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16. Abstract

Policymakers and the aviation industry are working to decarbonize commercial flights by replacing conventional jet fuel with sustainable aviation fuel (SAF). Logging residues have been identified as a valuable resource for SAF production. However, the quality of the feedstock, particularly the ash content, can adversely affect bio-oil yield and SAF production using the fast pyrolysis/hydrotreatment process, and potentially its supply chain optimization. Previous research often assumes fixed biofuel yields and neglects the variability in feedstock quality when optimizing the supply chain. Thus, this study seeks to address this gap in the literature by employing a two-stage mixed-integer linear programming (MILP) model to investigate the influence of varying ash content in logging residues on the potential maximum supply quantity (MSQ) and net revenue (NR) of SAF production. Two scenarios were conducted in the Southeastern United States (US): one assuming constant ash content and the other accounting for heterogeneous ash content in logging residues. Results indicate that ignoring ash variability in the feedstock could lead to overestimation of SAF MSQ and NR by 14.15 % and 18.27 %, respectively, in the study area. Additionally, higher ash content leads to lower bio-oil yields, resulting in fewer refineries and reduced capacity. The study emphasizes the need for best management practices to mitigate soil contamination during feedstock processing and improve the resilience of the biomass-based SAF supply chain. Furthermore, it is crucial to effectively manage the mechanisms of mineral uptake and their integration into the structure of lignocellulosic materials.

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Spatial optimization of the sustainable aviation fuel supply chains from forest residues via fast pyrolysis/hydrotreatment considering feedstock ash content variability

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ABSTRACT

Policymakers and the aviation industry are working to decarbonize commercial flights by replacing conventional jet fuel with sustainable aviation fuel (SAF). Logging residues have been identified as a valuable resource for SAF production. However, the quality of the feedstock, particularly the ash content, can adversely affect bio-oil yield and SAF production using the fast pyrolysis/hydrotreatment process, and potentially its supply chain optimization. Previous research often assumes fixed biofuel yields and neglects the variability in feedstock quality when optimizing the supply chain. Thus, this study seeks to address this gap in the literature by employing a two-stage mixed-integer linear programming (MILP) model to investigate the influence of varying ash content in logging residues on the potential maximum supply quantity (MSQ) and net revenue (NR) of SAF production. Two scenarios were conducted in the Southeastern United States (US): one assuming constant ash content and the other accounting for heterogeneous ash content in logging residues. Results indicate that ignoring ash variability in the feedstock could lead to overestimation of SAF MSQ and NR by 14.15 % and 18.27 %, respectively, in the study area. Additionally, higher ash content leads to lower bio-oil yields, resulting in fewer refineries and reduced capacity. The study emphasizes the need for best management practices to mitigate soil contamination during feedstock processing and improve the resilience of the biomass-based SAF supply chain. Furthermore, it is crucial to effectively manage the mechanisms of mineral uptake and their integration into the structure of lignocellulosic materials.

1. Introduction

Commercial flights have recovered from the COVID-19 pandemic in 2020 and are expected to continue growing in the long term. The strong demand for flights driven by international travel and business has raised concerns about the resulting air pollution and greenhouse gas emissions. The aviation sector accounts for approximately 2.5 % of global carbon dioxide (CO_2) emissions [1,2]. Several measures are proposed to decarbonize air traffic, including optimizing flight routes, improving jet engine efficiency, enhancing airport operational management, and utilizing SAF, among others. As a drop-in fuel, SAF is compatible with existing fuel infrastructure and can be utilized in the current aircraft engines. Thus, SAF has been considered the primary means for decarbonizing the aviation sector and meeting the SAF Grand Challenge's targets in the US [3].

Multiple feedstocks are available to produce SAF, including lipids, agricultural and forestry biomass, biomass residues, algae, and municipal solid waste [4–8]. Forest residues are attractive SAF feedstocks because they are available at substantial, economically accessible volumes in major timber regions. A recent report by the US Department of Energy estimates that 18.5 million dry tons/year of logging residues are economically available in the US before 2030 at up to $40 per dry ton,

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and up to 19.2 million dry tons/year in a mature-market scenario before 2050 [9]. The Southeastern US, often referred to as the nation's "wood basket" and historically producing roughly sixty percent of US timber, is therefore a particularly important source of logging and mill residues [10,11]. Forest residues are generated as byproducts of forest management activities, such as thinning, harvesting, and processing of wood. These residues, including treetops, branches, bark, and other woody debris, are typically left on the forest floor or discarded during forest management activities [12,13]. Second, utilizing forest residues for biofuel production can help minimize land-use conflicts that may arise when dedicated agricultural land is used for biofuel feedstock cultivation [14]. Using forestry residues as SAF feedstock can preserve valuable agricultural land for food production and minimize pressure on natural ecosystems. Additionally, SAF produced from forest residues has greater potential to reduce lifecycle CO_2 emissions, achieving reductions of up to 80 % compared to conventional jet fuel, making it a sustainable alternative for the aviation industry [15].

While forest residues present numerous advantages as SAF feedstocks, they also have limitations and challenges. First, it is crucial to ensure that forest residues collection is carried out consistently without compromising forest health and productivity or causing ecological damage. Studies showed that a retention level of 20–30 % is necessary for the residues to improve ecological conditions [16,17]. Second, the utilization of forest residues as a feedstock requires specific technologies and infrastructure for processing and conversion. As a result, additional investments in equipment or modifications to the processing facilities may be necessary [18]. Moreover, the availability of forest residues can vary depending on factors such as forest management practices, harvesting methods, and regional conditions. In addition, forest residues often have lower energy density and greater compositional and physical heterogeneity, such as ash content, compared to dedicated energy crops such as hybrid poplar, willow, or switchgrass [19]. Studies have shown that the ash content, a quality attribute of logging residues, is a notable source of variations for many biomass feedstocks [20]. A recent study also found that the calorific value of commercial wood pellets is affected by ash content and other characteristics [21]. Specifically, lower ash content is correlated with the pellet's higher mechanical durability. In thermochemical conversion, higher ash content also reduces biofuel yields along the fast pyrolysis/bio-oil hydrotreatment pathway [22,23].

Modeling and optimizing feedstock supply chains has been a focus in SAF development and policy discussion due to the challenges of locating biomass feedstock to meet national SAF targets [24]. The recent review and survey suggest that many studies have utilized mathematical programming models and geographic information system tools to design the biomass supply chain and identify potential feedstock areas and facility locations [25,26]. Among those studies, few recognize the importance and impact of feedstock quality in the supply chain. At the same time, most assume a fixed biofuel yield from a given biomass feedstock when assessing feedstock demand and locating the required feedstock area. The impact of ash content variability on biofuel yield is generally neglected in the biomass supply chain design, primarily because feedstock quality data are limited. Two studies incorporated the effect of feedstock quality on the biomass supply chain by adding the additional treatment process and related costs for the low-quality feedstock [27,28]. However, to the best of our knowledge, considering the impact of feedstock ash content on the SAF supply chain from forest residues, including SAF production cost and the choice of feedstock collection area and facility location, is still limited.

This study thus addresses a prevalent assumption in the literature regarding SAF supply chain optimization, that is, biofuel yields are fixed within a region for a given biomass feedstock, regardless of its quality. Recognizing the variability in feedstock quality, especially ash content, is vital because it impacts biofuel production. We analyze and compare the potential MSQ and NR of SAF derived from forest residues under two scenarios: one with constant ash content and another with heterogeneous ash content. To support this analysis, we develop a two-stage MILP model that captures the relationship between feedstock ash content and bio-oil yield from the fast pyrolysis/hydrotreatment process while optimizing the SAF supply chain. Additionally, we map prospective feedstock collection areas and facility locations to highlight the differences from varying quality assumptions. The insights from this study aim to enhance stakeholder understanding of how feedstock quality influences SAF production and facility location decisions, ultimately refining feedstock management strategies for environmental and economic sustainability in SAF supply chains derived from forest residues.

The remainder of the paper is organized as follows: the study area and dataset are first described in the next section, followed by a section that outlines the SAF supply chain network design and modeling. A case study is then presented to illustrate the two logging residue supply chains assuming constant and heterogeneous ash contents in feedstock for SAF production in the Southeast. Lastly, the main conclusion of our research and recommendations are outlined in the Conclusion section.

2. Materials

2.1. Study area

The Southeastern US has gained prominence as a significant supplier of logging residues, owing to its abundant and diverse forestry resources, and a thriving wood products industry [13,17]. This area produces more than 50 % of the nation's forest products [11] and generates substantial logging residues. The quantity of potentially recoverable logging residues within a 50-mile hauling distance in the Southeast is estimated to be more than 23 million dry tons [13]. This study focuses on a geographic area encompassing Alabama, Arkansas, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia, along with a 100-mile buffer zone around the states' borders. The study area is divided into 20,040 hexagons (the spatial unit in this study), each spanning 50 square miles. In addition, within this area, there are 1541 mills (pink plus signs for larger-size mills and blue hollow triangles for smaller ones in Fig. 1), 451 industrial parks (black hollow circles in Figs. 1), and 22 large or medium hub airports (red balloons in Fig. 1). Fig. 1 shows that the eastern and southern regions are characterized by larger sawmills (demand exceeding 30 million cubic feet) and that the eastern region stands out for its higher density of sawmills. The industrial parks in the study area serve as potential depot and refinery sites, facilitating the preprocessing and transformation of logging residues. Additionally, airports in the study area are the potential destinations for SAF.

2.2. Data

2.2.1. Forest inventory data

Forest inventory spatial data is gathered from the Forest Inventory and Analysis (FIA) database maintained by the US Department of Agriculture (USDA) [29]. This database contains a wide range of variables and attributes related to forest inventory. It includes information about forest structure, such as the number of trees, basal area, volume, biomass, and growth rates. Additionally, it includes data on land ownership, land use, disturbances such as wildfires and insect outbreaks, as well as indicators of forest health. The FIA database also incorporates geospatial information, providing precise coordinates for sample plots. This feature enables merging forest inventory data with other spatial datasets. Using the FIA sample database, four layers of timber are categorized into four groups: hardwood sawtimber, hardwood pulpwood, softwood sawtimber, and softwood pulpwood. Sawtimber is wood from trees with diameters greater than 11 inches for hardwood and greater than 9 inches for softwood, while pulpwood is wood from trees with diameters between 5 and 11 inches for hardwood and between 5 and 9 inches for softwood [17]. The sample data is then interpolated to generate the inventory level across the entire study area using

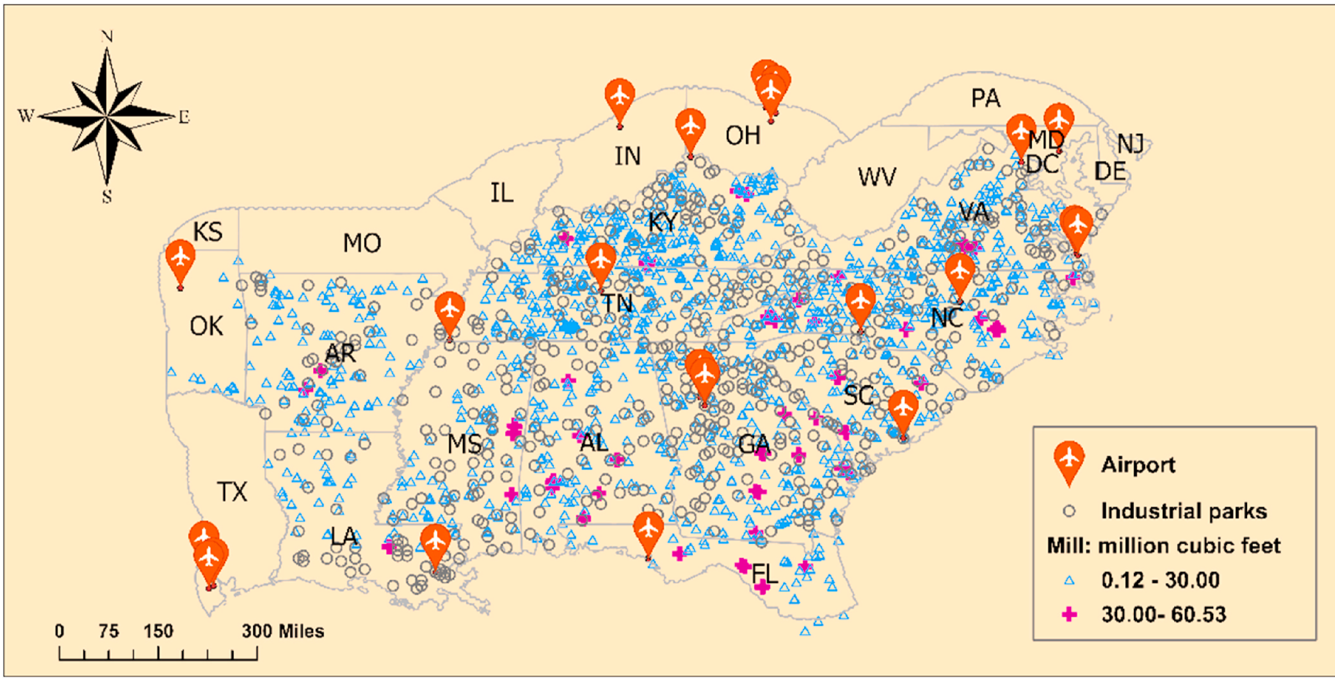

Fig. 1. The distribution of airports, sawmills, and industrial parks in the study area.

the Kriging method [30], and the results are grouped at the hexagon level. Fig. 2 depicts the interpolated forest inventory, showing that forest resources are more concentrated in the northeastern portion of the study area.

2.2.2. Timber products output (TPO) and sawmill data

The TPO database is the information resource for timber production and utilization in the US [31]. While the TPO database primarily focuses on timber products, it also includes data on forest residues. The TPO database collects information on forest residues through surveys and reporting from timber industry stakeholders, including sawmills, pulp and paper mills, and other wood processing facilities. The database includes information on different types of forest residues, such as logging residues, primary mill residues, and secondary mill residues at the county level. Based on the database, logging residues dominate all forest residues (85 %) in 2021. We thus focus on logging residues and calculate the ratio of logging residues to wood harvested. The available logging residues data layer is derived by multiplying the simulated wood harvests, based on sawmill capacity, by the ratio of logging residues over harvested wood [32].

Wood demand for sawmills is approximated by sawmill capacity, which is categorized into sizes 1–6 [33]. A k-nearest neighbor algorithm is used to interpolate the demand for 263 newly opened sawmills after 2009. The estimated wood demand is then adjusted by multiplying a factor to ensure that the sum of mill demand in each state matches the data in the TPO database [31].

2.2.3. Ash content data

We collected 68 different wood samples (around 10 kg each) across the Southeast, including materials from Georgia, South Carolina, Alabama, Virginia, Florida, and Tennessee during the summer of 2019. The wood species include hickory (*Carya sp*), red oak (*Quercus rubra*), white oak (*Quercus alba*), sweetgum (*Liquidambar styraciflua*), yellow poplar (*Liriodendron tulipifera*), cherry (*Prunus serotina* Ehrh.), elm (*Ulmus americana*), maple (*Acer saccharum*), and pine (*Pinus strobus*). After drying in a kiln at 40 °C for a week, the chipped samples are hammer milled to 40 mesh (0.425 μm) using Wiley mills (US). The ash content of the samples is determined following the National Renewable Energy Laboratory analytical procedure (NREL/TP-510-42622). The ash content of the as-received biomass falls between 0.2 % and 9.4 %. The ash content distribution is positively skewed, with most samples having an ash content below 2 %. The very high ash content (>6 %) indicates low-quality biomass, likely contaminated with soil.

As with the FIA data, the logging residues' ash content sample data is interpolated using the Kriging method across the entire study area. Fig. 3 depicts the distribution of the interpolated ash content in logging residues from our samples. The northeastern region, characterized by greater forest resources, has a relatively low ash concentration. The north central region, particularly Kentucky and Tennessee, and an area near the Georgia-South Carolina border have the highest concentrations of ash.

3. Methodology

3.1. Supply chain design

In this study, a two-stage logging residue-based SAF supply chain network is developed to model the entire process from forest harvesting to SAF delivery to airports, as shown in the left panel of Fig. 4. In the first stage, loggers contract with landowners and obtain permits for forest harvesting operations. Trees are felled, delimbed, and bucked to produce the desired logs for the sawmills while generating treetops, branches, bark, and other woody biomass that would normally be left on the forest floor (Fig. 4, ①). Logs are subsequently transported from the landing area to mills to meet their demands (Fig. 4, ②). The second stage begins with the in-field operations of harvesting logging residues, including treetops, branches, bark, and other woody biomass left behind after timber harvesting operations from the first stage. Once collected, logging residues need to be sorted and then transported to woody biomass depots for pre-processing, including sorting, drying, and shredding to the desired particle size (Fig. 4, ③). Processed logging residues in the form of 4 mm particle sizes are then delivered to biorefineries to produce SAF (Fig. 4, ④), which is ultimately transported to the destination airports to meet their demands (Fig. 4, ⑤).

The right panel of Fig. 4 displays the inputs and outputs in the supply chain network model. The top box in the dash line shows that the first

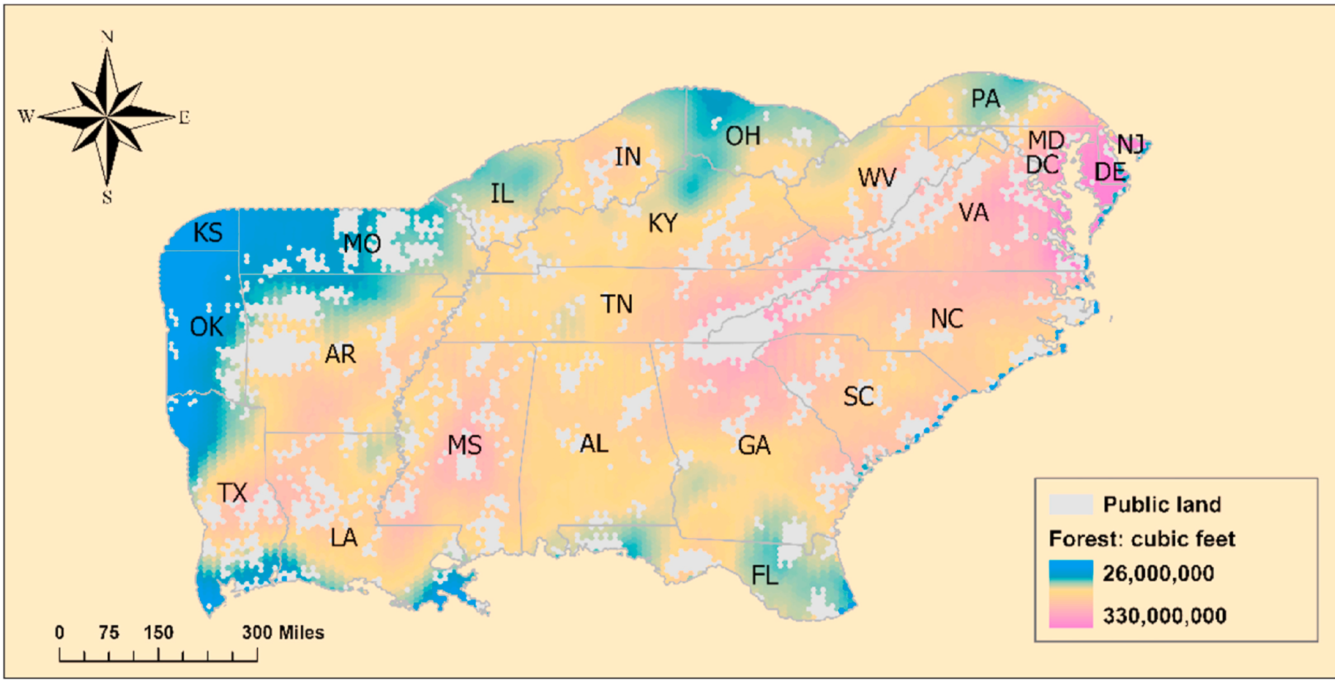

Fig. 2. The distribution of forest inventory.

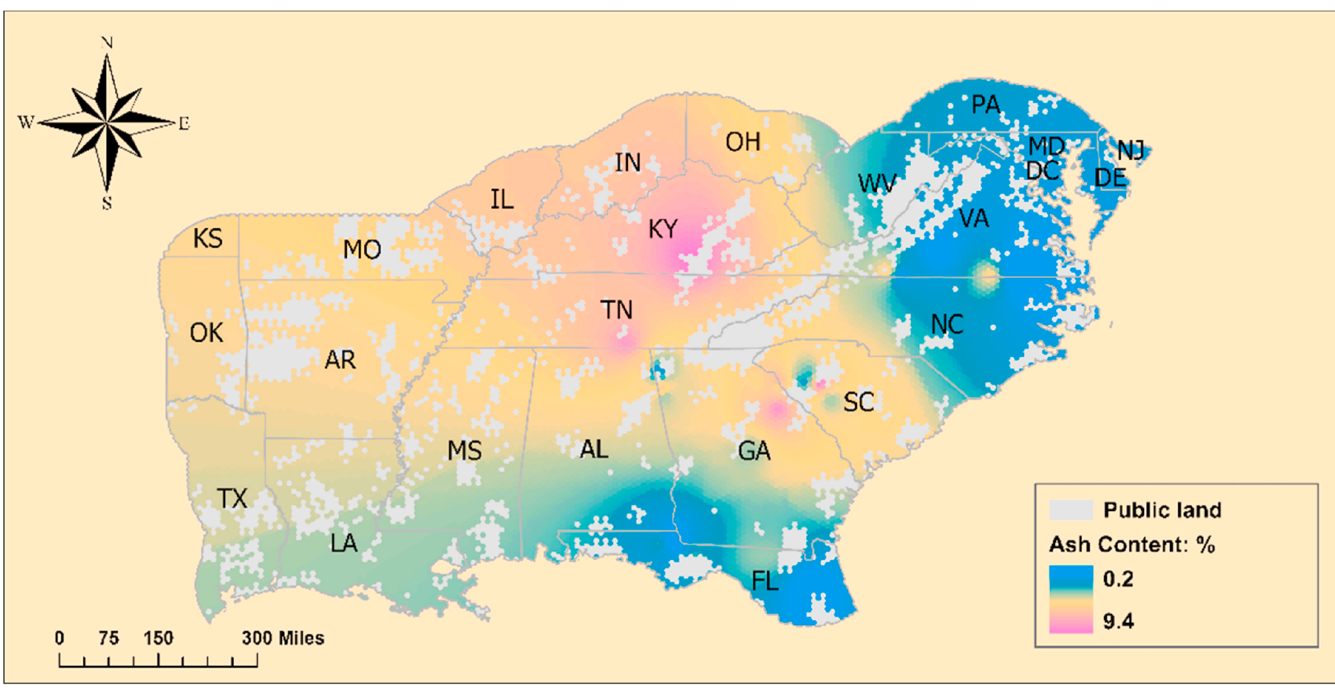

Fig. 3. Logging residues' ash content distribution using the Kriging method.

stage uses the initial forest inventory and growth, sawmill demand and location, and the distance matrix as the inputs to determine the amount and location of the harvested forest, and the corresponding quantity of logging residues. In the second stage (the bottom box of the right panel), we use residue availability derived from the stage one, along with candidate sites for preprocessing and conversion facilities, airport location and demand, and the distance network, to determine the optimal location, scale, technology, ash content category of preprocessing and conversion facilities, and the location and quantity of residues being harvested. The NR and MSQ of SAF are then estimated by maximizing the net present value (NPV) of the total profit incurred in the SAF supply chain.

Several technical assumptions are made in the SAF supply chains based on the industrial and research literature. First, the feedstock is preprocessed by hammermills with a particle size of 4 mm at the depot facility [34]. The preprocessed feedstock is converted to bio-oil, and then SAF and its coproducts (diesel, gasoline, and bunker fuel) through fast pyrolysis and bio-oil hydrotreatment at the biorefinery [35]. The fast-pyrolysis and hydrotreating process is an emerging pathway for SAF production [36]. The distillate breakdown among SAF, diesel, gasoline,

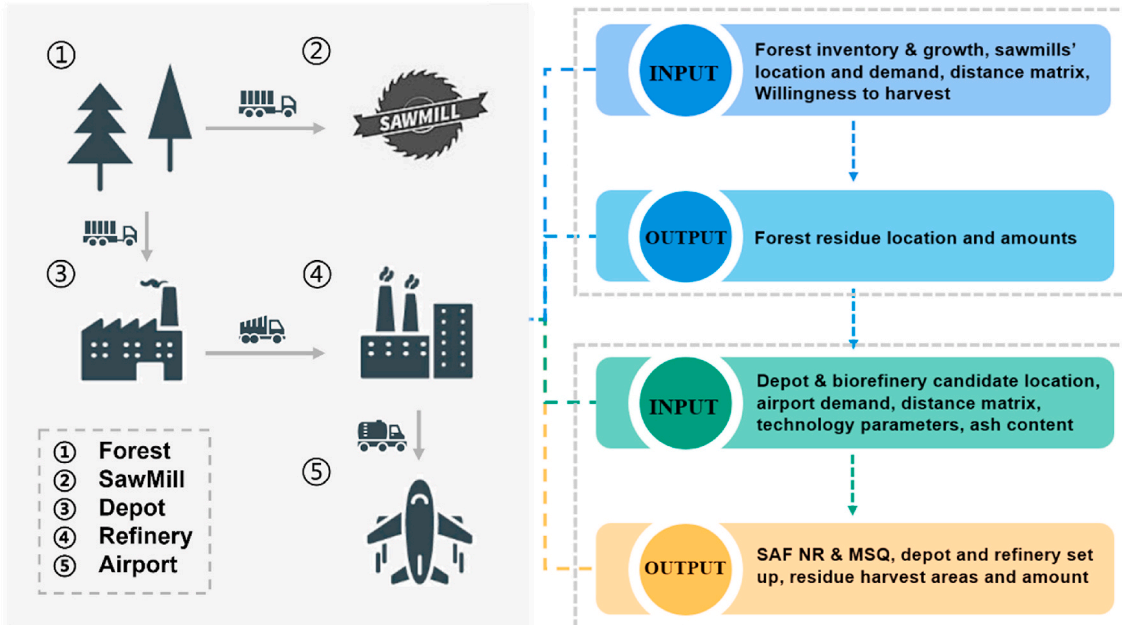

Fig. 4. Logging residue-based SAF supply chain network and model structure.

and bunker fuel is 50 %, 20 %, 20 %, and 10 %, respectively. Additionally, it is assumed that 45 % of the landowners of private forests are willing to harvest their logging residues, and up to 70 % of the total logging residues can be used for SAF production to prevent a significant impact on nutrient availability for forest tree regeneration [37].

3.1.1. *Ash category for depots and refinery*

Incorporating the impact of varying feedstock ash content on bio-oil yield requires calculating the weighted average feedstock ash content at depots and refineries, which leads to a nonlinear optimization problem as the decision variable of feedstock amount is on both the numerator and denominator of the weighted average ash content. The nonlinear structure results in a requirement for substantial computational power and time to solve the MILP. Thus, we approximate the aggregated ash contents by categorizing the facilities based on the ash content of the feedstock received. As shown in Fig. 5, there is a negative relationship between bio-oil yield and logging residues' ash content in natural logarithms. The solid red dots are samples, and the blue line is the fitted curve. Based on the linear relationship through the log transformation, we stratified the depots and refineries evenly into ten categories by the range of ash content in the natural logarithm in Table 1. Each category corresponds to a specific ash content range in weight percent, as shown in the last column of Table 1. When a refinery or depot falls into a specific ash category, we assume its ash content is equal to the average of that category's upper and lower bounds. For example, if a depot is classified as Category 2, its *LN*(ash) falls between −1.23 and −0.85, and its level ash content is between 0.29 % and 0.43 %; thus, its ash content is approximated as (0.29 % + 0.43 %)/2 = 0.36 % for further calculations. This discretization approximates continuous ash levels while keeping the optimization model computationally feasible.[1]

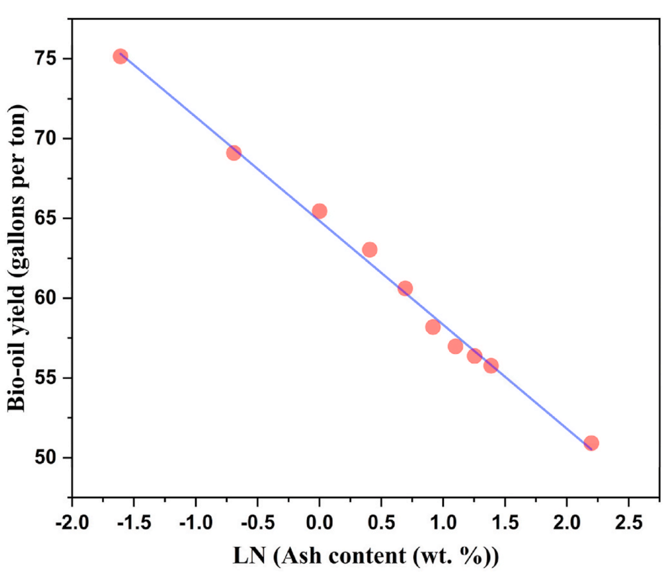

Fig. 5. Relationship between bio-oil yields and forest residues woody biomass ash content.

Table 1
Refinery and depot ash category.

Ash category	Received feedstock ash content at depot and refinery	
	LN (Ash content (wt. %))	Ash content (wt. %)
1	[NA, −1.23]	[0.00, 0.29]
2	[-1.23, −0.85]	[0.29, 0.43]
3	[-0.85, −0.47]	[0.43, 0.63]
4	[-0.47, −0.09]	[0.63, 0.92]
5	[-0.09, 0.29]	[0.92, 1.34]
6	[0.29, 0.67]	[1.34, 1.96]
7	[0.67, 1.06]	[1.96, 2.87]
8	[1.06, 1.44]	[2.87, 4.20]
9	[1.44, 1.82]	[4.20, 6.15]
10	[1.82, 2.20]	[6.15, 9.00]

3.1.2. *Optimization model description*

This study applies a two-stage MILP model to optimize the supply chains in Fig. 4. We evaluate two SAF supply chains from logging

[1] The discretization approach may affect the economics and layouts of the supply chain in the MILP model; however, the impact should be generally moderate, as the optimization decision is based on the relative input levels. Our robustness check confirms the modest influence.

residues and compare their SAF MSQ and NR: assuming either constant ash content in feedstock (like the conventional biofuel supply chain literature) or heterogeneous ash contents (illustrated in this study). Definitions of the parameters and decision variables are listed in Table 2.

3.1.3. First stage model

Equations (1)–(6) formulate the optimization of the first stage. The objective function (Equation (1)) in this study aims to minimize FHC on an annual basis, based on the highest harvesting density strategy [38] as well as the current year's forest inventory. Equation (2) ensures that the wood demands of the sawmills are met. Equation (3) ensures that the volume of logs harvested each year does not exceed the available forest inventory in the specific area. To accurately determine the available forest inventory for harvesting, Equation (4) differentiates private landowners into two categories, commercial and non-commercial, and assumes a WTH value of 0.45 for non-commercial landowners [37]. Equation (5) is an inventory balance constraint to assure that the forest inventory at the end of period t is equal to the inventory at the beginning of period t, minus the harvested volume and plus the forest growth from the ForSEAM model [39]. Equation (6) determines the quantity of newly generated residues as the product of the residue ratio and the harvested forest volume.

$$Min : FHC_t = \sum_i \sum_h \sum_a UFHC_{it} \times XF_{ihat} \tag{1}$$

$$DM_{hat} \leq \sum_i XF_{ihat} \tag{2}$$

$$\sum_h XF_{ihat} \leq AF_{iat} \tag{3}$$

$$AF_{iat} = FI_{iat} \times (CR + NCR \times WTH) \tag{4}$$

$$FI_{ia(t+1)} = FI_{iat} - \sum_h XF_{ihat} + FG_{iat} \tag{5}$$

$$RG_{it} = RR_i \times C2D \times \sum_h \sum_a XF_{ihat} \tag{6}$$

3.1.4. Second stage model

Equation (7) presents the objective of the second stage, which maximizes the NPVP associated with the logging residue-based supply chain that equals the total revenue, i.e., the product of *PSAF* and total SAF volume delivered to airports ($\sum_m YA_{mt}$), minus the total cost. According to the report from the Information Technology and Innovation Foundation (ITIF), the current costs of SAF from forest residue feedstock is about 3–4.5 times as much as conventional jet fuel and will decrease to 2.0 to 3.5 times by 2050 [40]. Our study assumes PSAF to be 3.0 times higher than the average US Gulf Coast Kerosene-Type Jet Fuel Price (adjusted for inflation) during 2022–2023, which is $9.09 per gallon [41]. The total cost encompasses the residue stumpage cost (SC_t), residue harvesting cost (RHC_t), residue preprocessing cost (PC_t), conversion cost (CC_t), and transportation cost (TRC_t). Equation (8) further breaks down the transportation cost (TCR_t) into three components: the cost of transporting green logging residues from harvesting sites to depots ($TCRD_t$), the cost of transporting pre-processed residues from depots to biorefineries ($TCDB_t$), and the cost of transporting SAF from biorefineries to airports ($TCBA_t$).

$$Max : NPVP = \sum_t \left[\left(PSAF \times \sum_m YA_{mt} - (SC_t + RHC_t + PC_t + CC_t + TRC_t) \right) \times (1 + IR)^{-t} \right] \tag{7}$$

Table 2
Definitions of subscripts, parameters, and variables.

Indices	Definition
i	Locations for forest inventory unit
a	Type of wood
h	Locations for sawmills
j	Locations for logging residues unit
k	Industrial park sites for depot
l	Industrial park sites for biorefinery
d	Biorefinery size
m	Locations for airports
t	Time period (year)
p	Depot ash category
q	Refinery ash category
Parameters	
UD	Upper bound of pre-processed feedstock send from a depot (dt)
LD	Lower bound of pre-processed feedstock send from a depot (dt)
UDA_p	Upper bound of ash content for each depot category
LDA_p	Lower bound of ash content for each depot category
LB_d	Lower bound of SAF produced from a size d biorefinery (gallon)
UB_d	Upper bound of SAF produced from a size d biorefinery (gallon)
LBA_q	Upper bound of ash content for q ash category biorefinery
UBA_q	Lower bound of ash content for q ash category biorefinery
RP	Conversion factor of logging residue to pre-processed feedstock (%)
BCY_q	Bio-oil conversion yield of q ash category biorefinery (gallon/dt of pre-processed feedstock)
DM_{hat}	The demand of wood type a from sawmill h in year t (cf)
DA_{mt}	The demand of aviation fuel from airport m in year t (gallon/year)
AF_{iat}	Available wood type a inventory that can be harvested at site i in year t (cf)
FI_{iat}	Private owned type a forest inventory at site i in year t (cf)
FG_{iat}	Type a forest growth amount at site i in year t (cf)
CR	Commercial share of private forest (%)
NCR	Non-commercial share of private forest (%)
WTH	Willingness to harvest (%)
AR_{jt}	Available logging residue could be harvested at site j in year t (dt)
RG_{jt}	Residue generated at site j in year t during the first stage (dt)
RRj	The ratio of logging residue vs. logs in site j
$C2D$	A conversion factor from a cubic feet to dry ton (dt/cf)
$UFHC_{it}$	Unit forest harvesting cost at forest site i in year t ($/ac)
IR	interest rate (%)
AC_k	Ash content of depot k (dt)
$SSAF$	Share of SAF among all bio-oil yields
$PSAF$	Price of SAF
Binary decision variables	
DVD_{kp}	whether an industrial k has been selected as any type p depot
DVB_{ldq}	whether an industrial l has been selected as any size d biorefinery of q ash category
Continuous decision variables	
XF_{ihat}	Amount of wood type a harvested at forest site i by loggers from sawmill h in year t (cf)
XR_{jkpt}	Amount of residues sent from residue site j to depot k of p ash category in year t (dt)
YD_{kpt}	Amount of preprocessed residues produced by depot k of p ash category in year t (dt)
XD_{kpldqt}	Amount of pre-processed residue sent from depot k of p ash category to size d biorefinery l of q ash category in year t (dt)
YB_{ldqt}	Amount of biofuel produced by size d biorefinery l of q ash category in year t (gallon)
XB_{ldmqt}	Amount of SAF sent from size d biorefinery l of q ash category to airport m in year t (gallon)
YA_{mt}	Amount of SAF sent to airport m in year t (gallon)
$SlackSAF_{mt}$	Slack variable of airport m in year t to ensure aviation fuel demand
$TCRD_t$	Total transportation cost from residue harvesting site to depot in year t ($)
$TCDB_t$	Total transportation cost from depot to biorefinery in year t ($)
$TCBA_t$	Total transportation cost from biorefinery to airport in year t ($)
TRC_t	Total residue transportation cost in year t ($)
PC_t	Total feedstock preprocessing cost in year t ($)
RHC_t	Total feedstock harvesting cost of the second stage in year t ($)

(*continued on next page*)

Table 2 (*continued*)

Indices	Definition
CC_t	Total conversion cost in year *t* ($)
SC_t	Total feedstock stumpage cost of the second stage in year t ($)
Objective variables	
FHC_t	Total forest harvesting cost in year t ($)
NPVP	Net present value of total profit over the study period ($)

$$TRC_t = TCRD_t + TCDB_t + TCBA_t \tag{8}$$

The residue inventory constraint at each hexagon is represented by Equation (9), which ensures that the residue harvested for each hexagon ($\sum_k\sum_p XR_{jkpt}$) does not exceed the available residues (AR_{jt}) each year. Equation (10) – (16) formulate all constraints relating to the depot. Equation (10) guarantees a material balance ratio (RP) between input ($\sum_j XR_{jkpt}$) and output (YD_{kpt}) (raw residues vs. preprocessed residues). Equations (11) and (12) establish the lower bound (LD) and upper bound (UD) for annual output at a depot, with the lower bound assumed to be 70 % of the nameplate capacity (i.e., the UD). Equation (13) ensures that the output of the depot (YD_{kpt}) and the quantity of feedstock transported to the biorefinery ($\sum_l\sum_d XD_{kcldt}$) are equal. Equation (14) restricts the establishment of only one depot in each hexagon. Finally, Equations (15) and (16) confirm that the amount of ash received by a specific depot falls within the corresponding range.

$$\sum_k\sum_p XR_{jkpt} \le AR_{jt} \tag{9}$$

$$YD_{kpt} = \sum_j XR_{jkpt} \times RP \tag{10}$$

$$LD \times DVD_{kp} \le YD_{kpt} \tag{11}$$

$$YD_{kpt} \le UD \times DVD_{kp} \tag{12}$$

$$YD_{kpt} = \sum_l\sum_d\sum_q XD_{kpldqt} \tag{13}$$

$$\sum_p DVD_{kp} \le 1 \tag{14}$$

$$LD \times DVD_{kt} \times LDA_p \le \sum_j AC_k \times XR_{jkpt} \tag{15}$$

$$\sum_j AC_k \times XR_{jkpt} \le UD \times DVD_{kt} \times UDA_p \tag{16}$$

Equations (17)–(23) outline all constraints for the biorefinery. Equation (17) guarantees a material balance between pre-processed residues and biofuel at conversion facilities. The lower and upper bounds for annual output of refineries of different sizes are defined by Equations (18) and (19). E quation (20) requires that the quantity of SAF transported to the airports ($\sum_m XB_{ldmqt}$) matches the output of the biorefinery (YB_{ldqt}). Equation (21) restricts the establishment of more than one refinery in a hexagon. Equations (22) and (23) ensure that the amount of ash received by a refinery falls within its designated range. Finally, equation (24) ensures that the amount of SAF shipped from the biorefinery ($\sum_l\sum_d XB_{ldmqt}$) equals the quantity shipped to the airport (YA_{mt}). Equation (25) meets the SAF demand at airports.

$$YB_{ldqt} = \sum_k\sum_p XD_{kpldqt} \times BCY_q \tag{17}$$

$$LB_d \times DVB_{ldq} \le YB_{ldqt} \tag{18}$$

$$YB_{ldqt} \le UB_d \times DVB_{ldq} \tag{19}$$

$$SSAF \times YB_{ldqt} = \sum_m XB_{ldmqt} \tag{20}$$

$$\sum_d\sum_q DVB_{ldq} \le 1 \tag{21}$$

$$LB_d \times DVB_{ldq} \times LBA_q \le \sum_k\sum_p \left[\left(UDA_p + LDA_p\right)/2\right] \times XD_{kpldqt} \times BCY_q \tag{22}$$

$$\sum_k\sum_p \left[\left(UDA_p + LDA_p\right)/2\right] \times XD_{kpldqt} \times BCY_q \le UB_d \times DVB_{ldq} \times UBA_q \tag{23}$$

$$YA_{mt} = \sum_l\sum_d\sum_q XB_{ldmqt} \tag{24}$$

$$YA_{mt} + SlackSAF_{mt} = DA_{mt} \tag{25}$$

4. Results and discussion

In the first stage, logging residues concentrate along the borders of Tennessee, Virginia, and North Carolina, as well as in northeastern Georgia and some southwestern areas (as shown in Fig. 6). Not surprisingly, the residue distribution pattern is aligned with the forest resources and sawmills' locations illustrated in Figs. 1 and 2. The demand for wood at sawmills drives the area of forest harvesting.

In the second stage, when using the average constant ash content of collected samples (1.62 %), i.e., constant ash content, and its corresponding bio-oil yield, the annual MSQ of SAF could reach 629 million gallons and an additional 446 million gallons of other biofuels (the left bar in the left panel of Fig. 7). A combination of 18 biorefineries (with an average annual capacity of 80 million gallons of biofuel) and 85 depots (handling 200,000 dry tons of pre-processed feedstock per year) is located under this scenario. The total cost is $5.76 per gallon, comprising harvesting ($0.38), stumpage ($0.10), preprocessing ($1.44), conversion ($3.25), and transportation ($0.59), as shown in the left bar of the right panel in Fig. 7. Given a $9.09 per gallon price for SAF defined in Section 3.3.2, its NR reaches $3.33 per gallon.

In the scenario of incorporating spatially heterogeneous ash contents, the MSQ of SAF per year reduces to 540 million gallons (the right bar in the left panel of the figure), generated from 16 biorefineries (with an average scale of 77 million gallons of biofuel per year) and 80 depots. In this scenario, the total production cost is $5.92 per gallon (up by 2.78 % compared to the constant ash content scenario), and the SAF NR is down to $3.17 per gallon (a 4.80 % reduction). The lower SAF production and higher production cost when considering ash content variations in logging residues are due to lower throughput in conversion (i.e., lower bio-oil yield from the same amount of logging residues) in areas with high ash content. Neglecting ash variations in feedstock and using a constant ash content and fixed bio-oil yield likely overestimates feedstock availability and the corresponding SAF production, as shown in the constant ash content scenario.

When assuming constant feedstock ash content, a total of 276 million dry tons of residues are harvested to meet the facilities' demand for a decade. After taking ash content variations into account, the harvested logging residues decrease to 252 million dry tons, representing an 8.70 % reduction, due to the higher ash contents in certain areas and the adverse impacts on SAF outputs. This spatial contraction highlights potential gains from deploying ash-reduction preprocessing selectively in high-ash areas [42]. Fig. 8 depicts the distribution of logging residue harvesting in both scenarios. The black dots in the lower panel of the figure present the reduced harvested areas in the heterogeneous ash content scenario compared to the constant ash content one, given the higher ash contents in these areas.

The reduction in harvest area has significant implications for the

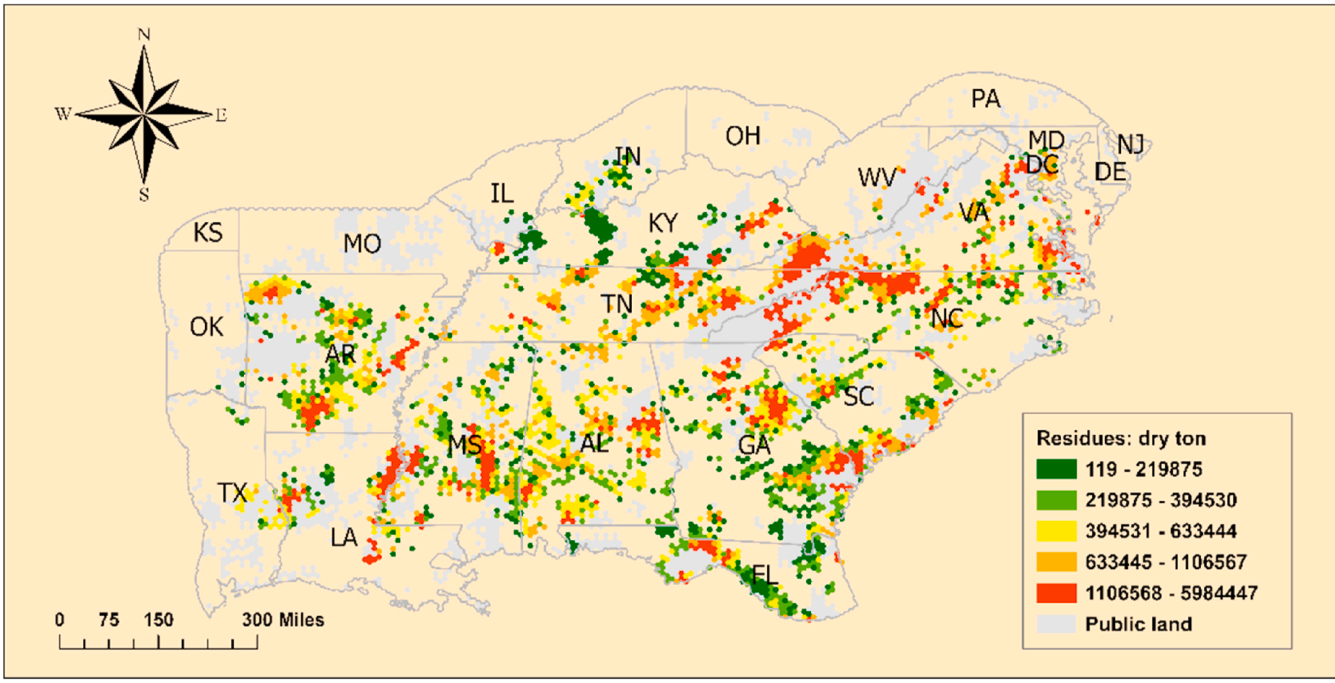

Fig. 6. The distribution of the total harvested logging residues in the study area.

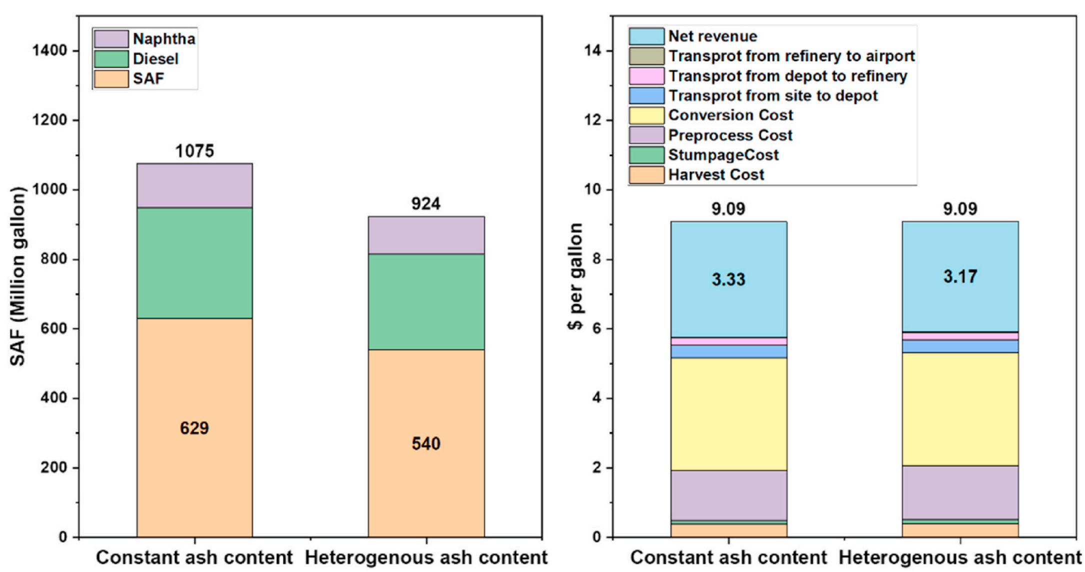

Fig. 7. MSQ and NR by segment.

spatial configuration of depots and refineries. As illustrated in Fig. 9, the model selects 17 refineries under the constant-ash scenario (top panel). In contrast, the heterogeneous-ash scenario results in the selection of only 15 refineries (bottom panel), leading to the exclusion of two sites: Meriwether, GA (60 million gallons) and Cleveland, NC (60 million gallons). Additionally, one site is relocated from Wilson, TN, to Davidson, TN, approximately 51 miles away.

Among the remaining operational sites, the model adjusts facility capacity with notable disparities: one site reduces capacity by 30 million gallons, two sites each downsize capacity by 20 million gallons, two sites each lower capacity by 10 million gallons, and only one site increases capacity by 10 million gallons. Consequently, accounting for feedstock ash variability results in an overall reduction of 200 million gallons in capacity compared to the constant-ash scenario. The average total cost per site varies, ranging from −1.44 % to +6.30 %, with a mean increase of 3.01 %. The observed spatial reconfiguration is consistent with the guideline delineated in the SAF Grand Challenge Roadmap, which underscores the influence of feedstock-quality variability on conversion performance and site selection decisions.

Fig. 10 depicts the estimated quantity of SAF shipped to various airports per year. Seven airports are identified as destinations of SAF in both scenarios. In the heterogeneous ash content scenario, Charlotte Douglas International Airport (CLT) and Hartsfield-Jackson Atlanta International Airport (ATL) experience the largest decline in SAF: The annual SAF availability decreases from 98 to 72 million gallons (26.53 % reduction) in the CLT and from 148 to 115 million gallons in ATL (22.30 % decrease). The disparity in SAF variation across different airports stems from the spatial heterogeneity of ash distribution generated from the samples in the study. The feedstock ash content near CLT and ATL airports is higher, while it is relatively low near other airports (as shown

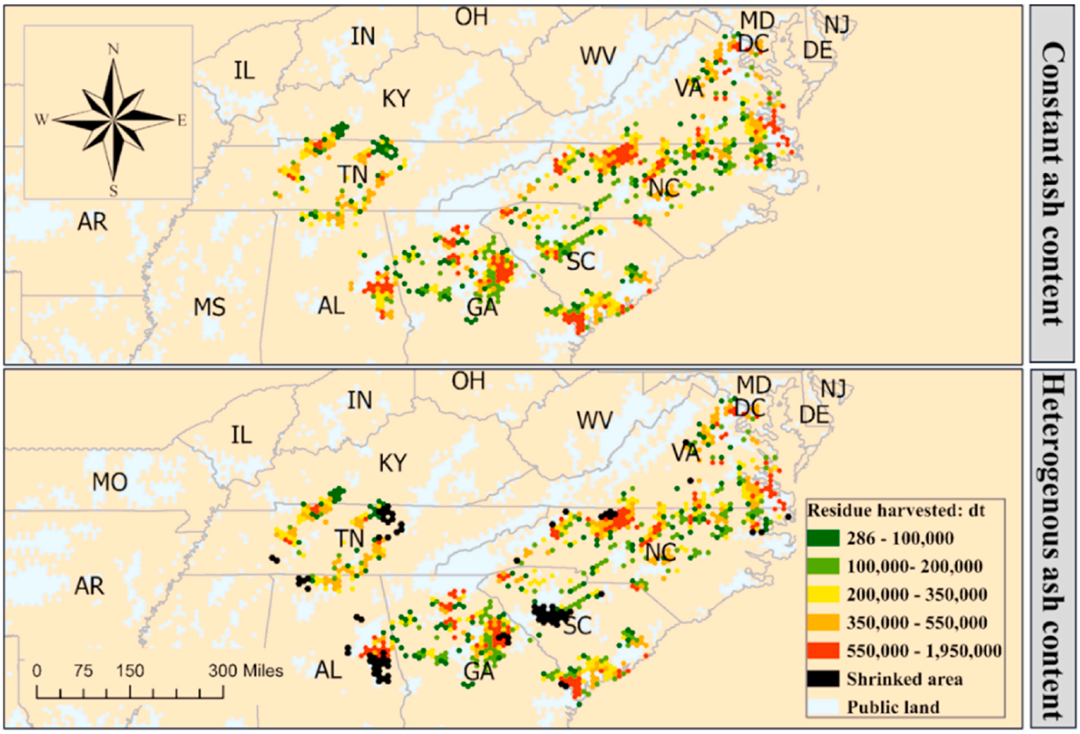

Fig. 8. Logging residue harvesting areas.

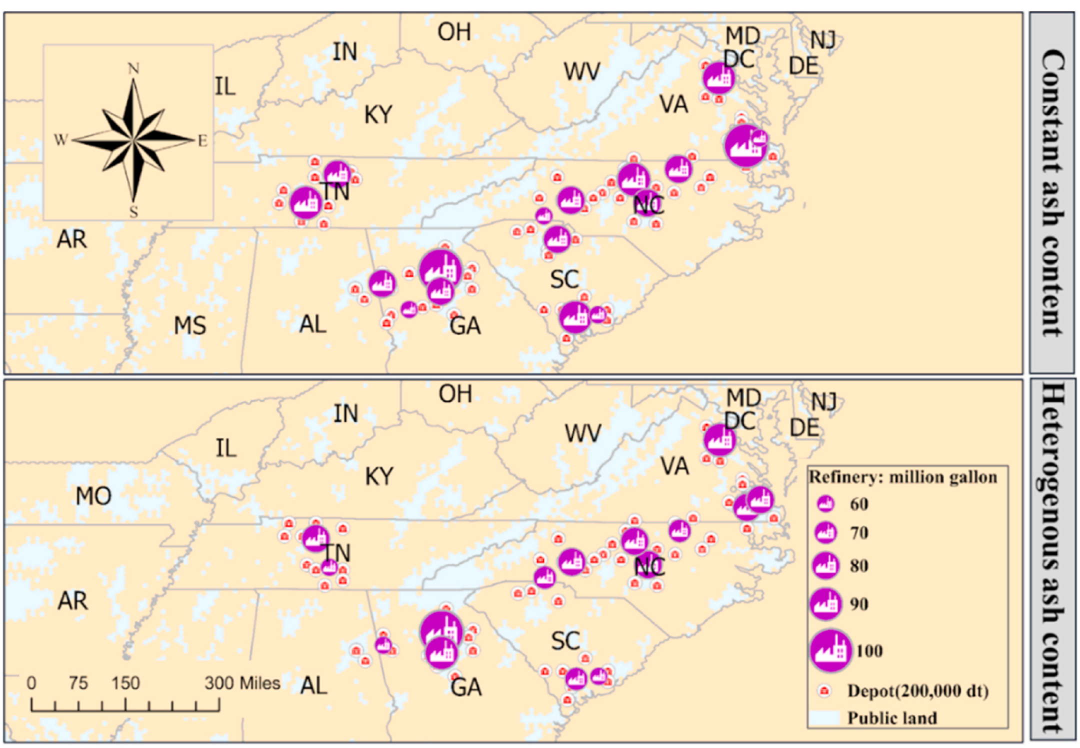

Fig. 9. Preprocessing and conversion facilities placements.

in Fig. 2). Primarily, the depots near CLT and ATL airports experience a significant decline in the raw materials harvested given their higher ash content. Moreover, higher feedstock ash content leads to lower throughput at the biorefinery, resulting in a substantial reduction in the amount of SAF supplied to these two airports.

5. Conclusion

This paper develops a spatial, two-stage MILP for a logging-residue-based SAF supply chain using fast pyrolysis and bio-oil hydrotreatment. The model explicitly links feedstock ash content to conversion yields in the supply chain when determining residue collection, depot and

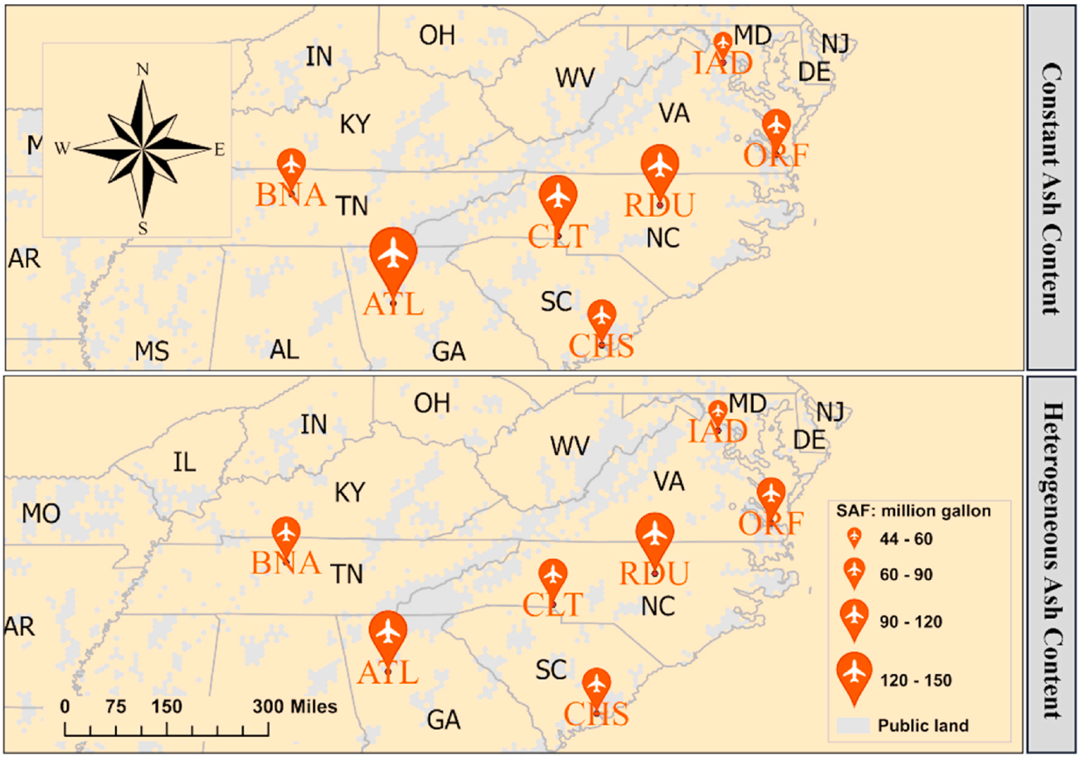

Fig. 10. Estimated SAF shipment to airports.

refinery sitting and sizing, and airport deliveries.

Accounting for spatially heterogeneous ash materially changes optimal system design and economics relative to a constant-quality baseline. In our case study, incorporating measured ash variability across the Southeast reduces annual SAF production by 14.15 %, net returns by 18.27 %, and harvested residues by 8.70 %. Additionally, the supply chain shifts toward fewer or smaller conversion facilities in different locations. Airport deliveries exhibit uneven reductions, with the most significant declines occurring near areas with high ash content in logging residues.

Our findings suggest that implementing quality-aware planning can more effectively manage project uncertainties and accelerate deployment. Developers are encouraged to integrate statistically sound quality sampling into their procurement processes and position depots and refineries to balance logistics with both volume and quality. Additionally, adopting best management practices and mechanical separation methods helps reduce the ash content in biomass during harvesting and processing, ultimately benefiting the supply chain for logging-residue-based SAF. Policymakers can enhance feedstock supply by supporting practices and infrastructure that reduce ash content and by promoting quality specifications in contracts.

One caveat of our study is the limited number of residue samples, which hinders our ability to precisely capture the spatial variability in ash content across the study area. The spatial pattern may change as more samples are collected, resulting in different supply chain economics and layouts. In addition, our study focuses on the fast pyrolysis/hydrotreatment pathway, but the impact of ash content on product yields will differ across various conversion pathways. Consequently, the supply chain optimization results are likely to vary as well. Nevertheless, the findings derived from our dataset underscore the significant implications of feedstock quality in the economics and configuration of the SAF supply chain.

Future research can enhance this analysis by increasing sample density and incorporating additional data sources. Additionally, we can broaden the scope to include other quality attributes beyond ash content, account for uncertainties across different stages in the supply chain, and assess the transferability of our findings across regions and conversion pathways.

CRediT authorship contribution statement

Pengzhen Li: Writing – original draft, Methodology, Formal analysis. **T. Edward Yu:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Nicole Labbé:** Writing – review & editing, Formal analysis, Data curation. **Nourredine Abdoulmoumine:** Writing – review & editing, Formal analysis, Data curation. **Manuel Garcia-Perez:** Writing – review & editing, Formal analysis. **Kevin P. Hoyt:** Writing – review & editing, Data curation. **Burton C. English:** Writing – review & editing.

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Data availability

Data will be made available on request.

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