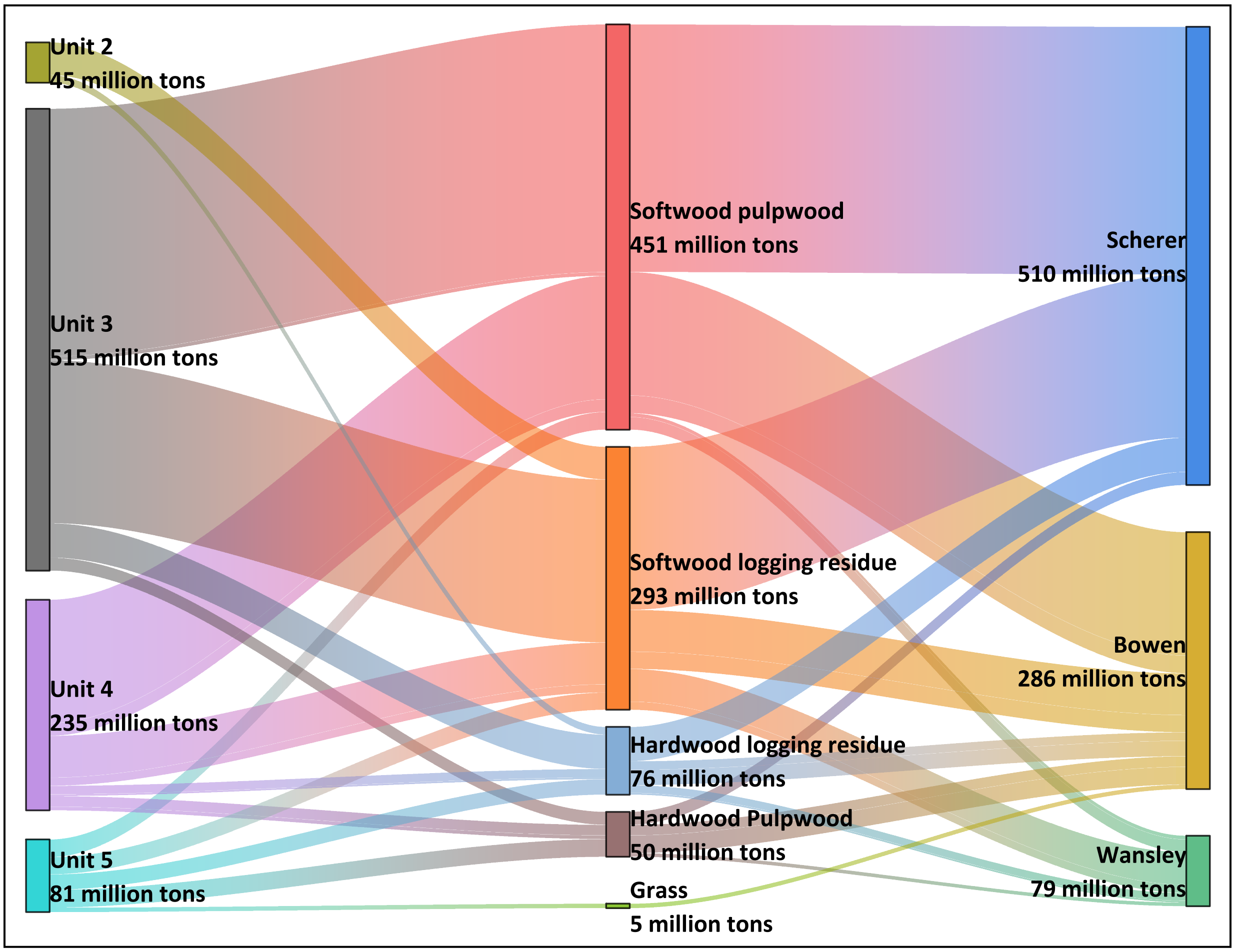

Figure 4.10: Pulpwood, logging residues, and grass transported to coal power plants in Georgia in Scenario 2

4.3.5. Carbon dynamics

4.3.5.1. Carbon in stand

In total, 577 million tons C was present in the pulpwood, sawtimber, and logging residues combined in the forests of Georgia before the planning horizon started. Approximately 289, 238, and 50 million tons C were in softwood, hardwood, and mixed stands, respectively. In the Baseline scenario, there was a net increase of 181 million tons in aboveground carbon (Figure 4.11).

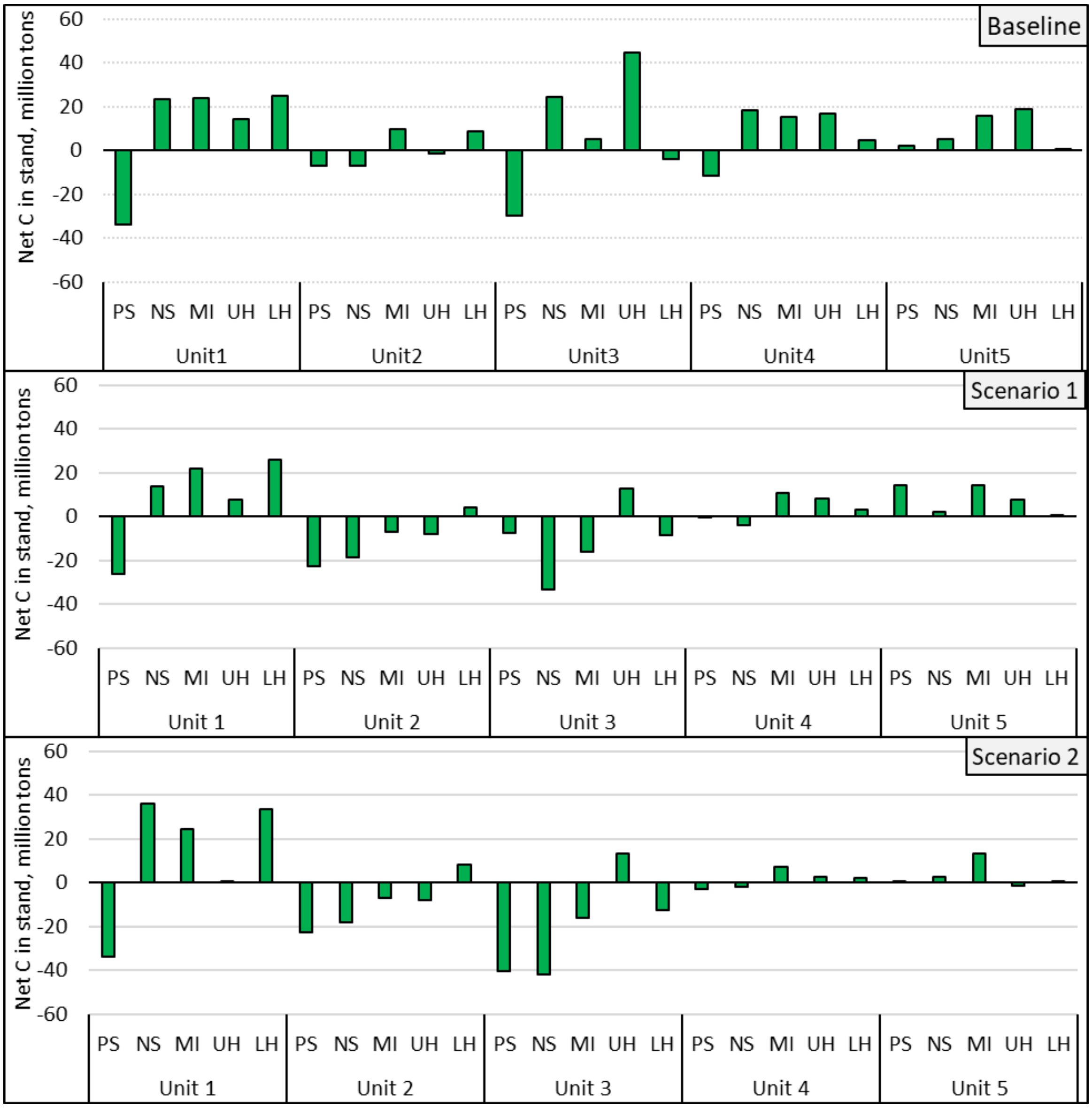

Figure 4.11: Changes in stand carbon before and after the planning horizon

In Scenario 1, the final aboveground carbon was about 570 million tons C, which was only a 1.2% decrease compared to initial carbon. However, it was 25% less than the final aboveground carbon in the Baseline scenario. Final C content in softwood, hardwood, and mixed forest was 206, 290, and 74 million tons C, respectively. Unit 1, 4, 5 experienced a net gain of C in 50 years while Unit 2 and 3 experienced net loss. This was because of the higher demands in these units, and therefore, these units were the highest producer of timber, and lands were cleared frequently and more in quantity compared to other units. The same was true for Scenario 2. However, in Baseline, no unit experienced a net loss in aboveground carbon. Carbon in planted softwood stands started with 153 million tons C before the planning horizon (Figure 4.12). In Scenario 1, after reaching the trough in T3 (84 million tons), it had a generally increasing trend. At T10, C in planted softwood stands was 110 million tons. This increase is mostly due to more land moving into planted softwood from other land uses. Scenario 2 mostly followed the Baseline trend. However, if land use change was not allowed and if land did not move in planted softwood, estimates for Scenario 2 could have been lower compared to Baseline. Because land use change was not allowed for bottomland hardwood, the C trend was similar in all three scenarios. In other stands, Baseline gained more C throughout the planning horizon.

It was interesting to observe that Scenario 2 had a lower C estimate compared to Scenario 1 because forestland increased in Scenario 2 and decreased in Scenario 1. The explanation lies in the higher annual average harvest of forestland in Scenario 2 compared to Scenario 1. As forestland to grassland conversion was expensive, more pulpwood and logging residues were collected from nearby locations that, in turn, led to more forestland harvest in Scenario 2. As a result, in Scenario 2, net C was negative for planted softwood stands, the largest land use category.

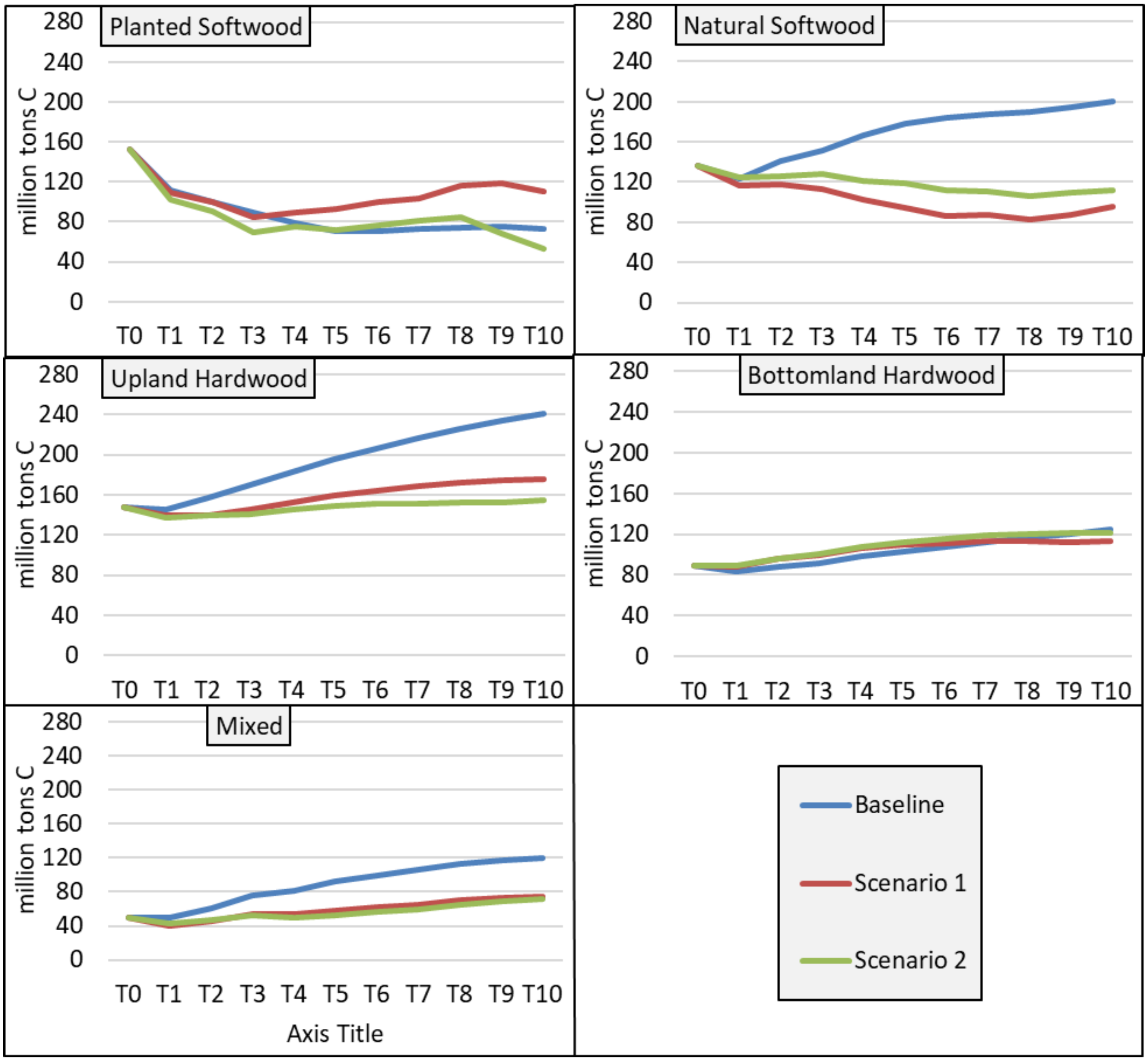

Figure 4.12: Stand carbon changes in all forest types of Georgia throughout the planning horizon*
*Note – T0 is the year before the planning horizon

4.3.5.2. Avoided C emission and net C balance

While the most carbon in forest stands was sequestered in the Baseline scenario, there was no avoided carbon emission from power generation via coal replacement. With 50% coal replacement with pulpwood and grasses, Scenario 1 had the highest net C benefit, about 246 million tons (Figure 4.13). In other words, replacing 50% carbon with pulpwood and logging residues in the presence of land use change would be better than no coal replacement in the power plants in

Georgia. Even though the same amount of coal was replaced in the power plant in both scenarios 1 and 2, Scenario 2 avoided more carbon as it used less grass, and there was less emission from pelletizing grass. Approximately 5.05 and 5.55 million tons C was avoided annually in the power sector. According to EIA (US EIA, 2018), about 12 million tons C is emitted from the power sector of Georgia. Since we replaced 50% coal, our estimates were acceptable.

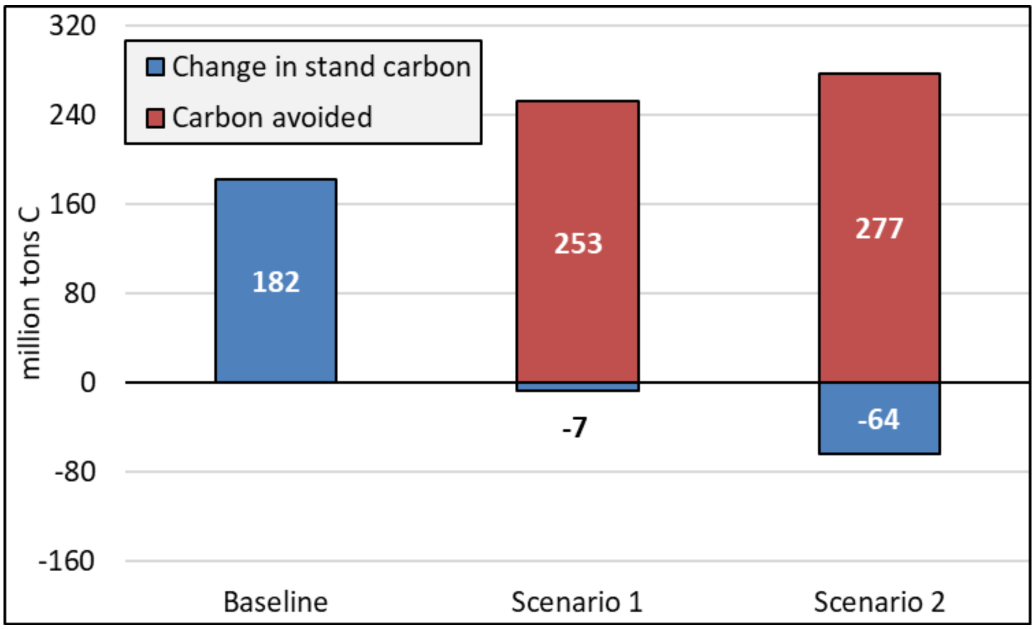

Figure 4.13: Net carbon change due to changes in stand carbon and carbon savings via coal replacement with biomass

4.3.6. Sensitivity analysis

The model provided optimal solutions for both situations, coal replaced with and without the presence of logging residues, in all percentages of coal replaced. With increasing percentages of coal replaced, forestland harvested increased in both conditions (Figure 4.14). However, it increased at a larger rate when all three feedstocks were used. In the presence of logging residues, forestland to grassland conversion was less compared to when logging residues were not used. This led to a higher forestland harvest because when logging residues were not available, forestland to grassland conversion increased with every increment in coal replacement (Figure 4.15). Conversion to grassland had almost no variation with increasing coal replaced when logging residues were used.

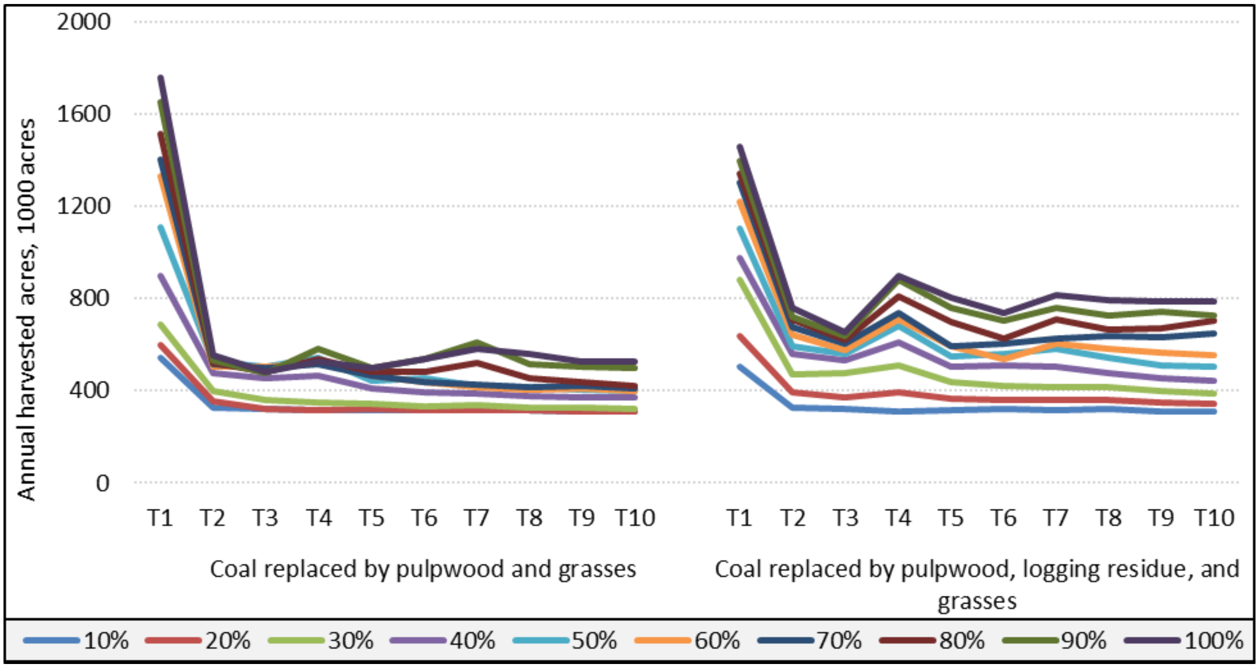

Figure 4.14: Area of forestland harvested annually under various percentages of coal replaced in power plants

From 10% to 40% of coal replaced in the power plants, no grass was used when logging residues were available (Table 4.3). Even with further increments up to 100%, only 7% of coal was replaced by grass. When logging residues were absent, grass can replace 10% coal without any pulpwood and can supply 70% biomass to replace 100% coal. Due to the combined effect of changes in stand carbon in the presence of land use change and carbon avoided in power generation, the highest C benefit was derived when 100% coal is replaced with all three feedstocks. Without logging residues, the highest C benefit was derived when 40% of coal was replaced.

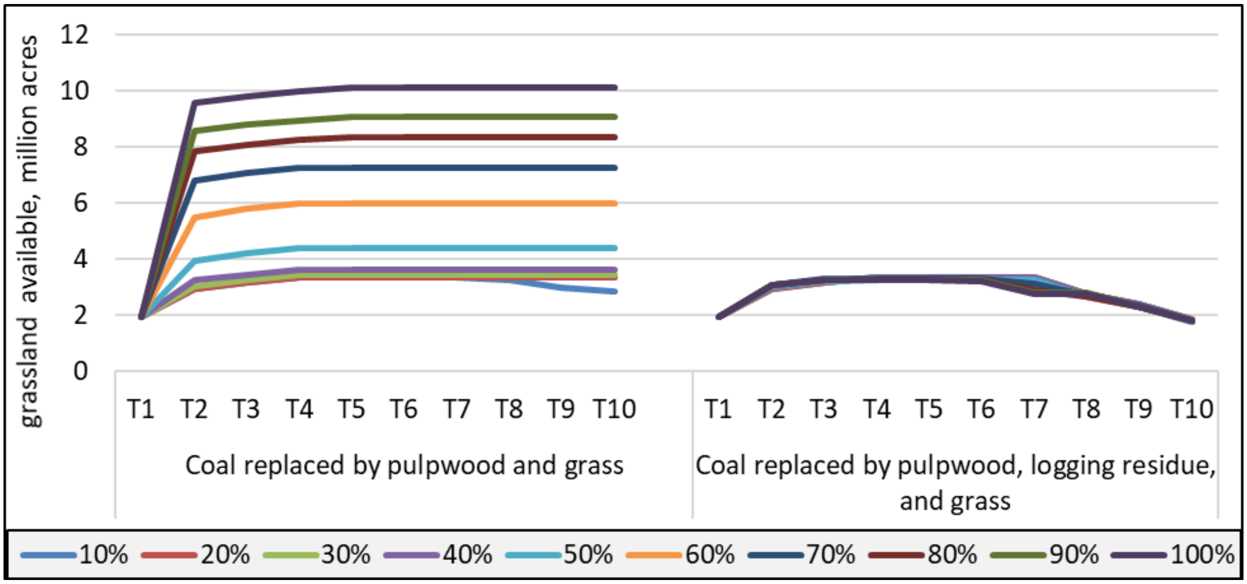

Figure 4.15: Area of grassland available under various percentages of coal replaced in power plant

Table 4.3: Share of coal replaced by grass and net carbon* changes with various level of coal replacement

	Coal replacement	% of coal replaced by grass	Change in stand carbon	Carbon avoided	Net C
			million tons C		
Coal replaced by pulpwood and grass	10%	100%	109	48	157
	20%	93%	137	97	234
	30%	83%	84	147	231
	40%	68%	52	201	252
	50%	64%	-7	253	245
	60%	72%	-85	300	216
	70%	74%	-134	348	214
	80%	74%	-213	398	185
	90%	71%	-295	450	155
	100%	71%	-362	501	139
Coal replaced by both pulpwood, logging residues, and grass	10%	0%	142	56	198
	20%	0%	98	111	210
	30%	0%	36	167	203
	40%	0%	-26	222	197
	50%	1%	-64	277	214
	60%	5%	-67	331	264
	70%	5%	-88	386	297
	80%	4%	-132	441	309
	90%	5%	-197	496	299
	100%	7%	-238	550	312

* Note – Net C may not add up due to rounding

4.4. Conclusion

In this study, we provided a thorough assessment of carbon performance if biomass replaces coal in the power plant of Georgia. We modeled optimal harvesting routine, with and without land use changes, for the next 50 years. We also provided optimal timber sourcing and allocation with and without coal replacement by biomass. We mathematically optimized for the least cost-effective ways to collect and allocate biomass to replace coal in the power plant along with satisfying traditional demand that would also maximize landowner's profit from their timberland. We showed that replacing 50% of coal with biomass increased the forestland in the presence of logging residues but decreases to grassland when logging residues are left on site. We also determined that replacing 100% coal with pulpwood, logging residues, and grasses in the presence of land use change can provide the highest carbon benefit.

The scope of this study can be expanded further by including neighboring states such as Alabama, Florida, North Carolina, South Carolina, and Tennessee. One limitation of the study was that we did not include belowground carbon in our study. Additionally, we considered poletimber from FIA inventory, and pulpwood demanded to be of equivalent size, although the diameter sizes were not an exact match. Furthermore, quantity demanded and biomass prices were constant throughout the planning horizon. Additionally, biogenic carbon emission was not included in this study. Despite these limitations, this paper painted a picture of how land use will change and how forest carbon will behave for the next 50 years. This study provided the least cost-effective ways of timber sourcing and allocation and provided guidelines to develop a sustainable supply chain of forest products in Georgia. By combining the impact of forest carbon changes and the benefit of avoiding carbon emission via coal replacement, this paper reduced the knowledge gap regarding the sustainability of biopower generation in Georgia. We expect that this article will help policymakers make an informed decision about using biomass to replace GHG intensive coal in the power sector.

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CHAPTER 5: CONCLUSION

The central theme of this dissertation was to validate the economic and environmental sustainability of using wood-based biomass to displace coal-based electricity in Georgia. In that light, this study evaluated nine biomass feedstocks that are either available or can be grown in Georgia. It modeled the least cost-effective ways of timber allocation and provided guidelines to develop a sustainable supply chain of forest products in Georgia. It also provided a comprehensive picture of the impact of timber collection and allocation on carbon benefits for the next 50 years with and without coal replacement by biomass. Additionally, it projected the future of land use change with and without the additional bioenergy demand.

The first significant conclusion from this dissertation is that wood chips are the least expensive and the least GHG intensive feedstock to replace coal. However, to be price competitive against coal, economic incentives will be required. About $8 of a carbon tax for each tonne of CO_2 emitted by coal-based electricity can make wood chips competitive in Georgia. Almost all perennial grasses will require a similar carbon tax to become competitive, but giant reed and switchgrass will require the least carbon tax. The second major conclusion this dissertation provides is that replacing coal with wood chips using pulpwood only will result in a net carbon reduction, combining both carbon in the forest stands and carbon avoided via coal replacement. In the absence of land use change, replacing 10% coal in the power plants of Georgia with both pulpwood and logging residues was the best option from carbon benefit perspectives. The third major conclusion from this dissertation is that if grassland is included and land use change is allowed, replacing

100% coal with pulpwood, logging residues, and grasses can provide the highest carbon benefit. The major argument this study makes is that biomass can be a viable alternative source for carbon reduction from electricity generation in Georgia. However, the share of coal replacement and the choice of feedstocks are important factors in obtaining the highest carbon benefit.

We expect that findings from this study will help policymakers make an informed decision about using biomass to replace coal in the power sector of Georgia. Policymakers can identify which feedstocks to incentivize to obtain maximum carbon efficiency using limited economic investment. Policymakers can also decide how much coal should be replaced in the power plants and whether to incentivize grass-based pellets for coal replacement. Additionally, this study has policy implications regarding land use change between forestland and grassland. Results from this study can also be useful for other southern states that share a similar policy and energy infrastructure, agriculture, and forestry conditions.