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Developing a supply chain model for sustainable aviation fuel using logging residues in Georgia, United States

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ABSTRACT

Sustainable aviation fuel (SAF) as a drop-in fuel from biomass feedstocks can reduce carbon emissions and provide resiliency to the aviation sector in light of the volatile nature of conventional aviation fuel (CAF) prices. This study aims to develop a supply chain model for SAF derived from unutilized logging residues across Georgia, a prominent forestry state located in the southern region of the United States. We employed a mixed-integer linear programming (MILP) model to minimize the total discounted cost of the SAF supply chain using the Ethanol-to-Jet (ETJ) production pathway over ten years of operation. Three SAF demand scenarios were selected, i.e., meeting 20 % (high), 10 % (medium), and 5 % (low) of total SAF demand at the Hartsfield-Jackson Atlanta International Airport. Results indicate a unit production cost of US \$1.92 L^{-1}, US \$2.03 L^{-1}, and US \$2.25 L^{-1} for the high, medium, and low demand scenarios, respectively. Over a period of ten years, to produce 3.74, 1.87, and 0.94 billion liters of SAF in scenarios A, B, and C, respectively, 38.5, 19.2, and 9.6 million Mg of logging residues are required. The capital investment and operating cost at biorefineries accounted for an average of 77 % and 22 % of the total unit cost, respectively, across scenarios. The GHG intensity of the SAF was 767 g CO_2e L^{-1} on average across scenarios, providing about 70 % of carbon savings relative to CAF. The supply chain model suggested 54 biomass processing units (BPUs) and 13 bio-refineries across Georgia under the high demand scenario, 27 BPUs and 7 bio-refineries under the medium scenario, and 14 BPUs and 4 bio-refineries under the low SAF demand scenario. Our study is expected to provide new insights into the emerging market of SAF in Georgia and beyond.

1. Introduction

The commercial aviation industry is responsible for 4 % of global greenhouse gas (GHG) emissions (Ritchie, 2024). However, the global consumption of conventional aviation fuel (CAF) is expected to double from 395.88 billion liters in 2018 to 883.11 billion liters in 2050 (US EIA, 2019) as more and more people are flying to meet personal and professional needs. An increase in air travel could substantially increase GHG emissions of the aviation sector, especially when other major sectors of the economy are decarbonizing at a rapid rate.

The United States alone accounted for 28 % of global aviation fuel consumption in 2022, using 62.97 billion liters (BTS, 2023; IATA, 2021a). The transportation sector in the United States is a major emitter, responsible for 28 % of the country's CO_2 emissions in 2022, and alarmingly, emissions from aircraft contribute 9 % to this sector's emissions (U.S. EPA, 2024a). Commercial air travel contributes a significant 3 % to the nation's overall greenhouse gas emissions (Overton, 2022). The Federal Aviation Administration (FAA) forecasted significant

Abbreviations: ATJ-SPK, Alcohol-to-jet Synthetic Paraffinic Kerosene; ATL, Hartsfield-Jackson Atlanta International Airport; BioGeSTO, Biofuel Supply Chain Geospatial and Temporal Optimizer; BPU, Biomass Processing Unit; CAF, Conventional Aviation Fuel; CFP, Clean Fuel Program; CHT, Catalytic hydrothermolysis; CO_2e, Carbon dioxide equivalent; ETJ, Ethanol-to-Jet; FAA, Federal Aviation Administration; FT, Fischer-Tropch; GAMS, General Algebraic Modeling System; GHG, Greenhouse gas; HTL, Hydrothermal Liquefaction; HW, Hardwood; IATA, International Air Transport Association; IRA, Inflation Reduction Act; kg, Kilogram; km, Kilometer; L, Liter; LCFS, Low Carbon Fuel Standard; LR, Logging Residue; MILP, Mixed Integer Linear Programming; MJ, Megajoule; MJSP, Minimum jet fuel selling price; Mg, Megagram/metric tons; MWh, Mega watt-hour; RFS, Renewable Fuel Standard; RIN, Renewable Identification Numbers; SAF, Sustainable Aviation Fuel; SOC, Soil Organic Carbon; SW, Softwood; TPO, Timber Product Output; US \$, United States Dollars.

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growth in air travel. Domestic traffic is expected to climb by an average of 2.3 % annually between 2025 and 2041, while international travel is projected to see even steeper growth at 3.3 % per year on average (FAA, 2021).

Alarmed by the rising emissions, the International Air Transport Association (IATA) has set an ambitious goal of reducing CO_2 emissions by 64 % by 2050. This translates to a significant reduction from 915 million Mg in 2019 to just 315 million Mg of CO_2e by mid-century (IATA, 2021b). To ensure a sustainable future, the aviation industry aims to achieve net-zero carbon emissions by 2050 through the widespread use of Sustainable Aviation Fuel (SAF), continued investment in innovative technologies, and improvement in airline efficiency (IATA, 2022a). While innovative technologies like hydrogen and electric-powered aircraft can potentially curb emissions by up to 13 % – their current feasibility is limited to shorter flights (less than three hours) (Bergero et al., 2023). On the contrary, SAF derived from biomass feedstock can contribute up to 65 % towards achieving net-zero carbon emissions (IATA, 2022a).

Transitioning from CAF to SAF derived from biomass offers a powerful solution for the aviation sector's growing need to minimize its greenhouse gas footprint. SAF production does not negatively impact food production, biodiversity, soil fertility, land clearing, or other crucial environmental factors (IATA, 2023). Previous studies of life cycle carbon emissions of SAF derived from oilseed crops show that potential CO_2 emission savings range between 50 % and 84 % than petroleum-based CAF (Alam et al., 2021; Fan et al., 2013; Lokesh et al., 2015; Zhu et al., 2022). The life cycle GHG emissions of SAF derived from lignocellulosic biomass such as sugarcane bagasse, corn stover, and switchgrass ranged from 13 % to 85 % compared to CAF (De Jong et al., 2017; Santos et al., 2018; Staples et al., 2014; Zhu et al., 2022).

In the United States, the SAF Grand Challenge aims to achieve annual production of SAF up to 3 billion gallons (11.36 billion liters) by 2030 or 35 billion gallons (132.5 billion liters) by the year 2050 (US DOE, 2021a). The SAF blenders tax credit (NBAA, 2021), proposed in the Sustainable Skies Act (Congress.gov, 2021) and approved in the Inflation Reduction Act (IRA) 2022, aims to provide tax credits to the producers of SAF ranging from \$0.33 L^{-1} up to \$0.46 L^{-1} depending on the reduction potential of the life cycle carbon emissions (US DOE, 2022). The federal government offers a loan guarantee program of up to \$250 million to support the development and manufacturing of advanced biofuels, including SAF. However, to be eligible, projects must be located within the country (USDA Rural Development, 2022). To incentivize production, the second-generation biofuel producer tax credit was amended in 2020 to offer a credit of \$0.27 L^{-1} for fuel derived from lignocellulosic biomass. This tax credit expired in January 2022 (U. S. DOE, 2022). The Renewable Fuel Standard (RFS) introduced a taxable credit called RINs (Renewable Identification Numbers) to incentivize the mixing of renewable fuels like ethanol or biodiesel into conventional gasoline and diesel (U.S. EPA, 2024b). SAF can qualify for this credit based on production pathway and biomass feedstock choice (U.S. EPA, 2024c). California's Low Carbon Fuel Standard (LCFS) and Oregon's Clean Fuel Program (CFP) also incentivize the use of SAF by awarding credits based on its potential to reduce GHG emissions (IATA, 2022b; Oregon Department of Environmental Quality, 2021). While the high production cost of SAF remains a major obstacle for airline companies, these policies could potentially make SAF competitive with CAF.

The use of SAF is also gaining popularity among commercial airlines (IEA, 2022). Delta Airlines aims to replace 10 % of its CAF usage with SAF by 2030 (Delta News, 2021). Until now, SAF has been used in more than 490 thousand flights. To achieve net-zero carbon emissions by 2050, SAF production needs to skyrocket to a staggering 449 billion liters, whereas global SAF production in 2023 was only 600 million liters (IATA, 2023). This necessitates accelerating the production of SAF through investment in appropriate technologies and sustainable feedstocks.

Interest in SAF production from woody biomass collected from forest residues after harvest operations is continually growing. Logging residues can be defined as lignocellulosic biomass, including treetops and branches left unutilized after commercial harvest and thinning operations (USDA FS, 2023). The logging residues are either collected into piles and burned or left on the ground to decompose. Burning of logging residues can result in increased GHG emissions as well as wildfire hazards (Springsteen et al., 2011). Around 17.24 million Mg of logging residues are recovered annually from forest sites in the United States (Davis et al., 2024). Although 98 % of the logging residues could be recovered within 56.3 km (35 miles) of hauling distance from mills, only 4 % of them were utilized by the mills (Pokharel et al., 2019). Producing SAF from logging residues could be one of the uses of this unutilized biomass while simultaneously replacing CAF to mitigate climate change.

SAF can be produced using woody logging residues as feedstocks following Fischer-Tropch (FT), Hydrothermal Liquefaction (HTL), Alcohol-to-jet (ATJ), and pyrolysis-based production pathways. Several studies have found that SAF produced from forest residues can reduce GHG emissions from 42.5 % to 91 % compared to coal-based CAF (Almena et al., 2024; Björnsson and Ericsson, 2024; Ganguly et al., 2018; Michaga et al., 2022; Puschnigg et al., 2023; Ringsred et al., 2021; Zhu et al., 2022). However, the minimum jet fuel selling price (MJSP) of woody biomass-based SAF ranged between \$0.83 L^{-1} and \$2.70 L^{-1}, making it economically infeasible compared to CAF (Brandt et al., 2022; Brandt et al., 2020; Seufitelli et al., 2022; Tanzil et al., 2021). Fan et al. (2024) explored spatial variation of breakeven cost and GHG intensity of ATJ-based SAF from different feedstocks. Switchgrass from the Southeast produced the highest yield, resulting in the lowest breakeven cost (\$1.4 L^{-1}) and the lowest GHG intensity (−31[1] g CO_2e MJ^{-1}) with the most soil organic carbon (SOC) sequestration. Akter et al. (2024) found that the MJSP of logging residues-based SAF produced using ethanol-to-jet (ETJ) pathway ranged between \$2.71 L^{-1} to \$0.83 L^{-1}, depending on co-product credit and different federal incentives.

A closer look at the existing studies suggests that most existing studies have analyzed the unit production cost and carbon savings of SAF produced using wood-based feedstocks only on per unit area level. This severely restricts our understanding of commercializing the use of woody feedstocks for SAF production, as it is critical to understand the supply chain level unit production cost and carbon intensity of SAF production to make informed investment decisions. Only a handful of studies have analyzed the supply chain level economic and environmental attributes related to sustainable biofuel development (Gilani and Sahebi, 2020; Jeong et al., 2019; Leila et al., 2018; León-Olivares et al., 2020; Sharifzadeh et al., 2015). Masum et al. (2023) employed a cost-minimizing mixed integer linear programming (MILP) model to determine the optimum locations of storage units, oil extraction facilities, and biorefineries for carinata-based SAF production. Huang et al. (2019) developed a MILP model for the multi-objective optimization of corn stover-based SAF supply chain following ATJ, FT, and HTL production pathways in the Midwestern United States. They concluded that a centralized supply chain system with large facilities is economically viable, whereas distributed systems with small refineries offered environmentally optimum decisions. Ebrahimi et al. (2022) investigated the impact of direct monetary policies on carinata-based SAF supply chain in the southeastern United States employing the MILP model. However, a closer look into existing studies suggests that no study has evaluated the role of scale on the unit production cost and carbon intensity of logging residues-based SAF production; again, a critical gap as potentially, at larger scales, the unit production cost and carbon intensity could reduce significantly, thereby, supporting the nationwide policy targets.

In this context, the study aimed to develop a supply chain model for SAF derived from unutilized logging residues from harvest and thinning

[1] Negative emission indicates the system sequesters more carbon than it releases during the life cycle of SAF production

operations across Georgia. A cost-minimizing MILP model was formulated to develop the optimal supply chain system of logging residues-based SAF production using the ATJ production pathway to meet the SAF demand at the Hartsfield-Jackson Atlanta International (ATL) Airport. The ATJ process was estimated to be the most cost-effective lignocellulosic biomass-based SAF production route from an economic perspective (Alves et al., 2017; Neuling and Kaltschmitt, 2018). The optimal location of biomass processing units (BPUs) and biorefineries and the flow of materials over 10 years in the supply chain were determined by the MILP model. Additionally, based on the information generated from the developed supply chain model, this study estimates the unit cost and carbon intensity of produced SAF at three different scales for assessing the role of different SAF demands on the overall costs and reduction in carbon emissions. Together, this study will provide insights into the sustainable management of logging residues for SAF production in Georgia, and, therefore, would support the development of a resilient bioeconomy in the region.

2. Methods

2.1. Study area

Georgia, a prominent forestry state located in the Southern United States, was selected as the study area. Private forestlands cover almost 90 % of all the forestlands (8.9 million hectares) in the state (Georgia Forestry Association, 2023). The state provides 4 % of the national roundwood products (Oswalt et al., 2019). The state also accounts for 11.1 % of the national export of forest products, and the economic impact of the industry was $42 billion in 2022 (Georgia Forestry Association, 2023). Around 13 % of the total softwood (SW) volume and 23 % of the total hardwood (HW) volume were left on the ground unutilized after harvest as logging residues in Georgia (Wall et al., 2018). The state produces 1.45 dry million Mg of hardwood and 2.41 dry million Mg of softwood logging residues each year (Whitley, 2021), which can be utilized as a source of cellulosic biomass to make SAF by using the appropriate production pathways (Fig. 1). Furthermore, the ATL airport in Georgia witnessed a significant rise in passenger traffic, reaching 104.7 million in 2023, reflecting an 11.7 % growth rate (AtlantaAirport.info, 2023). The economic engine of Atlanta, ATL airport, generates a direct economic impact of $66 billion (Business Focus, 2024). The growing aviation industry necessitates a vast supply of aviation fuel, ranking the state as the 6th largest consumer nationwide (US EIA, 2021).

2.2. Production pathway

We followed the ETJ production pathway to produce SAF from the available logging residues. ETJ pathway involves hydrolysis of cellulosic biomass to extract polymer sugar, and the sugar is then fermented to produce alcohol. The ETJ process utilizes dilute acid pretreatment, a chemical process that disrupts the lignocellulosic structure of biomass, before enzymatic hydrolysis (Hamelinck et al., 2005). The produced alcohol then goes through dehydration, oligomerization, hydrogenation, and finally, fractionation of the paraffinic product to produce drop-in ATJ-SPK (Alcohol-to-Jet Synthetic Paraffinic Kerosene) fuel (Doliente et al., 2020; Geleynse et al., 2018). Renewable diesel, gasoline, and electricity are also produced as co-products along with SAF in the ETJ process (GREET, 2022). SAF is a drop-in fuel meaning it can be blended directly with CAF without any alteration of the aircraft due to comparable properties. The blending limit of SAF is determined by the ASTM D7566 standards based on the conversion pathway and feedstock choices (Wang et al., 2024). SAF produced by the ETJ process is certified by the ASTM D7566 and approved for a maximum 50 % blend with CAF (Geleynse et al., 2018). Fig. 2 provides a more detailed illustration of the ETJ production pathway.

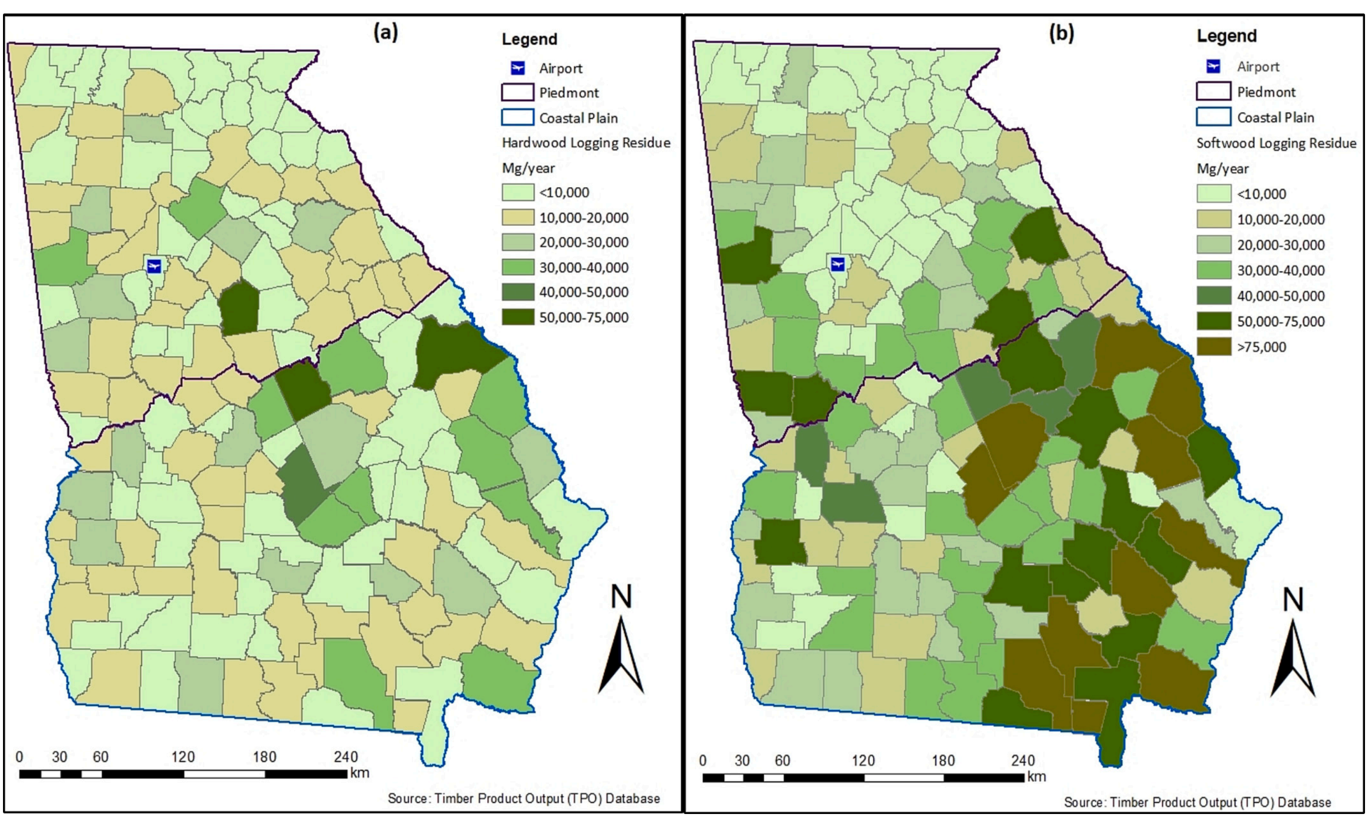

Fig. 1. Average annual availability of logging residues in Georgia between 2011 and 2020. (a): Hardwood, (b): Softwood.

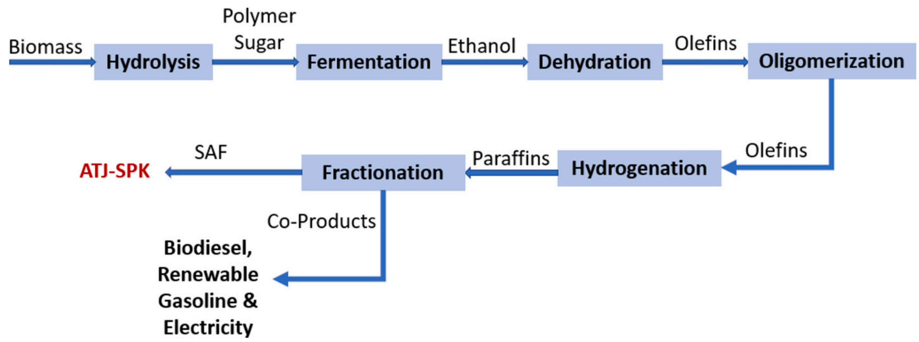

Fig. 2. A generalized system layout of ETJ-based SAF production pathway (Geleynse et al., 2018).

2.3. System boundary

The system boundary of the logging residues-based SAF supply chain model is shown in Fig. 3. The system boundary included 159 counties of Georgia as the supply nodes, biomass processing units (BPU) and biorefinery and the ATL airport as the demand node. The system boundary started by collecting softwood and hardwood logging residues in the forms of tops and limbs from forest stands in each of the 159 counties of Georgia. The estimates of each county's softwood and hardwood logging residues were obtained from the Timber Product Output (TPO) database for 10 years (2011–2020). Following harvest, logging residues are left on the stand to undergo natural transpirational drying, reducing their moisture content from 50 % to 18 % over time (Greene et al., 2014; Roise et al., 2013). We assumed that logging residues were collected with 30 % moisture content. The logging residues are then chipped to a particle size of 5 cm and loaded in the chip truck with an average payload of 25.4 green Mg (Taylor et al., 2014). We accounted for 5 % of dry material loss during the processing of logging residues through chipping (Hartley et al., 2018). The collected hardwood and softwood chipped logging residues would be transported in the chip truck separately to the BPUs, where the residues will be processed through grinding to reduce the particle size to 3 mm (Vidal et al., 2011) and dried to a moisture content of 10 % (Hartley et al., 2018). Drying and size reduction of biomass are critical steps that significantly enhance the effectiveness of biorefinery processes. By reducing moisture content and increasing surface area, these processes improve substrate uniformity and accessibility for the subsequent process (El Hage et al., 2023). The processed dry biomass would then be transported to the biorefineries. Finally, SAF produced in biorefineries would be transported to ATL airport. From the initial exploratory analysis, we found that annually, on average, 519 million liters of SAF can be supplied to the ATL airport from the available logging residues (both hardwood and softwood).

2.4. Mathematical modeling

We used Eq. (1) to estimate the SAF demand at the ATL airport.

$$D_{a,t} = PS \times GA_{CAF,t} \times b2L \times B_{SAF} \tag{1}$$

where $D_{a,t}$ refers to the demand for SAF at ATL airport at year t, PS is the average percentage share of the passengers on board at ATL airport, 96.74 % (BTS, 2022), $GA_{CAF,t}$ is the amount of CAF in barrels consumed in Georgia at year t, which is reported in Table S1a (US EIA, 2022a), $b2L$ is the ratio of barrels to liters for aviation fuel in the United States (1 barrel = 159 L), B_{SAF} is the maximum blend level of SAF with CAF, which is 50 % for the ETJ pathway (US DOE, 2021b). We assume that the percentage share of passengers on board at any airport is proportional to the consumption of CAF in that airport. The estimated demand is reported in Supplementary Table S1b. The trajectory of SAF demand at ATL airport following Eq. (1) is illustrated in Fig. 4. The demand for SAF ranged between 1.13 billion liters and 2.07 billion liters from 2011 to 2020. Annually, on average, around 28.64 % of demand can be met by the available supply of logging residues in Georgia. However, due to the COVID-19 Pandemic, the consumption of CAF went down, consequently lowering the SAF demand in Fig. 4. The supply of logging residue did not change drastically in 2020; therefore, the supply of SAF exceeded the demand, as represented by the opposite direction of supply and demand in Fig. 4.

We employed MILP in the General Algebraic Modeling System (GAMS) studio, version 31.2.0, which solved the model using a CPLEX solver. The dynamic supply chain optimization model was used to minimize the total cost of the process along with finding suitable locations to build BPUs and biorefineries across Georgia. All the sets, parameters, and variables used in the model are reported in Tables 1, 2, and 3, respectively. The values of the parameters and scalars used in the model are reported in Table 4.

Distances between one county to another county and from each county to the airport are reported in Supplementary Tables S2 and S3. Moreover, the availability of softwood and hardwood logging residues are provided in Supplementary Tables S4 and S5.

Eq. (2) represents the objective function of the cost-minimizing supply chain model where Eqs. (3)–(5) and Eq. (9) were used to estimate the variables in Eq. (2).

$$\begin{aligned} Minimize\ TotalCost = min(&CollectionCost + CapitalCost + ProcessingCost \\ &+ TransportCost) \end{aligned} \tag{2}$$

$$CollectionCost = \sum_{c,t} VLRSW_{c,t} \times CSWLR_{c,t} + \sum_{c,t} VLRHW_{c,t} \times CHWLR_{c,t} \tag{3}$$

$$CapitalCost = \sum_{b} NBPU_b \times CCapBPU + \sum_{r} NRef_r \times CCapRef \tag{4}$$

$$ProcessingCost = \sum_{b,t} PVBPU_{b,t} \times PCBPU_{b,t} + \sum_{r,t} PVRef_{r,t} \times PCRef_{r,t} \tag{5}$$

$$TCCB_{c,b,t} = HR\_CB_{c,t} \times MinHD + IHR\_CB_{c,t} \times Id\_CB_{c,b} \tag{6}$$

$$TCBR_{b,r,t} = HR\_BR_{b,t} \times MinHD + IHR\_BR_{b,t} \times Id\_BR_{b,r} \tag{7}$$

$$TCRA_{r,a,t} = F\_RA_{r,t} \times \mathrm{d}\_RA_{r,a} \tag{8}$$

$$\begin{aligned} TransportCost = &\sum_{c,b,t} VTSW_{c,b,t} \times TCCB_{c,b,t} + \sum_{c,b,t} VTHW_{c,b,t} \times TCCB_{c,b,t} \\ &+ \sum_{b,r,t} VTDB_{b,r,t} \times TCBR_{b,r,t} + \sum_{r,a,t} VTSAF_{r,a,t} \times TCRA_{r,a,t} \end{aligned} \tag{9}$$

Eqs. (6)–(8) were used to estimate various types of transportation costs. The cost of transporting chipped logging residues from each county to BPUs was estimated in Eq. (6). The cost for transporting dry

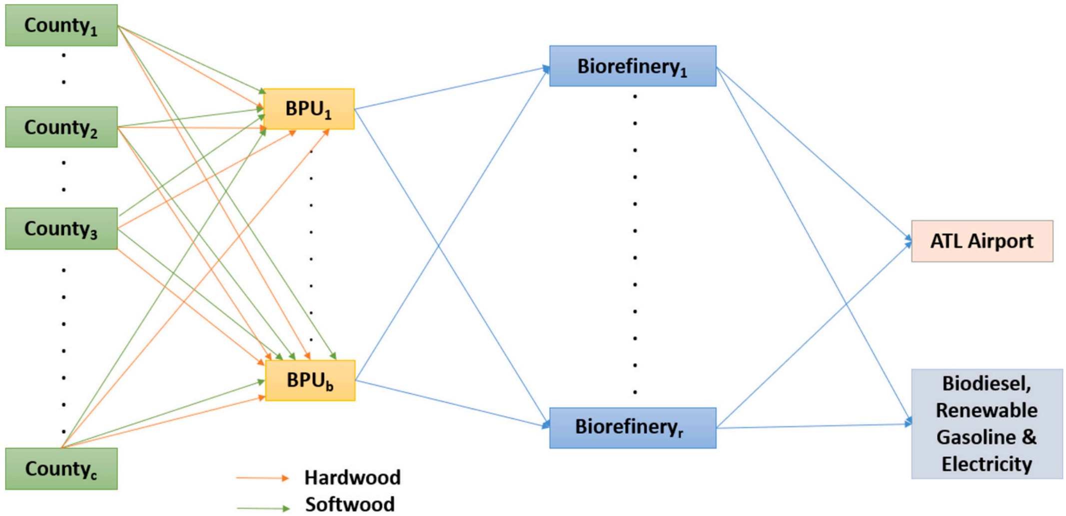

Fig. 3. System boundary of logging residues-based SAF supply chain model in Georgia. BPU refers to the biomass processing unit whereas BPU_b and $Biorefinery_r$ refer to the b^{th} number of biomass processing unit and r^{th} number of biorefinery, respectively.

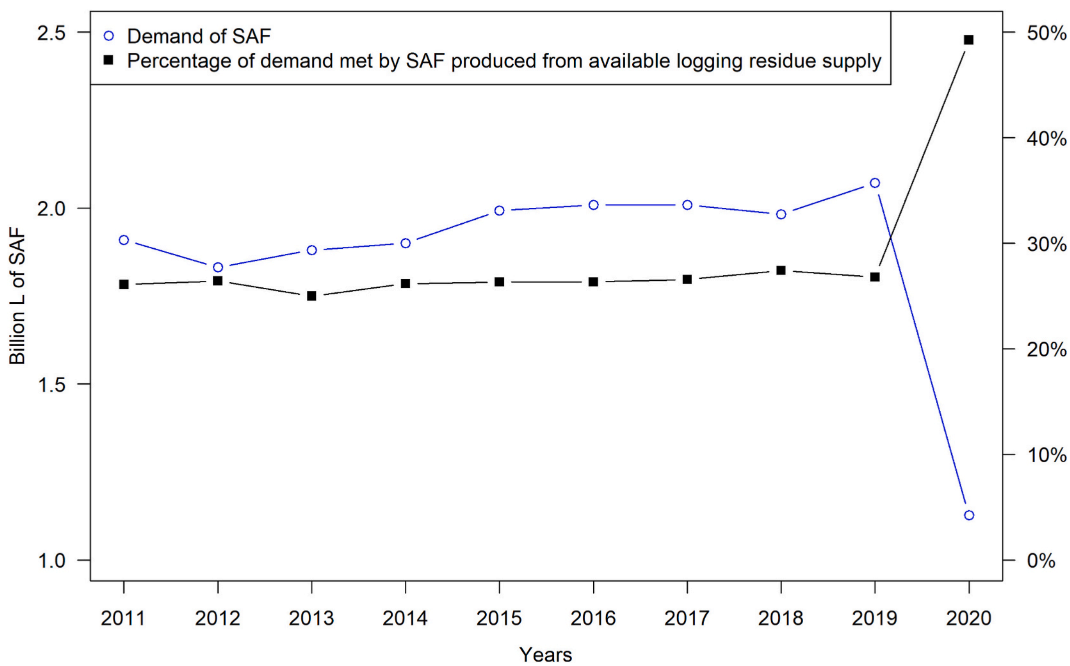

Fig. 4. Trajectory of SAF demand at the Hartsfield-Jackson Atlanta International Airport in Georgia between 2011 and 2020 and the share of demand that can be met by the SAF derived from the available logging residue supply in the state for the same period.

biomass from BPUs to biorefineries is shown in Eq. (7). The transportation costs in Eqs. (6) and (7) were computed by multiplying the minimum haul distance (*MinHD*), 64 km (40 miles) for the Southern States, with the minimum haul rate following the work of Conrad (2021). When the actual one-way distance exceeds the *MinHD,* each incremental distance above the *MinHD* was multiplied by the incremental haul rate, finally estimating the total cost of transporting biomass. The transportation cost of SAF from biorefineries to ATL airports was estimated in Eq. (8), where the fuel transport rate was multiplied by the distance from the biorefinery to the airport.

The cost of collecting logging residues from forest stands after harvest and thinning operations was \$1.65 green Mg^{-1} for softwood (Masum et al., 2022) and \$1.98 green Mg^{-1} for hardwood (assumption) for year 1, which was discounted by a 5 % rate for the remaining years. Moreover, the chipping cost of logging residues at the forest landing was \$7.45 green Mg^{-1}, whereas the grinding and drying costs at BPU were \$7.15 green Mg^{-1} and \$15.82 green Mg^{-1} for year 1, respectively (Jacobson et al., 2016).[2] The cost parameters were then discounted for the subsequent years by a 5 % rate. The discount rate for the supply chain was assumed to be 5 % based the similar study on the existing literature (Akter et al., 2024; Leila et al., 2018; Li et al., 2024; Masum et al., 2023).

The constraints of the model are illustrated in Eqs. (10)–(21).

$$VLRSW_{c,t} \le ASWLR_{c,t} \times (1 - MRTD) \text{ for every } c \text{ and } t \tag{10}$$

$$VLRHW_{c,t} \le AHWLR_{c,t} \times (1 - MRTD) \text{ for every } c \text{ and } t \tag{11}$$

[2] The reported value of Jacobson et al. (2016) were adjusted for 2022 USD for an annual inflation rate of 3.36 % (U.S. Bureau of Labor Statistics, 2023)

Table 1
Description of sets and scalars used in the model and the associated equation number.

Sets	Definition	
c	Each of 159 counties in Georgia	
b	Location where BPUs can be built	
r	Location where biorefineries can be built	
a	Airport	
t	Time period in years (2011 to 2020)	
Scalars		Equation #
CCapBPU	Capital cost of establishing BPUs in each county ($)	(4)
CCapRef	Capital cost of establishing biorefinery in each county ($)	(4)
MRTD	Moisture reduction in the field by natural transpirational drying (%)	(10) & (11)
LR2CB	Conversion rate of logging residue to chipped biomass (green Mg green Mg^{-1})	(12) & (13)
CB2DB	Conversion rate of chipped biomass to processed dry biomass (dry Mg green Mg^{-1})	(16)
DB2SAF	Conversion rate of processed dry biomass to SAF (L Mg^{-1})	(19)
CTBPU	Annual capacity of each BPU (green Mg year^{-1})	(15)
CTRef	Annual capacity of each biorefinery (dry Mg year^{-1})	(18)
MinHD	Minimum haul distance (km)	(6) & (7)
DS	Percentage share of total SAF demand to be satisfied at the airport	(21)

Table 2
Description of parameters used in the model.

Parameters	Definition	Equation #
$CSWLR_{c,t}$	Cost of collecting & chipping softwood logging residues from county c at year t ($ green Mg^{-1})	(3)
$CHWLR_{c,t}$	Cost of collecting & chipping hardwood logging residues from county c at year t ($ green Mg^{-1})	(3)
$ASWLR_{c,t}$	Initial availability of softwood logging residues at county c during year t (green Mg)	(10)
$AHWLR_{c,t}$	Initial availability of hardwood logging residues at county c during year t (green Mg)	(11)
$PCBPU_{b,t}$	Processing cost of logging residues at BPU b during year t ($ green Mg^{-1})	(5)
$PCRef_{r,t}$	Processing cost of biomass at biorefinery r during year t (*$ dry Mg*$^{-1}$)	(5)
$HR\_CB_{c,t}$	Minimum haul rate for transporting logging residue from counties to BPUs at year t ($ green Mg^{-1} km^{-1})	(6)
$IHR\_CB_{c,t}$	Incremental haul rate for transporting logging residue from counties to BPUs at year t ($ green Mg^{-1} km^{-1})	(6)
$HR\_BR_{b,t}$	Minimum haul rate for transporting biomass from BPUs to biorefineries at year t ($ dry Mg^{-1} km^{-1})	(7)
$IHR\_BR_{b,t}$	Incremental haul rate for transporting biomass from BPUs to biorefineries at year t ($ dry Mg^{-1} km^{-1})	(7)
$F\_RA_{r,t}$	Freight cost of SAF from biorefineries to airports at year t ($ L^{-1} km^{-1})	(8)
$Id\_CB_{c,b}$	Incremental haul distance above 64 km from county c to BPU b (km)	(6)
$Id\_BR_{b,r}$	Incremental haul distance above 64 km from BPU b to biorefinery r (km)	(7)
$d\_RA_{r,a}$	Distances from biorefinery r to airport a (km)	(8)
$TCCB_{c,b,t}$	Transportation cost of logging residues from counties to BPUs at year t ($ Mg^{-1})	(6) & (9)
$TCBR_{b,r,t}$	Transportation cost of dry biomass from BPUs to biorefinery at year t ($ Mg^{-1})	(7) & (9)
$TCRA_{r,a,t}$	Transportation cost of SAF from biorefineries to airport at year t ($ L^{-1})	(8) & (9)
$D_{a,t}$	Demand of SAF at airport a during year t (L)	(1) & (21)

$$\sum_b VTSW_{c,b,t} \leq VLRSW_{c,t} \times LR2CB \text{ for every } c \text{ and } t \tag{12}$$

$$\sum_b VTHW_{c,b,t} \leq VLRHW_{c,t} \times LR2CB \text{ for every } c \text{ and } t \tag{13}$$

Eq. (10) and Eq. (11) state that the amounts of softwood and hardwood logging residues collection cannot exceed the available supply of them after the moisture reduction (20 %) in the field by natural drying in each county. Eq. (12) and Eq. (13) denote the conversion of logging residues to chipped biomass and the chipped biomass transported to the BPUs from counties cannot exceed the biomass collected for softwood and hardwood logging residues after accounting for material losses during chipping, respectively.

Table 3
Description of variables declared in the model.

Variables	Definition	Equation #
$VLRSW_{c,t}$	Volume of softwood logging residue collection from county c at year t (green Mg)	(10)
$VLRHW_{c,t}$	Volume of hardwood logging residue collection from county c at year t (green Mg)	(11)
$PVBPU_{b,t}$	Volume of chipped logging residues processed at BPU b at year t (green Mg)	(14)–(16)
$PVRef_{r,t}$	Volume of biomass processed at biorefinery r at year t (dry Mg)	(17)–(19)
$VSAF_{a,t}$	Volume of SAF supply at airport a during year t (L)	(20) & (21)
$NBPU_b$	Number of BPUs to be built in each county (integer)	(15)
$NRef_r$	Number of biorefineries to be built in each county (integer)	(18)
$VTSW_{c,b,t}$	Volume of chipped softwood logging residues transported from county c to BPU b during year t (green Mg)	(9) & (14)
$VTHW_{c,b,t}$	Volume of chipped hardwood logging residues transport from county c to BPU b during year t (green Mg)	(9) & (14)
$VTDB_{b,r,t}$	Volume of dry biomass transport from BPU b to biorefinery r during year t (dry Mg)	(9) & (17)
$VTSAF_{r,a,t}$	Volume of SAF transport from biorefinery r to airport a during year t (L)	(9) & (20)

Table 4
The reported values of parameters and scalars used in the model.

Parameters	Value	Equation #	Reference
CCapBPU	$5.05 million	(4)	(Jacobson et al., 2016; Lamers et al., 2015)
CCapRef	$415 million	(4)	(Geleynse et al., 2018; Humbird et al., 2011)
$CSWLR_{c,t}$	$9.1 green Mg^{-1}	(3)	(Jacobson et al., 2016;
$CHWLR_{c,t}$	$9.43 green Mg^{-1}	(3)	Masum et al., 2022)
MRTD	20 %	(10) & (11)	(Hartley et al., 2018)
LR2CB	0.95	(12) & (13)	
CB2DB	0.80	(16)	
DB2SAF	141.21 L Jet Mg^{-1} dry biomass	(19)	(GREET, 2022)
CTBPU	68,138 green Mg of chipped logging residues per year	(15)	(Lamers et al., 2015)
CTRef	244,159 Mg of dry biomass per year	(18)	(Geleynse et al., 2018)
$PCBPU_{b,t}$	$22.96 Mg^{-1} of Logging residues processed*	(5)	(Jacobson et al., 2016)
$PCRef_{r,t}$	$77.8 Mg^{-1} of dry biomass processed*	(5)	(Geleynse et al., 2018)
MinHD	64 km	(6) & (7)	
$HR\_CB_{c,t}$	$0.13 Mg^{-1} km^{-1}**	(6)	(TimberMart-South, 2022)
$IHR\_CB_{c,t}$	$0.13 Mg^{-1} km^{-1}**	(6)	
$HR\_BR_{b,t}$	$0.13 Mg^{-1} km^{-1}**	(7)	
$IHR\_BR_{b,t}$	$0.13 Mg^{-1} km^{-1}**	(7)	
$F\_RA_{r,t}$	$0.0001 L^{-1} km^{-1}**	(8)	(Masum et al., 2022)

$$PVBPU_{b,t} \leq \sum_b VTSW_{c,b,t} + \sum_b VTHW_{c,b,t} \text{ for every } c \text{ and } t \tag{14}$$

$$PVBPU_{b,t} \leq NBPU_b \times CTBPU \text{ for every } b \text{ and } t \tag{15}$$

Table 5
List of co-products generated, and their conversion ratio used in the study.

Co-Product	Conversion rate	Reference
Renewable gasoline	DB2Gasoline: 0.212 MJ MJ^{-1} SAF	(GREET, 2022)
Renewable diesel	DB2Diesel: 0.115 MJ MJ^{-1} SAF	
Electricity	DB2Electricty: 0.032 kWh MJ^{-1} SAF	

$$\sum_{r} VTDB_{b,r,t} \leq PVBPU_{b,t} \times CB2DB \text{ for every } b \text{ and } t \tag{16}$$

Eq. (14) and Eq. (15) state that neither the processing amounts of chipped logging residues could exceed the incoming amounts of both softwood and hardwood logging residues, nor the biomass could exceed the capacity of the BPUs. Eq. (16) denotes the conversion of chipped logging residues to dry biomass, and it can meet the demand for biomass to be transported to biorefineries.

$$PVRef_{r,t} \leq \sum_{b} VTDB_{b,r,t} \text{ for every } r \text{ and } t \tag{17}$$

$$PVRef_{r,t} \leq NRef_{r} \times CTRef \text{ for every } r \text{ and } t \tag{18}$$

$$\sum_{a} VTSAF_{r,a,t} \leq PVRef_{r,t} \times DB2SAF \text{ for } r \text{ and } t \tag{19}$$

Eqs. (17)–(18) state that the amount of dry biomass processed to produce SAF cannot exceed both the incoming amount of dry biomass from BPUs and the capacity of the biorefinery. Eq. (19) states the conversion of dry biomass to SAF. Eq. (20) denotes that the volume of SAF supplied to the airport cannot exceed the incoming SAF from biorefineries. Eq. (21) denotes that the supply of SAF must be able to meet the demand for SAF.

$$VSAF_{a,t} \leq \sum_{r} VTSAF_{r,a,t} \text{ for every } a \text{ and } t \tag{20}$$

$$VSAF_{a,t} \geq D_{a,t} \times DS \; for \; every \; a \; and \; t \tag{21}$$

2.5. Unit cost

The ETJ process produces renewable diesel, renewable gasoline, and electricity together with SAF (GREET, 2022) presented in Table 5. Finally, we computed the unit production cost of logging residues-based SAF throughout the supply chain following Eq. (22).

$$UnitCost_{SAF} = \frac{TotalCost}{\sum_{a,t} VSAF_{a,t}} - \frac{\sum_{i} CoProduct_{i} \times Price_{i}}{\sum_{a,t} VSAF_{a,t}} \tag{22}$$

The price of each co-product from 2011 to 2020 is reported in Table S6. We ran the optimization model separately for three different demand scenarios. Scenario A (high demand) is for 20 % demand share, scenario B (medium demand) is for 10 % demand share, and scenario C (low demand) is for 5 % demand share of total SAF demand that must be met at the airport.

$$GHG\ Abatement\ Cost = \frac{Unit\ cost\ of\ SAF\ per\ MJ - Price\ of\ CAF\ per\ MJ}{GHG\ emission\ from\ CAF\ per\ MJ - GHG\ emission\ from\ SAF\ per\ MJ} \tag{32}$$

2.6. Greenhouse gas (GHG) emission

The total GHG emission from the logging residues-based SAF supply chain was estimated by Eq. (23).

$$GHG_{SAF} = \left(GHG_{LR} + GHG_{transCB} + GHG_{BPU} + GHG_{transBR} + GHG_{Ref}\right) \times EAR - GHG_{Electrcity} + GHG_{transSAF} \tag{23}$$

Eqs. (24)–(31) define the information present in Eq. (23).

$$GHG_{LR} = LRcollect_{GHG} \times \sum_{c,t} \left(VLRSW_{c,t} + VLRHW_{c,t}\right) \tag{24}$$

$$GHG_{transCB} = TransLR_{GHG} \times \sum_{c,b,t} \left(VTSW_{c,b,t} + VTHW_{c,b,t}\right) \tag{25}$$

$$GHG_{BPU} = ProsBPU_{GHG} \times \sum_{b,t} PVBPU_{b,t} \tag{26}$$

$$GHG_{transBR} = TransDB_{GHG} \times \sum_{b,r,t} VTDB_{b,r,t} \tag{27}$$

$$GHG_{Ref} = ProsRef_{GHG} \times \sum_{r,t} PVRef_{r,t} \tag{28}$$

$$GHG_{transSAF} = Transfuel_{GHG} \times \sum_{r,a,t} VTSAF_{r,a,t} \tag{29}$$

$$EAR = \frac{E_{SAF}}{E_{SAF} + E_{Gasoline} + E_{Diesel}} \tag{30}$$

$$GHG_{Electricity} = Electricity_{GHG} \times \sum_{a,t} VSAF_{a,t} \times DB2Electricity \tag{31}$$

Eq. (24) computes the total GHG emissions from both hardwood and softwood logging residues collection and chipping, where $LRcollect_{GHG}$ is the unit emissions related to logging residues collection and chipping and are equal to 21.9 kg CO_2e Mg^{-1} of logging residues (GREET, 2022). *EAR* is the energy allocation ratio, estimated by the ratio of the energy value of SAF, renewable gasoline, and renewable diesel co-produced (Eq. (30)). Eq. (25) estimated the emissions from transporting chipped logging residues from counties to BPUs, where $TransLR_{GHG}$ is the unit emission from logging residues transport, 0.10 kg CO_2e Mg^{-1} km^{-1} (GREET, 2022). Eq. (26) and Eq. (28) calculated GHG emissions coming from processing chipped logging residue and dry biomass in BPUs and biorefineries, respectively, where $ProsBPU_{GHG} = 69.1$ kg CO_2e Mg^{-1} of logging residues and $ProsRef_{GHG} = 0.78$ kg CO_2e L^{-1} of SAF (GREET, 2022). Finally, Eq. (27) and Eq. (29) estimated the GHG emissions from dry biomass and SAF transport, where $TransDB_{GHG} = 0.07$ kg CO_2e Mg^{-1} km^{-1} and $Transfuel_{GHG} = 0.06$ g CO_2e L^{-1} km^{-1} of SAF, respectively (GREET, 2022). Eq. (31) calculates the electricity displacement credit coming from electricity cogeneration where, $Electricity_{GHG} = 0.44$ kg CO_2e kWh^{-1} (GREET, 2022).

2.7. GHG abatement cost

We have calculated the GHG abatement cost of all three demand scenarios following the work of Dwivedi et al. (2015) using Eq. (32):

The price of CAF was \$0.73 L^{-1} (\$0.02 MJ^{-1}) (IATA, 2024) and the GHG emission intensity of CAF was 89 g CO_2e MJ^{-1} (Pavlenko and Searle, 2021).

3. Results and discussions

3.1. Optimal total cost of the SAF supply chain

The total cost of the SAF supply chain for Scenario A was $8.66 billion for 10 years of operation, producing a total of 3.74 billion L of SAF. Co-products from the biorefinery process generated a significant $1.47 billion in credit. The optimal total cost of Scenario B was $4.53 billion for producing 1.87 billion L of SAF. After ten years of operation, co-product revenue amounted to $0.73 billion. Similarly, Scenario C incurred a total cost of $2.47 billion over 10 years operation to produce 0.94 billion L of SAF. Renewable gasoline, renewable diesel, and electricity as co-products generated $0.37 billion in revenue. The associated relative gaps[3] obtained in GAMS were 0.08 %, 0.005 %, and 0.007 % for Scenarios A, B, and C, respectively.

3.2. Location of facilities

The location and total number of BPUs and biorefineries under different demand scenarios is presented in Fig. 5. The SAF supply chain model for Scenario A provided 54 BPUs across Georgia, 28 of them are in the Piedmont Ecoregion (upper Georgia), and 26 of them are in the Coastal Plains Ecoregion (lower Georgia). The model suggested building 2 BPUs each in Bartow, Greene, Monroe, Morgan, Putnam, Upson Counties in Piedmont Ecoregion and Dodge, Glascock, Taylor, Telfair, Terrel, Turner Counties in Coastal Plain Ecoregion, respectively. Moreover, Emanuel and Twiggs Counties of Coastal Plain Ecoregion had 4 and 3 BPUs, respectively. The model also established 13 biorefineries across the state divided between the Piedmont (Baldwin, Fayette, Fulton, Henry, Monroe, Newton, and Pike Counties) and the Coastal Plains (Marion, Pulaski, Twiggs and Washington Counties) Ecoregions. The model for Scenario B resulted in 27 BPUs, 25 of which are in the Piedmont Ecoregion and the remaining 2 in the Coastal Plains Ecoregion. The model also estimated 7 biorefineries in Fayette, Fulton, Henry, Newton and Pike Counties. For Scenario C, the model established 14 BPUs, all of which are in the Piedmont Ecoregion. The model yielded only 4 biorefineries in Fayette, Fulton, and Henry Counties.

3.3. Materials flow throughout the SAF supply chain

Under Scenario A, annually, 1.20 million Mg of HW logging residues are collected on average from all the counties across Georgia with 30 % moisture content, out of which 0.63 million Mg and 0.51 million Mg are transported to the BPUs located in the counties of the Piedmont Ecoregion and the Coastal Plain Ecoregion, respectively. The remaining 60,147 Mg of HW biomass is lost during chipping in the forest landing. Similarly, 2.28 million Mg of SW logging residues with 30 % moisture content are collected annually from the forest landings across Georgia, 1.19 million Mg of which is transported to BPUs of the Piedmont Ecoregion, and 0.98 million Mg is transported to the BPUs of the Coastal Plain Ecoregion, and the remaining 0.11 million Mg of the biomass is lost during biomass chipping. Annually, around 1.82 million Mg of logging residues is processed at the BPUs of the Piedmont Ecoregion, and 1.49 million Mg is processed at the BPUs of the Coastal Plain Ecoregion. Only 80 % of this processed dry biomass is transported to the biorefineries, and the other 20 % is lost during processing (moisture reduction).

A total of 0.28 million Mg of SAF is produced annually at the 13 biorefineries across Georgia after processing 2.65 million Mg of lignocellulosic biomass through the ETJ process. Along with SAF, 61,458 Mg of renewable gasoline, 32,754 Mg of renewable diesel, and 400,450 MWh of electricity are co-generated during the biorefinery process every year on average throughout the supply chain. SAF is then supplied to the ATL airport to meet the percentage share of SAF demand (Fig. 6).

In Scenario B, annually, 1.13 million Mg of SW logging residues with 30 % moisture content is available on average from the forest landing of each county across Georgia, out of which 1.02 million Mg is supplied to the BPUs located in the Piedmont Ecoregion, and 0.26 million Mg of logging residues goes to the BPUs located at the Coastal Plain Ecoregion. The remaining 0.57 million Mg of SW biomass is lost during chipping in the forest landing. Similarly, 0.61 million Mg of HW logging residues with 30 % moisture content on average are available per year across Georgia, out of which 0.55 million Mg is supplied to the Piedmont Ecoregion, and 30,305 Mg is supplied to the Coastal Plains Ecoregion and the remaining 30,500 Mg is lost during chipping. From all the 27 BPUs in the Piedmont and Coastal Plains Ecoregions, 1.33 million Mg of processed dry biomass is supplied to the biorefineries across Georgia. A total of 0.14 million Mg of SAF is produced from all 7 biorefineries, which are then transported directly to the ATL airport to meet the percentage share of the SAF demand. Around 30,729 Mg of renewable gasoline, 16,377 Mg of renewable diesel, and 200,224 MWh of electricity are co-generated during the biorefinery process (Fig. 7).

Likewise, 54,394 Mg of hardwood and 817,446 Mg of softwood logging residues with 30 % moisture content are collected from all the counties in Georgia every year under Scenario C. Around 828,249 Mg of the total collected volume of HW and SW logging residues are transported on an average directly to the BPUs located in the Piedmont Ecoregion and the remaining 43,592 Mg of the biomass is lost during chipping. After processing incoming logging residues into dry biomass, 477,551 Mg is supplied to the biorefinery at Fayette County, 32,963 Mg to the biorefinery at Fulton County, 152,085 Mg to the biorefinery at Henry County, respectively. Of all the biorefineries, a total of 70,929 Mg of SAF is produced annually along with 15,365 Mg of renewable gasoline, 8187 Mg of renewable diesel, and 100,112 MWh of electricity cogeneration to meet the percentage share of SAF demand at the ATL airport (Fig. 8).

3.4. Unit cost at the supply chain level

The unit costs for demand Scenarios A, B, and C are $1.92 L^{-1}, $2.03 L^{-1}, and $2.25 L^{-1}, respectively, after considering the revenue generated from all the co-products (Fig. 9). On average, revenue generated from co-products compensated 19 % of the unit cost for all three models. The unit cost is still about 163 %, 178 %, and 209 % higher for Scenarios A, B, and C, respectively, compared to the price of CAF ($0.73 L^{-1}) in 2023 (IATA, 2024) (Fig. 9). The highest expense occurred at the capital investment of biorefineries, accounting for 77 % of the total cost on average, followed by the processing cost of the biorefineries, constituting 22 %. This number is similar to the study of Huang et al. (2019), where biorefinery-related costs comprised 64 % of the unit production cost of ATJ-based facilities. Elia et al. (2013) reported that the investment cost of the facilities accounts for 68 % of the total cost of hardwood-based SAF. Other components that add up to the total cost on average are the processing cost of chipped logging residues at BPU (8 %), capital cost of BPU (3.6 %), the transportation cost of processed dry biomass from BPUs to biorefineries (2.3 %), collection and chipping costs (3.4 %) of SW and HW logging residues, transportation of chipped logging residues to BPUs (2.9 %), and transporting SAF to the airport (0.17 %).

Fig. 10 illustrates a systematic comparison of unit production costs of the SAF supply chain or regional scale analysis between our estimate and estimates in different studies. Perkis and Tyner (2018) reported break-even price of cellulosic SAF derived from corn stover, wheat straw, and switchgrass was $0.91 L^{-1} following a fast pyrolysis-based pathway. The authors developed a sequential start-up model using a mixed integer non-linear model to optimize unit costs of the SAF supply chain in Indiana. Leila et al. (2018) introduced the Biofuel Supply Chain Geospatial and Temporal Optimizer (BioGeSTO) model using MILP to

[3] Relative Gap in GAMS means how far is the optimal output from the best integer output.

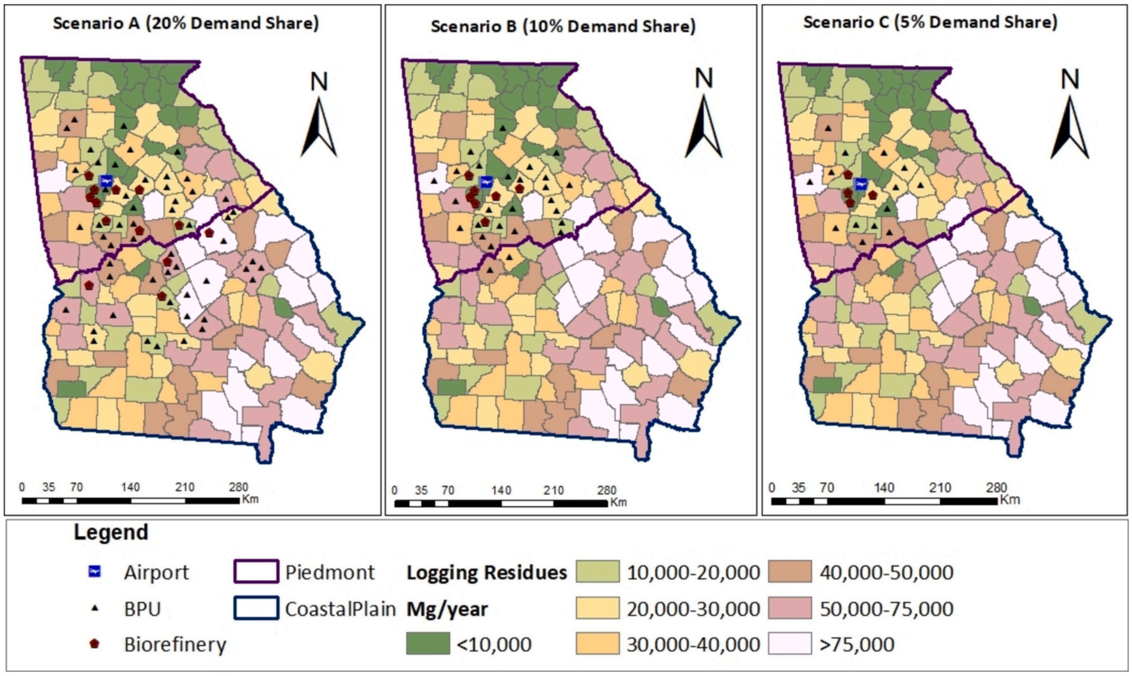

Fig. 5. Location and number of BPUs and Biorefineries across Georgia under different demand scenarios (Source: Timber Product Output (TPO) database).

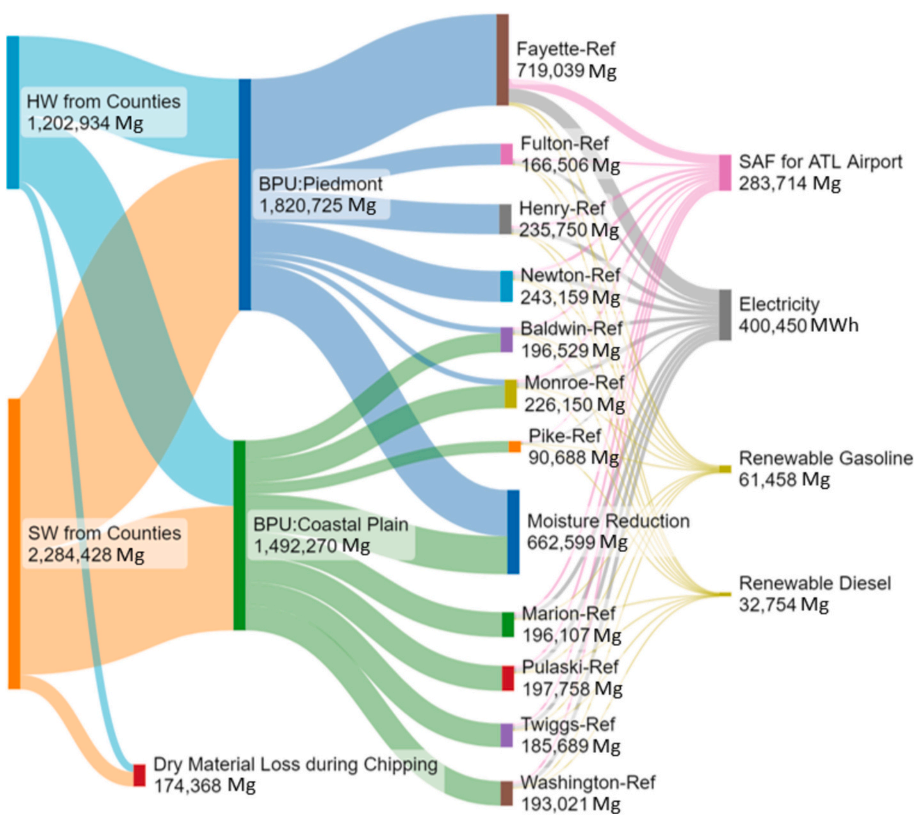

Fig. 6. Annual flow of materials throughout the supply chain for Scenario A.

optimize the SAF supply chain for 20 years simulation period to meet the annual military biofuel target in California. The minimum selling price of forest residues-based SAF in the FT pathway was \$1.48 L^{-1}. Seufitelli et al. (2022) performed a techno-economic analysis of an integrated biorefinery with different capacities using poplar biomass for SAF. They concluded that the MJSP decreases with large-scale biorefineries, and the MJSP for an intermediate-scale ATJ-based biorefinery was \$0.83 L^{-1}. A regional scale analysis was performed by Bhatt et al. (2023) for the deployment of SAF at Chicago's O'Hare International Airport. They found that the FT pathway had the lowest unit production cost of \$0.68 L^{-1} using woody biomass as feedstock. Li et al. (2024) revealed the impact of pre-processing and conversion technology for forest residues-

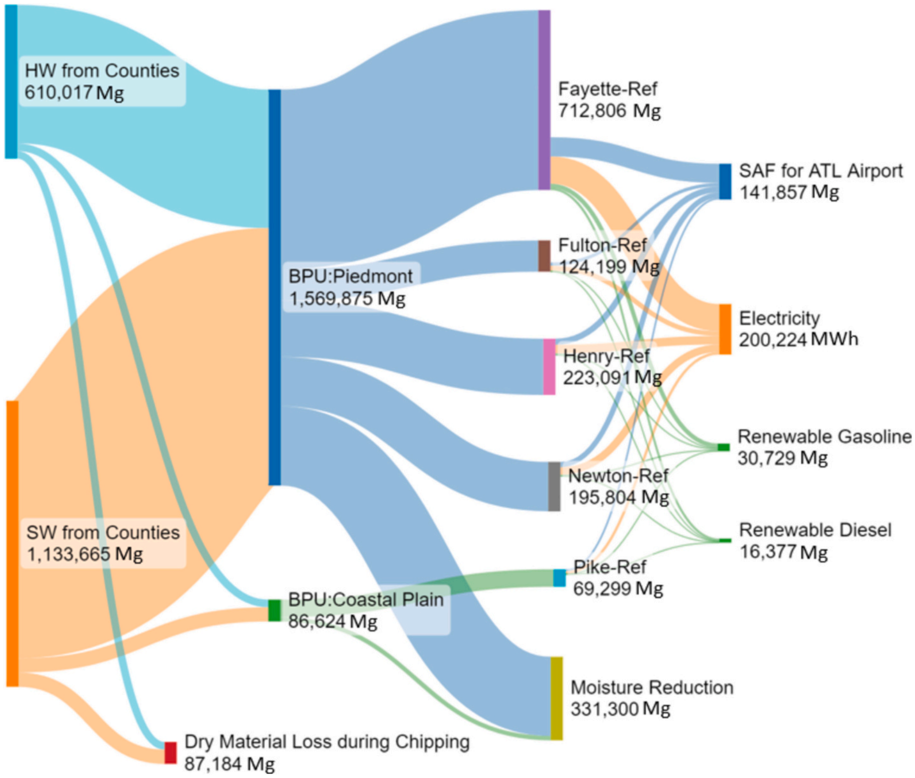

Fig. 7. Annual flow of materials throughout the supply chain for Scenario B.

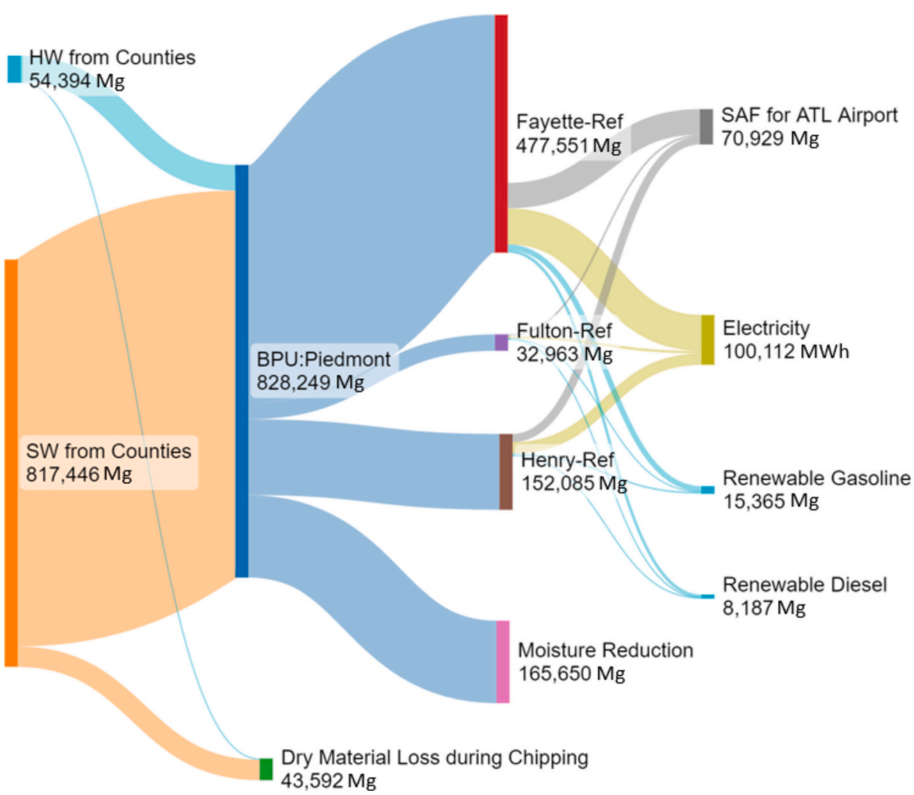

Fig. 8. Annual flow of materials throughout the supply chain for Scenario C.

based SAF supply chain in the Southeast United States. The breakeven price was \$1.48 L^{-1} with the pyrolysis pathway. Moreover, the unit price of the SAF supply chain using carinata oilseed crop was \$0.89 L^{-1} with catalytic hydrothermolysis pathway (Masum et al., 2023) and corn stover-based SAF with ATJ process was \$1.70 L^{-1} (Huang et al., 2019). Our estimate of the unit cost of the SAF supply chain is higher than the abovementioned studies. The high cost can be attributed to the feedstock choice and price, conversion pathway, capital investment cost,

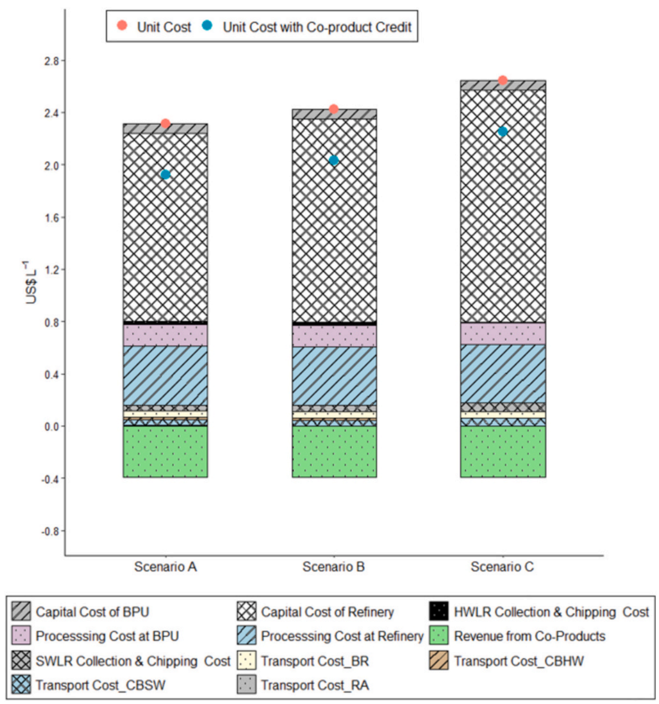

Fig. 9. Unit cost of different stages throughout the supply chain of SAF. HW LR: hardwood logging residues, SW: softwood, CB: county to BPU, BR: BPU to biorefinery, RA: biorefinery to airport.

transportation distances, capacity of biorefinery, and scale of analysis.

3.5. GHG emissions at the supply chain level

The GHG emissions attributed to the logging residues-based SAF supply chain is 769 g CO_2e L^{-1}, 766 g CO_2e L^{-1}, and 765 g CO_2e L^{-1} for scenarios A, B, and C, respectively. The SAF supply chain model from logging residues can provide 70 % of relative carbon savings on average of the three-demand scenario compared to CAF (GHG intensity of CAF was 2576 g CO_2e L^{-1}) (US EIA, 2022). Moreover, the average carbon intensity of the three SAF supply chain scenarios is 22.96 g CO_2e MJ^{-1} on energy basis. SAF production at the biorefinery is the most carbon-intensive stage, accounting for 76 % of GHG emissions. This is followed by the processing of chipped logging residues at the BPU (60 %) and the collection and chipping of softwood logging residues (14 %). Nonetheless, the displacement credit from co-generated electricity achieved by substituting grid electricity lowered the overall GHG emissions by 65 %. Other stages have minimal impact on the overall supply chain GHG emissions (Fig. 11). Björnsson and Ericsson (2024) performed a lifecycle analysis of logging residues-based SAF production chain and found that the GHG emission reduction potential ranges between 89 and 91 % based on conversion technologies. The FT-SPK pathway incorporating carbon capture and storage for producing SAF

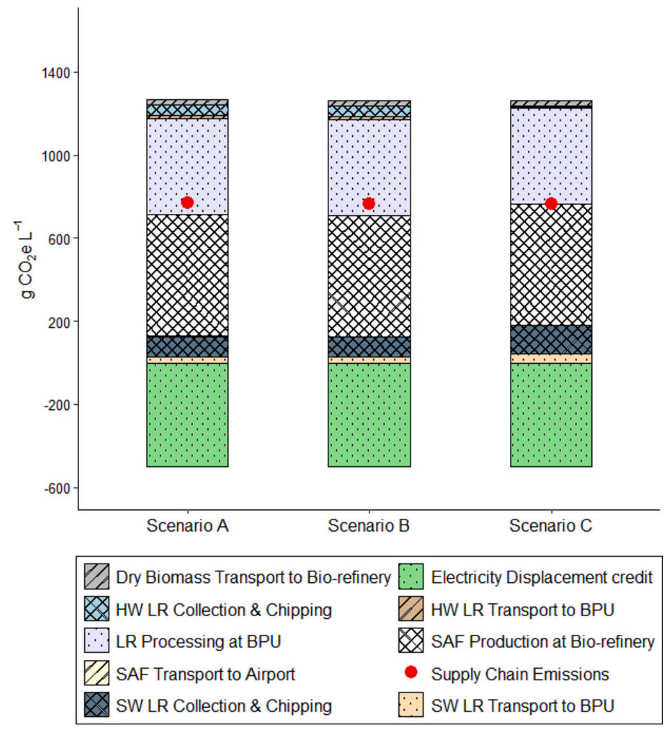

Fig. 11. GHG emission throughout the logging residues-based SAF supply chain. The GHG intensity of CAF is 2576 g CO_2e L^{-1}.

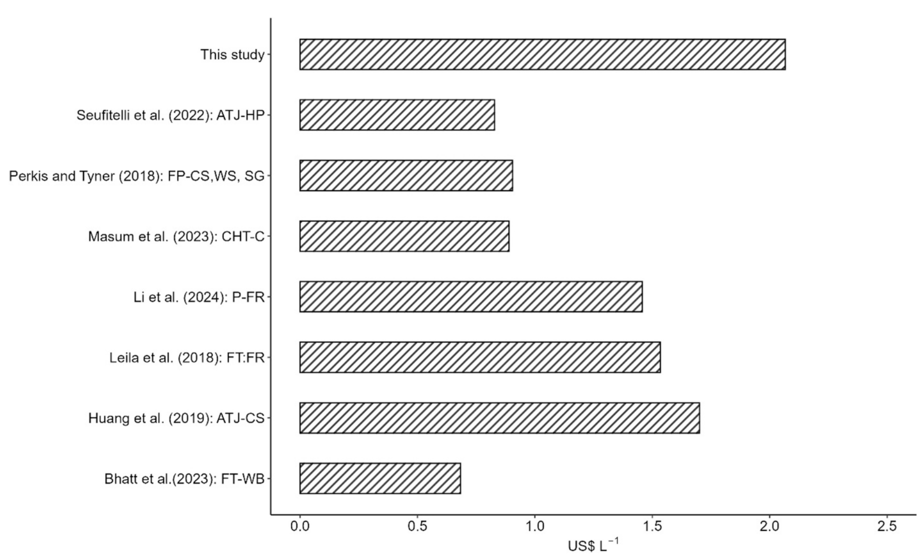

Fig. 10. Comparison of unit production costs of SAF supply chain in existing literature. ATJ-HP: Alcohol-to-jet (Hybrid poplar); FP-CS, WS, SG: Fast pyrolysis (Corn stover, wheat straw, switchgrass); CHT-C: Catalytic hydrothermolysis (Carinata); P-FR: Pyrolysis (Forest Residue); FT-FR: Fischer-Tropsch (FR); ATJ-CS: ATJ (Corn stover); WB: Woody biomass. Unit cost with co-product credit in our study: Scenario A = \$1.92 L^{-1}, Scenario B = \$2.03 L^{-1} and Scenario C = \$2.25 L^{-1}.

from forest residues in the United Kingdom offered 74 % reduction in GHG emission compared to CAF (Almena et al., 2024). Puschnigg et al. (2023) found that the GHG emissions reduction potential of SAF from softwood residues was 79–80.1 %. The SAF produced from corn and cassava following ETJ process in China provided 64 % of the GHG saving compared to CAF (Wang et al., 2023). The relative lifecycle carbon emissions savings from logging residues-based SAF production following the ETJ pathway was 71 % in the study of Akter et al. (2024). Most of the estimates of GHG savings in the existing literature are higher than ours. However, these studies were performed at the unit level for life cycle analysis, whereas our study calculated the total GHG saving on the supply chain level for 10 years of operation.

3.6. GHG abatement cost

The GHG abatement cost for the SAF supply chain was the highest without co-product credits for all three scenarios, i.e., \$732 Mg CO_2e^{-1} for Scenario A, \$779 Mg CO_2e^{-1} for Scenario B and \$880 Mg CO_2e^{-1} for Scenario C, respectively. However, incorporating co-product credit, the GHG abatement cost decreased to \$554 Mg CO_2e^{-1} for Scenario A, \$602 Mg CO_2e^{-1} for Scenario B and \$703 Mg CO_2e^{-1} for Scenario C, respectively (Fig. 12). Though SAF is more expensive to produce, it generates less carbon emissions. The higher GHG abatement cost reflects this difference. The cost of reducing GHG emissions by consuming SAF influences the carbon tax needed to make SAF equally priced as CAF.

3.7. Potential shortcomings of the study

This study has some potential shortcomings. First, the SAF demand was estimated assuming the average percentage share of passengers on board at ATL airport is proportional to the CAF consumption in Georgia due to the unavailability of data on CAF consumption in ATL airport. Second, the assumption of linear distances between counties in the distance matrix. Transportation network analysis with the restriction of driving logging trucks on interstate highways can provide more robust estimates of the model. Third, the impact of logging residue removal from the forest floor on soil productivity, carbon (C) pools, and overall biodiversity of the area was not considered in the study. Curzon et al. (2014) found that removing logging residues affects the productivity of the forest stand. However, the impact varies depending on site conditions and soil quality. James et al. (2021) revealed that logging residue removal caused the loss of soil C and nitrogen (N), yet the detrimental effects subsided over time since harvest. Furthermore, the authors proposed that removing less than 80 % of harvest residues can yield a sustainable biomass supply. Compared to stem-only harvesting, logging residues extraction had a negligible adverse impact on biodiversity, according to Ranius et al. (2018). The effects varied according to wood and forest types, management techniques, and geographic location. Creating standards for management techniques and residue extraction based on species, forest types, and site quality could minimize the effect of residue removal for bioenergy development.

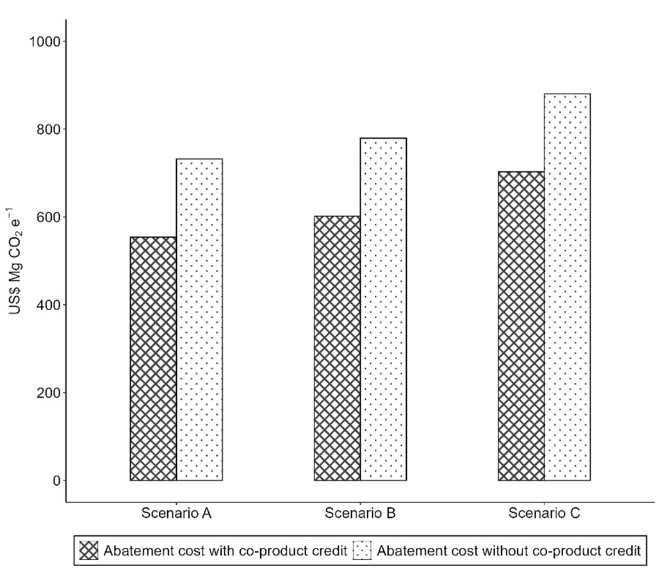

Fig. 12. GHG abatement cost for three different supply chain scenarios.

4. Conclusion

The advancement of logging residues-based SAF production necessitates system-level analysis for economic viability. We developed a supply chain optimization model incorporating spatial and temporal data to minimize the present value of the total cost at the state level. The model was applied in Georgia to assess the supply chain configuration of logging residues-based SAF production following the alcohol-to-jet production pathway. The model yielded unit production costs of \$1.92 L^{-1}, \$2.03 L^{-1}, and \$2.25 L^{-1} for the high (Scenario A), medium (Scenario B), and low demand (Scenario C) scenarios, respectively. The biorefinery cost comprised much of the total cost. The cost optimization model recommended a distributed system of facilities with 54 BPUs and 13 biorefineries in Scenario A, 27 BPUs and 7 biorefineries in Scenario B, and 14 BPUs and 4 biorefineries in Scenario C of SAF model, respectively. The system is more sustainable because it requires no land use change or additional crop production cost. After all, logging residues are the byproduct of harvesting operations in Georgia. Moreover, the SAF supply chain provided 70 % of relative carbon saving on average compared to CAF, making it suitable to incorporate subsidies such as RIN credit or tax credits from IRA 2022 to make SAF price competitive to CAF. Further research can focus on techno-economic comparison among different production pathways with varying biorefinery scales for logging residues-based SAF to identify the most cost-effective conversion technology. Moreover, this study can also be extended to the entire southern region of the United States, including all the major airports, to get a broader perspective of logging residues-based SAF potential in the wood basket of the world. The optimal configuration of the logging residues-based SAF supply chain will benefit investors and the industry for informed decision-making. Our study will recommend solutions to increase the resiliency of forest resources in Georgia, considering emerging bioenergy markets.

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Declaration of generative AI in scientific writing

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CRediT authorship contribution statement

Hosne Ara Akter: Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Yu-Kai Huang:** Writing – review & editing, Validation, Software. **Puneet Dwivedi:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2024.103401.

Data availability

Data will be made available on request.

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