sustainability

MDPI

Review

Effects of Production of Woody Pellets in the Southeastern United States on the Sustainable Development Goals †

Keith L. Kline [1,*], Virginia H. Dale [2,3], Erin Rose [2] and Bruce Tonn [2]

1 Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA
2 Three3, Inc., Knoxville, TN 37902, USA; vdale@utk.edu (V.H.D.); erose@threecubed.org (E.R.); btonn@threecubed.org (B.T.)
3 Department of Ecology and Evolutionary Biology, University of Tennessee, Knoxville, TN 37996, USA
* Correspondence: klinekl@ornl.gov

Abstract: Wood-based pellets are produced in the southeastern United States (SE US) and shipped to Europe for the generation of heat and power. Effects of pellet production on selected Sustainability Development Goals (SDGs) are evaluated using industry information, available energy consumption data, and published research findings. Challenges associated with identifying relevant SDG goals and targets for this particular bioenergy supply chain and potential deleterious impacts are also discussed. We find that production of woody pellets in the SE US and shipments to displace coal for energy in Europe generate positive effects on affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), industry innovation and infrastructure (SDG 9), responsible consumption and production (SDG 12), and life on land (SDG 15). Primary strengths of the pellet supply chain in the SE US are the provisioning of employment in depressed rural areas and the displacement of fossil fuels. Weaknesses are associated with potential impacts on air, water, and biodiversity that arise if the resource base and harvest activities are improperly managed. The SE US pellet supply chain provides an opportunity for transition to low-carbon industries and innovations while incentivizing better resource management.

Keywords: bioenergy; forests; pellets; southeastern United States; Sustainable Development Goals

Citation: Kline, K.L.; Dale, V.H.; Rose, E.; Tonn, B. Effects of Production of Woody Pellets in the Southeastern United States on the Sustainable Development Goals. *Sustainability* **2021**, *13*, 821. https://doi.org/10.3390/su13020821

Received: 19 November 2020
Accepted: 11 January 2021
Published: 15 January 2021

1. Introduction

Since 2007, wood-based pellets have been produced in the southeastern United States (SE US) and shipped primarily to Europe for the generation of heat and power. As such, the supply chain has implications for forests in the SE region of the US, local forestry-sector employment, trans-Atlantic trade, and European efforts to reach renewable energy goals. Areas that source biomass for wood pellets in the SE US range across 13 states, from the Atlantic seaboard in the east (Virginia, North and South Carolina, Georgia, and Florida) to the eastern fringes of Oklahoma and Texas in the west, with Louisiana, Mississippi, and Alabama along the Gulf of Mexico and north to include the land-locked states of Arkansas, Tennessee, and Kentucky. In this paper, the SE US includes these 13 states (Figure 1). However, states that lead production of wood pellets for bioenergy are those with efficient access to large shipping ports such as North Carolina and Georgia.

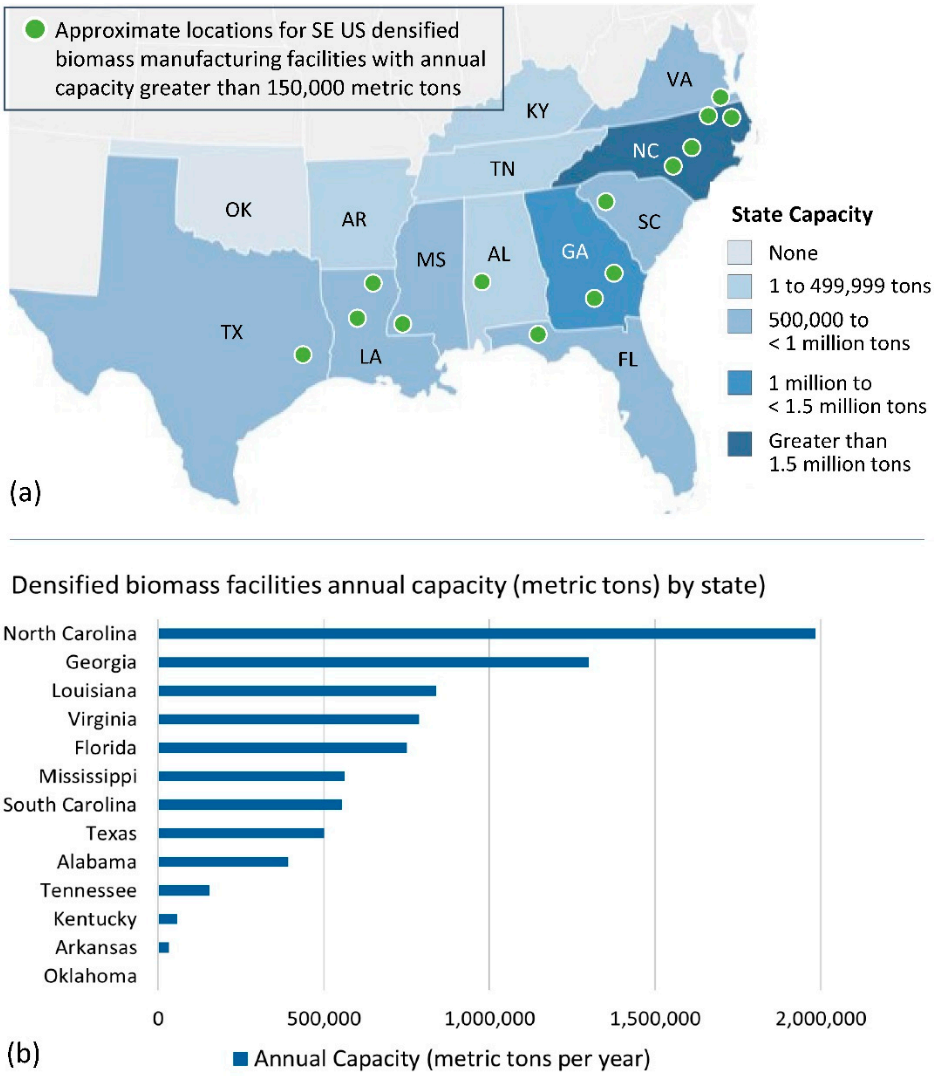

Figure 1. (**a**) SE US states and approximate locations of largest operating pellet mills; (**b**) annual operational production capacity by state reported by the US Energy Information Administration as operating in September 2020.

Understanding the wood pellet supply chain requires some knowledge of the history of the timberlands in the SE US from which the pellets are sourced. Timberland is defined by the US Forest Service as "nonreserved forest land capable of producing at least 20 cubic feet of wood volume per acre per year" [1]. Timberlands are the primary source for woody biomass supporting SE forest industries. The timberland definition excludes reserved forest lands where logging is prohibited due to federal, state, or local restrictions. The definition includes land that is managed for forestry and meets the productivity threshold, even if land that has recently been logged or disturbed and temporarily lacks forest cover.

Before European settlement in the new world, SE US forests were actively managed by extensive and repeated use of fire for thousands of years by Native Americans [1–3]. Subsequent decades led to expanding settlements, large-scale logging, land clearing, and continued, widespread use of fire until the 20th century [4–6]. Up until the end of the Civil War in 1865, the landscape was dominated by large plantations for cotton, tobacco, rice, and other crops. Over centuries, as land was claimed for agriculture, accessible mature forest stands were logged, with a boom in timber removal from 1860 to the 1920s [7]. However, steep slopes, thin soils, and climatic conditions make much of the landscape unsuited to agriculture. Fields suffered from soil erosion and nutrient depletion and were abandoned over time to become secondary forests [8,9]. The composition and extent of secondary forests reflects historical disturbances, competing land uses, and anthropogenic enhancement or suppression of fire [4]. Over the course of the twentieth century, agriculture production in the US shifted to the midwestern states, and forests in the SE recovered (Box 1). Thus, this region supports more forests today than it did a century ago [1,7].

Box 1. Historic patterns and drivers of forest transitions in the SE US.

The land-cover changes that lead to current forest cover and composition in the SE follow a general pattern since the 1920s. Land-cover transitions from open or scrubland, to secondary pine forests, to mature pine stands or to southern mixed hardwoods, and, in recent decades, to developed uses [9]. The location and timing of developments such as dams, wetland draining, river dredging, establishment of highways, and other human disturbances related to settlements and infrastructure, as well as natural disturbances (hurricanes, tornadoes, floods, droughts, wildfire), also influence today's forests.

Unlike other regions where political, regulatory, and geophysical boundaries offer protection to forests, extensive private forest lands in the SE US have few restrictions to conversion to other uses [10]. Indeed, conversion of forests to development and other uses and effects associated with climate change are among the top threats to the SE forest ecosystems today [9,11]

Analyses of the region's timber sector help illustrate that the types and rates of transition from agricultural lands to secondary forests and plantations varied temporally and spatially, e.g., [12,13]. From the 1920s to 1950s, areas undergoing transitions were relatively small and dispersed, and change was gradual. Large pine plantations were rare, and forest recovery occurred as abandoned farm fields returned to pine or mixed pine-hardwood forests via natural regeneration. From 1950-1960, pine plantations began to increase rapidly, peaking at over 400,000 hectares per year in new plantations (or expansionary planting as opposed to replacement planting following timber harvest) in the early 1960s. This 1960–62 spike in tree planting is attributed to subsidies under the US Department of Agriculture (USDA) Soil Bank program [13]. A similar and more prolonged spike in expansionary tree planting occurred from 1986 to 2000, again catalyzed by USDA subsidies, as low crop prices led to massive enrollment to plant trees in the SE through the USDA Conservation Reserve Program (CRP). Eligibility for the Soil Bank and CRP subsidies was limited to private, non-industrial landowners. Their investments in tree planting created a large group of stakeholders among family farmers and small landowners distributed throughout the region. In 2017, these non-corporate owners held 57% of total timberland in the region [7]. As these subsidized pine plantations mature, they require harvest or management interventions. However, many dispersed, privately owned woodlots on former fields received little management attention after initial tree planting and, therefore, have become timberland stands of mixed species and qualities.

Private industrial interests, meanwhile, were accumulating land and establishing plantations in strategic locations per business plans. Annual rates of tree planting by these industrial parties reflects a gradual expansion of plantations designed to align future harvests with expected demand. Over the decades since 1950, corporate and industrial plantations have grown to represent about 30% of total timberland in the SE [7]. Corporate plantations tend to be clustered around large mills or near rail and water transport facilities and are more actively managed and harvested than non-corporate timberland.

Land ownership, tax laws, and external economic factors influence SE forest management and markets. Since the 1970s, tax and investment incentives have encouraged the widespread sale of large timberland real estate assets by the traditional forest product industry (i.e., industrial landowners such as Weyerhaeuser). Large timberland blocks have been sold to timberland real estate investment trusts, known as REITs, or other large institutional investors (e.g., endowments, foundations, state pension funds) who, in turn, hire timberland investment management organizations, or TIMOs to manage the forests [14]. Four major forest management groups in the SE US can now be distinguished by their distinct ownership and investment goals: private, non-industrial, family owners; TIMOs; REITs; and forest product company, industrial owners [14]. Unlike most other parts of the world, the influence of public land policies on forest products and biomass supply is minimal, as less than 13% of timberland in the SE is owned by federal, state, or local governments [7]. Furthermore, most public timberlands in the SE are managed for multiple uses other than timber production. Harvests from federal timberlands represented just one percent of total removals in 2016 in the SE US [7].

In addition to the effects of changing land management across the region's forest systems, the SE US experiences frequent disturbances to forests including floods, fire, insect outbreaks, droughts, tornadoes, hurricanes, and invasion of nonnative species [15]. Furthermore, climate change is fostering salt-water intrusion into coastal forests. While the SE US forests often quickly reestablish after perturbations, these landscapes are a patchwork of tree ages and species composition depending on the type, intensity, and time since past disturbances. Forest resources have been harvested for timber, chips, and pulp for centuries. However, large-scale production of densified biomass, or wood pellets, for energy and export is a new enterprise that has been rapidly growing since 2008.

The aim of this paper is to evaluate how the production of wood pellets in the SE US affects the Sustainable Development Goals (SDGs) adopted in 2015 by the United Nations (UN) General Assembly [16]. Seventeen SDGs were developed through a multi-year process facilitated by the UN to provide a "blueprint to achieve a better and more sustainable future for all" [17]. The SDGs are intended to be achieved by the year 2030, and each goal has specific targets [18]. The goals and targets are designed to acknowledge that ending poverty and other deprivations must build upon strategies to improve health and education, reduce inequality, and foster economic growth while also addressing climate change and preserving our oceans and forests. Hence, evaluating how production of wood pellets in the SE US affects the SDGs provides insights about opportunities and constraints for similar supply chains to contribute to the achievement of international goals for social, environmental, and economic improvements.

The SDGs set ambitious 2030 targets to sustainably manage forests, stop land degradation and biodiversity loss, and increase the use of renewable energy twofold [16]. To achieve these goals, it is essential to improve the efficiency and effectiveness of forest management, because forests support the livelihoods of more than 1.6 billion people as well as more than 80 percent of all terrestrial species of animals, plants, and insects [19]. Furthermore, economical, renewable fuels need to be provided in a way that is environmentally sound and socially accepted. Woody fuels are used by more than 3 billion people worldwide to meet basic energy needs [20]. Thus, producing wood-based energy in a way that helps achieve environmental, social, and economic goals simultaneously is strategically important for achieving progress toward the SDGs.

Woody biomass for bioenergy is promoted to help mitigate climate change through displacement of fossil fuels and by increasing the resilience of forest ecosystems as carbon sinks through better management of natural resources [21,22]. However, bioenergy's climate mitigation potential, as well as effects on other SDGs, depends, in part, on local conditions [23], as well as on the scale and intensity of production for different types of feedstock and their supply chains [24].

This paper represents one example of over 30 distinct supply chain analyses that are being assembled by the IEA Bioenergy inter-task project on the "Role of Bioenergy in a WB2/SDG world" [25]. Each case study summarizes a specific supply chain and its relationships with selected SDGs. The aim of the inter-task project is to expand and disseminate knowledge about how biomass production systems can be designed to contribute to the SDGs by improving conditions for society, biodiversity, and continued provision of multiple ecosystem services [25]. This paper contributes to that aim.

Here, we summarize the supply chain for procurement of wood pellets in the SE US including their transport to Europe and use for electricity and heat. The effects of the supply chain on the selected SDGs and established SDG targets are discussed. The benefits and challenges of this approach to evaluate progress toward sustainability are also discussed. Major lessons about the use of SDGs to assess sustainability of wood pellets based on this review and preliminary results of the IEA Bioenergy analysis of 20 systems are also presented.

2. Materials and Methods

This analysis is based on a review of literature and data on the SE US biomass pellet supply chain and evaluates its effects on selected SDGs. The full set of 17 SDGs was initially screened to identify five SDGs that were considered most relevant in terms of effects attributable to this supply chain, in compliance with the guidance from the IEA Bioenergy inter-task project. The narrowed focus is meant to facilitate structured data aggregation, analyses, and comparison across case studies from around the world. The process to narrow the focus on five SDGs was iterative and based on discussions among coauthors of candidate SDGs and the corresponding targets established for each SDG as well as on guidance from IEA Bioenergy collaborators.

Selecting a manageable set of SDGs (5 of 17) and targets (7 of the total 169) was not trivial. By using industry information, available energy consumption data, and published research findings, we determined that enough evidence exists to suggest that the production of woody pellets in the SE US for the purposes of bioenergy, on net, generates positive effects on affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), industry innovation and infrastructure (SDG 9), responsible consumption and production (SDG 12), and life on land (SDG 15). The seven targets selected for these five SDGs were increasing the share of renewable energy (7.2); increasing efficiency and sustainability—decoupling growth from environmental degradation (8.4); developing inclusive, sustainable, small-scale industries (9.2 and 9.3); upgrading industries with clean, climate-smart technologies (9.4); implementing more sustainable natural resource management (12.2); and halting deforestation and restoring degraded forests (15.2).

The author team discussed options to document supply chain effects (both beneficial and detrimental) on SDG 1 to end poverty, SDG 3 for good health, SDG 6 for clean water, SDG 13 on climate and air emissions, and SDG 17 to strengthen partnerships and resource mobilization. However, we found that information on these additional SDG targets was more limited, anecdotal, or impossible to interpret and clearly link to the woody pellet supply chain. However, supply chain weaknesses and potential detrimental impacts that were identified are considered in the discussion below.

The ability to cite reliable data and published research results that focus on the effects of this supply chain was ultimately the key factor that helped narrow the focus on five SDGs. Our determination of effects of woody pellet production on SDGs is based on publicly accessible industry information; government reports and data on US energy resources, feedstocks, and use; and published scientific findings focusing on a timeframe from pre-pellet industry expansion to most recent available data (i.e., approximately 2000–2019). Data that were reported by US industrial sources and agencies in short tons or acres were converted to metric tons and hectares. Thus, "tons" herein refers to metric tons.

3. Results

3.1. Processes, Feedstocks, and Stakeholders Involved in the Production of Woody Pellets in the SE US

Wood-based pellets are produced in the SE US and shipped to Europe for the generation of heat and power (Figure 2). This supply chain, although relatively new, has been the subject of many published analyses as well as new data acquisition efforts to monitor and account for wood pellet trade volumes, e.g., [26–30]. One of the most important cost elements for large operations designed for pellet exports in the SE US is the feedstock cost [31]. Thus, new pellet mills are typically located in areas with large volumes of standing timber with relatively low value (i.e., low stumpage price) due to lack of market demand or areas where other forest industries generate large volumes of woody residues. Timberlands with low prevailing stumpage prices have stands available for harvest that have not been cut either because they are low-grade and do not meet quality requirements for local markets for lumber and/or pulp production or because they have become stranded forest assets, meaning that there are no operating mills close enough to make harvesting and shipment economically competitive at a higher price. Such stands are scattered across the region and contribute to the trend of significantly expanding timberland stocks relative to removals in the SE [7]. The low-value woody biomass in such timberlands, although sometimes described as "unloved wood", offers potential resources to help society achieve renewable energy goals [32]. In recent decades, dozens of paper mill closures across the SE US have contributed to such economically stranded stands [33–35].

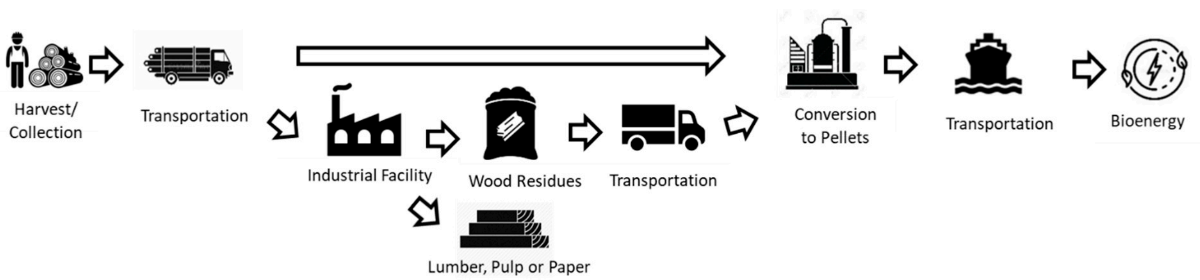

Figure 2. SE US supply chain for production of woody pellets used for bioenergy.

Pellet mills that export to Europe employ business models for sourcing biomass from least-cost suppliers that can demonstrably meet established requirements for quality and sustainable forest management [26]. While the local conditions and opportunities vary over time and space, woody material is typically sold for pellets only if market conditions make it impossible to sell that biomass for higher-value products such as sawtimber, pulp, paper, fiber, and composites [28]. Hence, wood-based pellets produced in the SE US derive primarily from residuals of timber harvested and processed for other products [30] (addressing SDG 9: responsible consumption and production).

Although production of wood-based pellets for export to Europe and Asia has drastically increased in the past decade, data sets on timber product outputs maintained by the US Department of Agriculture's Forest Service (USFS) suggest that biomass for wood-based pellets comprised only about 3% of total industrial wood harvest removals in the SE US in 2018 [33,36]. An analysis of wood sources and use by pellet mills in 2011 found that pellets accounted for less than 1 percent of total timber use in the SE US, increasing to under 2% in 2015 [36]. The same study found that pellet production (for domestic use and export) represented 27% of all industrial fuelwood uses in the region in 2015, illustrating the continued importance of woody residues as a source of industrial heat and power in forest products industries. More recent timber-products output data show that all biomass and residues used for energy (which includes wood residues used for other manufacturing processes in the mills, firewood, chips, pellets, residues burned for domestic use as well as woody biomass exports for bioenergy) sum to 18 million tons green (undried biomass) in 2018 [33] (Core Table 3.1 Volume (green tons) of roundwood by timber product, major species, and source, 2018). This amount represents about 6% of the 363.3 million green tons of total removals that year in the SE US. Estimating that pellets make up 27% of the total industrial fuelwood uses in 2018, woody biomass in pellets would represent under 2% of the volume of total annual removals in the region.

Woody biomass for utility grade densified pellets derives from multiple sources. Virtually all biomass for pellets in the SE US is sourced from private forests. In the SE, 60% of private timberlands are owned by families where harvesting operations are typically conducted by professional loggers in accordance with best management practices established by state authorities [37,38]. Landowners often hire professional foresters to manage and harvest their trees and are not aware of the practices employed. Influences on the willingness of landowners to supply biomass for energy include having a good price, noninterference with traditional sawtimber income, and compatibility with the owners' management and conservation goals [39]. About 20% of feedstock is roundwood [30] derived from forest thinning or timberlands planted to supply mills that have closed and become economically stranded from other potential markets. The other 80% of feedstock for pellets comes from secondary sources, such as sawdust and residues from primary timber processing activities associated with other mills. Forest sector residues also include biomass collected from harvest activities that primarily serve higher-value markets, such as the tops of trees cut for sawmills and roundwood that is culled as otherwise unmerchantable. Residues collected at time of harvest typically are delivered directly from the forest harvest site to the pellet mill.

Forest industry residues from primary mills have many potential uses. Residues can be shipped to neighboring pellet mills if prices and logistics are mutually beneficial. However, the chain of custody becomes more difficult to verify, and supply is less reliable, when biomass residues are supplied to pellet mills from secondary sources, leading some mills to prefer vertical integration to retain control over the entire supply chain [26]. The share of feedstock for pellets reported as being sourced from mill residues and wastes has been increasing in recent years, along with increasing output from SE US sawmills [30,36]. An analysis of industrial survey data found that in 2015 more than 45 million green tons of primary mill residues were generated and utilized, with 2.1 million tons for pellets, 9.5 million tons for energy in the primary mills themselves, and the remainder going to fiber, composites, small dimension products, animal bedding, mulch, charcoal, and many other uses [36].

While effects associated with forest management and harvest have dominated public debates surrounding wood pellets [40], subsequent steps in the supply chain are important both economically and with regard to potential impacts on air, water, health, and worker safety. About 20% of the roundwood for forests is transported directly to a pellet mill, and 80% goes to industrial processing mills for structural lumber, composite panels, veneer, poles, posts, pulp, and fiber products. From these forest industrial product facilities, sawdust and residues are shipped to pellet mills. The pellet mill grinds and densifies the feedstock into pellet form by onsite chipping, hammering, drying, and milling. These processes generate noise and air emissions, including smoke from low-grade biomass used for drying and heating—influencing both SDG 3 (good health) as well as SDG 13 (climate and air emissions). From pellet mills, the densified product is transported to a port facility and onward by deep-water marine transportation to the end users, which are primarily in the United Kingdom (UK) and other European nations. Anytime that large quantities of biomass are handled and stored, risks arise that require precautions to avoid accidents and fires [41].

Primary drivers for the SE wood pellet supply chain are (a) reducing fossil fuel dependency in the UK and European Union based on national incentives and the European Renewable Energy Directive [42,43]; (b) having volumes of growing stock in the SE US region that exceed other demands, combined with having established infrastructure for timber harvest and transportation to ports [1,44]; and (c) promoting more sustainable forest management and resilient rural economies based on renewable forest products.

Exports of wood pellets from the SE US have grown from near zero in 2007 to more than 738,000 tons exported during a single month in 2019 [44]. Total annual US pellet exports for 2019 sum to 6.9 million tons and are valued at 945 million US dollars. These exports are used to reduce greenhouse gas emissions from coal combustion by increasing the use of renewable energy in electric power plants in response to European Union (EU) policies [45,46] (addressing SDG 17: strengthen partnerships and resource mobilization). Recently, US pellet exports are also being shipped to Asian markets.

The stakeholders in this supply chain include residents in communities sourcing primary biomass and providing labor, private forest landowners (family and corporate), foresters, truck drivers, pellet mill owners, the shipping industry, utilities in the UK and EU, forest certification groups, local governments and businesses, civil society organizations such as environmental non-governmental organizations (ENGOs), and other members of society who benefit from forest ecosystem services such as aesthetic value and carbon sequestration. Effects of the supply chain on stakeholders vary depending on many contextual conditions. Stakeholders most directly affected economically include contractors and other workers involved in the harvest, collection, loading, and transport of biomass for delivery to pellet mills and workers involved in construction, operation and maintenance of the mills as well as other forest product industries that generate residues or compete for feedstocks.

Private (non-industrial) forest landowners are important stakeholders. Most timberland in the eastern US is held by small, private landowners. Therefore, private landowner willingness to provide biomass and attitudes toward sustainable management requirements are important considerations for the bioenergy supply chain and have been studied extensively, e.g., [39,47–54]. In the SE US, the majority of nonindustrial private landowners are open to selling woody biomass for producing bioenergy, particularly when competitive prices are supported by long-term markets, such as an established mill in the vicinity [39]. Private landowner willingness to sell biomass for energy can increase if technical assistance is provided to improve stand productivity, and if they believe that biomass removals will reduce fire and disease risk (concerning SDG Target 15.2: restoring degraded forests).

In rural areas where traditional forestry activities have recently declined and mills have closed, jobs and investments associated with the pellet supply chain generate interest from local stakeholders such as foresters, truckers, workers in ports and shipping, local governments, and businesses [34,35] and addresses SDG 8: decent work and economic growth; as well as SDG 9: industry innovation. However, ENGOs raise concerns about the effects of pellet production and use on forest biodiversity and carbon dynamics [40]. Environmental justice concerns about community impacts (e.g., excessive emissions of air pollutants from mills not properly implementing environmental safeguards) are raised due to pellet mill establishment in areas of high poverty [55]. Thus, although some stakeholders, including local leaders, emphasize communities' desire for investments in value-added processing that can improve livelihoods [56] and hence addresses SDG 1 (ending poverty), the effects of mill operations on other stakeholders need to be monitored and negative impacts mitigated. European stakeholders include utilities that are incentivized to replace fossil fuels with pellets by the national goals for clean energy and the European Renewable Energy Directive [42], addressing SDGs 9 (clean, climate-smart industries) and 13 (actions to combat climate change). The maritime shipping industry sees advantages in transporting pellets because shipping lanes between the US and Europe are well established, low cost, and close to forests from which pellets can be harvested [57].

3.2. SDGs Relevant to Production of Woody Pellets in the SE US

Five of the 17 SDGs were identified as being most relevant and directly affected by the production of woody pellets in the SE US for use in Europe (Table 1). The way in which woody pellet production affects each of these goals and relevant targets is discussed below.

Table 1. Relation of pellet production in SE US to selected Sustainable Development Goals and targets.

SDG	SDG Target Number and Relationship	Evidence
7 AFFORDABLE AND CLEAN ENERGY	7.2: Increase share of renewable energy. Bioenergy makes important contributions to national and regional renewable targets.	Biomass contributed to raising the share of energy from renewable sources consumed in the EU to 19% in 2018 (double that from 2004).
8 DECENT WORK AND ECONOMIC GROWTH	8.4: Increase efficiency and sustainability; decouple growth from environmental degradation. Improved forest management using woody residues to displace fossil coal for energy.	New industries in depressed rural areas provide needed investments in infrastructure, value-added processing, and more sustainable 'green economy' jobs relative to nonrenewable alternatives.
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	9.2, 9.3: Develop inclusive, sustainable, small-scale industries. Small land holders play important roles in forest management and feedstock supply. 9.4 (also SDG 13): Upgrade industries with clean, climate-smart technologies. Pellet industry adds value to otherwise unmerchantable but renewable feedstocks; Net CO_2 emissions are reduced relative to fossil fuels.	60% of SE US private timberland is family owned with activities underway to provide technical assistance and facilitate group certification to improve market access for sustainably sourced biomass. Overall GHG emissions are substantially reduced when wood pellets replace fossil coal.
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	12.2: Sustainable natural resource management. Bioenergy affects environmental, economic, and social indicators of sustainability through more efficient natural resource use.	Knowledge, skills, and financial resources are generated by pellet industry to support continual improvement in forest management aiming toward optimal use of residues.
15 LIFE ON LAND	15.2: Halt deforestation, restore degraded forests. Pellet markets provide incentives to protect and conserve SE forest lands.	Demand for forest products and emphasis on sustainability promotes good forest stewardship in the SE US and helps retain private lands in forest.

SDG 7 has the goal of ensuring "access to affordable, reliable, sustainable and modern energy for all". Target 7.2 calls for "increasing substantially the share of renewable energy in the global energy mix" by 2030. This target is directly supported by increasing the production and use of renewable wood pellets. Wood pellets contributed to increasing the renewable energy share in the EU up to 19% in 2018 (double that from 2004). In 2018, biomass provided 15% of European total renewable electricity and 8% of global renewable electricity [58]. Furthermore, developing efficient logistics and supply chains for pellet production and distribution makes this densified biomass more competitive and accessible in other markets, including domestic uses in pellet stoves, where it offers a cleaner and more efficient source of heat than traditional wood-burning stoves.

SDG 8 refers to "decent work and economic growth" with target 8.4 calling for "increased efficiency and sustainability", meaning that growth does not induce environmental degradation. The production of wood pellets in the SE US brought a new industry to the region and uses wastes, residues, and stranded resources. The pellet mills that ship to Europe employ the Sustainable Forestry Initiative's certified Fiber Sourcing Standard, which requires procurement of all woody fiber by trained foresters who utilize best management practices as audited by an independent third party. Importantly, sustainability standards imposed on the pellet supply chain have had impacts much greater than one might expect, given that pellets represent just 3% of total forest removals in the region. Sustainability requirements for the pellet supply chain are applicable to timber harvests that are primarily destined for other markets when the associated residues are used for pellets.

To be competitive, pellet operations invest in planning, equipment, and technologies that increase both efficiency and sustainability (SDG target 8.4) of forestry activities in the region. Pellet supply chains also support employment and economic growth goals through many skilled jobs along the supply chain (Figure 2). Jobs involve sustainable forest management planning, harvests, planting, grading, processing, transportation, and maintenance in the mills, with spillover effects and investments in ports and corollary industries. It is estimated that 20% more value is added to local economies from bio-based pellet power systems than from coal-based systems, with the more important difference being that the former is sustainably managed while a fossil fuel option relies on destructive, boom-and-bust resource extraction [59]. An input-output assessment of the potential for sustainable expansion of wood pellet industries in the SE US found that over 100,000 jobs and $16 billion in economic output could be supported [60]. These potential impacts occur across rural areas of the SE that are characterized by high levels of unemployment and poverty.

SDG 9 is to "build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation". Targets 9.3 and 9.4 refer to increasing "the access of small-scale industrial and other enterprises" and upgrading "infrastructure and retrofit industries to make them sustainable". Using woody biomass for energy provides a new market for woody biomass that is abundant on small, private land holdings in the SE US but may otherwise be unvalued. Furthermore, addressing SDG 9, by expanding the use of sustainable, renewable woody biomass for energy, can provide a means to tackle SDG 13: to "take urgent action to combat climate change and its impacts", for life-cycle CO_2 emissions are reduced relative to alternatives based on fossil fuels [27,61,62]. Transport of pellets to Europe from the SE US is facilitated by improved and more efficient port and rail facilities, and carbon- and cost-efficient maritime shipping, and because pellets displace coal, the supply chain results in significant net greenhouse gas reductions [27,63].

SDG 12 is to "ensure sustainable consumption and production patterns". Target 12.2 refers to achieving "the sustainable management and efficient use of natural resources". Processing residues, wastes, and roundwood into pellets for bioenergy and displacing coal offer a more efficient use of the biomass than many alternative fates for the feedstocks utilized. This benefit is especially true for the woody feedstocks that otherwise would be disposed of by fire or left in piles to decay, alternatives that remain common in areas of the SE US without pellet mill demand. The pellet market for products made from low-value stems, residues, and roundwood provides multiple benefits and extra income [64]. Bioenergy markets, for example, reduce the need for slashing and burning to dispose of unmerchantable material and the income provides additional incentive to invest management practices such as thinning that decrease the risk of insect outbreaks, disease, and destructive wildfire [65]; increase site productivity and hence carbon uptake rates [66]; and support nontimber objectives such as recreation and habitat for wildlife [67]. These factors increase returns from managed forests and reduce the likelihood that small, private landowners will convert forests to other uses [68]. Potential negative impacts of bioenergy harvests can be avoided or reduced by identifying priority areas for conservation and using management plans designed to achieve multiple goals [69,70].

SDG 15 is to "protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests . . . and halt and reverse land degradation and halt biodiversity loss". Target 15.2 calls for promoting "the implementation of sustainable management of all types of forests". The sustainable management targets established for pellet supply chains are thus parallel to those for SDG 12. The production of pellets in the SE US helps retain forest area by providing a market (and therefore a reason to keep forest as forest) [27,71]. In addition, healthy bioenergy markets supplement incomes to private rural landholders and support forest management practices that benefit water quality and wildlife and reduce risk of fire and disease, e.g., [37,64,65]. Hence support for these markets address SDG 6 (clean water) and SDG 15 (life on land). For example, removal of hardwood trees and management of understory vegetation is key for restoring the longleaf pine ecosystem across its former range and maintaining open canopy conditions in other pine forest types [72,73]. While there are concerns about the effects of an increase in pellet exports on biodiversity, e.g., [21,40,74,75], a framework has been developed to identify mitigation practices that can help offset the potential impacts on species of concern from logging, thinning, and dead wood removal [76]. The framework, designed to help users systematically examine and address effects of management actions on life-history conditions of species of concern, was applied to the case of an endemic, keystone species in the SE US, the gopher tortoise (*Gopherus polyphemus*). However, the levels of wood-pellet production appear to have minimal effects on SE US forest ecosystem services thus far [71,77]. The research and planning required to identify habitat for species of concern and other areas of high conservation value, and for subsequent implementation and monitoring of the site-specific management plans, involve expertise and investments that can be supported by forest industry stakeholders. Attention to opportunities to conserve areas of high conservation value is important for stakeholders aiming to supply bioenergy markets that impose sustainability requirements [78].

4. Discussion

4.1. Strengths and Weaknesses of the SE US Pellet Supply Chain

The strengths and weaknesses of the pellet supply chain in the SE US create both opportunities and threats, summarized in Table 2. Strengths of this supply chain include the displacement of fossil fuels (primarily coal) with bioenergy; support for renewable energy goals; conservation of forests through sustainable, green economy jobs; and more efficient use of waste materials. These strengths relate to SDGs and their targets as discussed above.

Weaknesses include the fact that wood pellets represent a tiny fraction of SE forest products industries and thus have limited influence on market-based incentives. Yet pellet mills must rely on good management practices across the industry and invest resources to ensure sustainable sourcing of feedstocks. Another weakness is that opportunities for larger local benefits are being missed because, with the right policy incentives, more fossil fuels could be displaced in the SE US with locally produced pellets. In addition, pellet supply chains, like most energy technologies, could cause many potential negative impacts on water and air quality, biodiversity, and other ecosystem services if improperly implemented. These are examples of weaknesses linked to the SE US context of pellet production that are not captured when assessing progress toward SDG targets.

Table 2. Strengths, weaknesses, opportunities, threats of SE US pellet supply chain.

Strengths	Opportunities
• Displacement of fossil fuels (primarily coal) with bioenergy supports renewable energy goals • Reduced probability of losses and emissions due to wildfire, disease, and pests • Increased forest values strengthen incentives to retain private land in forests • Conservation of forests through green economy jobs and more efficient use of residues	• Economic and social benefits from transition to low-carbon economy industries • Dispatchable power to complement other intermittent renewable energy sources • More efficient, decentralized options to meet needs for reliable and affordable energy • Rural jobs, investments, and innovations • Expansion of incentives for management designed to benefit water quality and wildlife
Weaknesses	**Threats**
• Accounts for small share of forest industry products and employment • Lack of domestic policies to support local use • Prolongs utilization of centralized and relatively inefficient, thermal-electric generation • Detrimental for short-term GHG emissions • Potential negative impacts on water, air quality, biodiversity and other ecosystem services if improperly implemented	• Exclusions of wood-based bioenergy from renewable energy and climate programs • Lack of awareness of local conditions, culture, and land ownership and the likely alternatives if biomass markets are eliminated • Public perspectives driven by passion to protect forests without adequate scientific analysis of options to conserve and manage SE US forest ecosystems

Other weaknesses of the pellet supply chain include relatively inefficient conversion of wood energy to power in electric power plants. This drawback supports a perception that renewable biomass extends the life of centralized thermal-electric stations that should be replaced with cleaner alternatives, such as wind and solar. Critics ask if the pellet supply chain extends the life of inefficient thermal-electric plants that would otherwise be retired. We find no data to quantify this potential weakness. Yet, reasonable concerns arise under conditions that involve co-firing with fossil fuels and extending the utilization of an inefficient plant that would otherwise be replaced. The concern can be addressed by employing state-of-the-art technologies and combined-heat-and-power plants designed for efficient energy conversion, distribution, and utilization. Furthermore, the transition to replace infrastructure for the distribution of electricity from existing central plants will be costly and take several decades. Dispatchable green power generation is needed to fill-in when other intermittent renewable sources such as wind and solar are insufficient to meet demand. Requirements for dispatchable power on existing infrastructure provide a niche for bioenergy until cleaner, distributed, renewable systems can be established to provide generation and storage capacity with full-time reliability. Hence, biomass supply chains are an essential element for more sustainable, circular economies envisioned to support the SDGs.

The weakness (Table 2) that the pellet supply chain could be counterproductive to GHG emission reductions in the short term depends on several context-specific factors. Woody biomass generates considerable emissions at the time and place of combustion, creating an immediate climate-forcing effect that is temporarily counterproductive unless the biomass would have been burned for disposal anyway. This immediate impact is compared to the time required for carbon payback, which can be estimated as the number of years needed for a forest to sequester the amount of carbon that is released throughout the supply chain as biomass is harvested, transported, and used for energy. The carbon payback time depends on how an analysis is temporally framed and other variables, ranging from the alternative fates for the feedstock to the type and location of sourcing forests [79,80]. If, as many models assume, a forest plot is clear-cut for only bioenergy purposes, the carbon payback time for a typical managed pine plantation in the SE US is calculated to be about 18 years, while mixed pine-hardwood, naturally regenerating forest stands may require three times longer [81,82]. However, forests in the SE US are primarily harvested for higher-value markets. The forest harvest and management operations generate tops, unmerchantable stems, and other residues. Only a portion of total forest industry residues, less than 10%, is used for pellet production. The alternate fates for the remaining 90% include (1) local combustion for process heat, drying, and energy to produce other forest industry products; or (2) rapid decay as mulch, animal bedding, or inefficient use as firewood and charcoal [33,36]. The carbon payback period compared to these alternative residue fates is short, on the order of months to a few years.

In contrast, the fossil fuels displaced offer no payback, for they represent the one-way movement of carbon from stable underground storage to the earth's atmosphere. Thus, even though natural gas generates electricity with fewer emissions per MW than pellets, such efficiency advantages are inconsequential if the same energy could be produced by sustainably sourced biomass from SE forest residues. The key difference is that the emissions from biomass would soon occur regardless of whether the biomass is used to produce electricity or not; whereas there would be no emissions if fossil fuels are retained in the ground. This difference illustrates how the complexities of emission accounting and alternative fates for feedstocks are critical determinants of social and environmental impacts but are not adequately captured in targets established for either SDG 9 or 13. It is important to take into account such limitations of the SDG indicators when setting goals for carbon emission reductions.

Weaknesses associated with negative impacts on water and air quality can arise if the pellet supply chain is not properly implemented or when local regulations are insufficient or not enforced. Best forest management practices are adapted to local conditions based on lessons learned from prior decades when forestry activities caused erosion and other downstream impacts, particularly when new access roads were involved, e.g., [37]. While best management practices (BMPs) are required for forest certification and help mitigate negative effects such as accelerated erosion and soil degradation, additional practices are required for pellets to be certified to meet sustainability requirements. Local governments must not relax environmental regulation to attract economic development, a practice that led to cases where specific mills were found to create excessive air pollutants, e.g., [83]. Civil society organizations can play a valuable role in identifying problems and promoting corrective actions when environmental safeguards are not met by industrial actors including those in forestry and the pellet supply chain.

4.2. Threats to the SE US Pellet Supply Chain

Threats to the supply chain include reliance on policies and subsidies that could be eliminated at any time, which would result in major disruptions in demand. That threat is exacerbated by concerns raised by groups who believe the pellet supply chain will cause deforestation rather than investments in improved forest management. An underlying threat is a lack of understanding, or limited knowledge and documentation, about local conditions in the SE US, such as the alternative fates for residues and private forest lands in the absence of demand for low-value biomass. Another threat is related to local impacts that large industrial mills have on neighbors (traffic, dust, noise, and air pollution), as the impacts can foment opposition to new mills and increase costs associated with expansion of the supply chain. Local resistance generated by both real and perceived impacts can hinder future bioenergy development and undermine political support [84]. Passionate opposition to the concept of "burning forests for energy" and proposals to tax bioenergy emissions without adequate compensation for supply chain impacts on forest management and carbon sequestration are factors that further erode public support and, if reflected in policies, not only threaten the supply chain but could be counterproductive to addressing climate-change goals [27].

4.3. Opportunities for the Pellet Industry to Make Progress toward Sustainability

A limited understanding by some of SE US forest ecosystems—as well as social, political, and cultural conditions—have fostered opposition to pellets as a renewable energy source. Yet, the wood pellet supply chain offers valuable opportunities to transition toward low-carbon industries (SDG 9). Increased efficiencies in the utilization of residues and local bioenergy resources, creation of sustainable rural jobs, and investments in rural infrastructure, skills, and innovations, are among the positive effects that can be realized in support of multiple SDGs. We recommend transparent and timely reporting, effective monitoring, and accountability to build trust and support for managing forest landscapes to provide multiple services to society. A pellet supply chain should be considered as one small piece to be integrated with other landscape management goals.

To realize the stated vision for a "just transition towards environmentally sustainable economies and societies for all", the International Labour Organization (ILO) promotes the concept that "greening" should achieve social objectives and be considered within the context of poverty eradication [85] (p. 4). According to the ILO, low-carbon economies, such as those supported by the SE US pellet supply chain, have the potential to generate decent jobs, advance social inclusion, and enhance resilience. While some studies find that pellet supply chains support such goals, e.g., [59,60], some stakeholders raise questions about environmental justice. We recommend that stakeholder engagement strategies be inclusive of all perspectives and consider potential costs, benefits, and tradeoffs associated with wood pellet production from the perspectives of those most directly impacted. Any supply chain effects attributable to forest conservation, environmental quality, and social and economic opportunities in communities affected by the supply chain should be documented.

While the scientific community may appear to disagree about the effects of the SE US pellet supply chain, there is an opportunity to build consensus around effects based on reliable data and monitoring, such as the Forest Inventory and Analysis [1,37,71]. Under some assumptions for supply chain attributes and alternative fates for feedstocks, increases in wood pellet production lead to increased harvest in timberlands in the SE US [75] and changes in forest structure [86]. Other studies suggest that robust pellet markets reinforce good management practices and help retain private lands in forest rather than transitioning from forest to other uses e.g., [11,27,43,87]. Effective monitoring of SE US forest conditions and mechanisms to quickly respond to undesirable changes are keys to a constructive path forward.

Government programs and policies that incentivize wood pellet production (e.g., production tax credits, renewable energy credits) should ensure transparent and balanced accounting for both emissions and sequestration. This role for clear policies and strong institutions relates to SDG 16 (justice and strong institutions). For example, carbon rental and carbon-tax-and-subsidy approaches have been identified as efficient and beneficial to forests [27]. Incentives should support technical assistance to small forest owners and innovation while assuring standards are met for social and environmental protections. Furthermore, incentives for better management of SE US forests that are linked to growing demand for wood-based pellets should support continual improvements in water quality and habitat for wildlife, while reducing risks of wildfires and insect outbreaks [69]. The role for good governance is important to hold the industry accountable through (1) monitoring supply chain emissions, (2) providing incentives to employ best available control technologies and equipment to minimize dust and pollutants, and (3) enforcing relevant environmental regulations across the wood pellet life cycle.

Caution is recommended with respect to government subsidies. For example, unless functional carbon markets are established for forest landowners and demand is provided for low-value biomass, subsidies for tree plantations without regard to future markets could result in supply bubbles and depressed stumpage prices, as occurred in the past [88]. Subsidies can distort markets and lead to reduced investments in management and increased conversion of timberland to non-forest use [27]. Market demand for low-value biomass is a key factor to conserve, manage, and expand SE forest estates.

4.4. Challenges in Assessing SDG Indicators for Wood Pellets

Several challenges arose when evaluating the effects of the woody pellet supply chain on the SDGs. First, the SDGs are global, and SDG targets and indicators are designed for national reporting. Thus, SDG targets refer to national or multi-national policies and broad measures, rather than to a particular region, and within that region, a specific supply chain. However, matching bioenergy feedstocks and management practices to local conditions and constraints is essential [89]. The disconnect between SDG indicators and the more specific metrics that are relevant for the context of a particular biomass supply chain, is a common challenge encountered among cases assessed by the IEA Bioenergy Inter-Task project [90].

Second, data to assess progress toward SDG targets are often insufficient to monitor the corresponding indicators, even at broad national scales. The United Nations Statistical Commission [17] reported that SDG progress monitoring was hampered by missing data, and, where data do exist, other problems such as timeliness and comparability often arose. Timely, reliable, and complete data necessary to assess the effects of a regional supply chain on SDG targets are difficult to assemble.

Third, multiple uncertainties and issues associated with attribution are ever present. Attribution of an observed effect to the bioenergy supply chain is challenging, for indicators are impacted by other variables and are often measured at national or regional scales. Furthermore, it is necessary to determine the proper reference scenario or counterfactual conditions that would have prevailed in the absence of the observed expansion of wood pellet production [28,91]. These issues are especially complicated when dealing with dynamic human economies and biological systems across landscapes that are subject to many different but simultaneous forces of change [92].

Fourth, several SDG targets are appropriately designed to address specific needs in developing countries, such as "universal access to modern energy services" under SDG 7, or access to financial services in developing nations under SDG 9. The needs in each nation are distinct, but the SE US forest sector has an advantageous foundation of science-based research and statistically-sound historical data with systematic and timely updates. Information about forest landowners and reliable data on forest conditions over recent decades is critical to understand and evaluate the effects of different policies, management practices, climate change, and other phenomena, e.g., [1,7,12,54,71,77,93]. Reliable historical and current data sets such as the Forest Inventory and Analysis provide evidence to determine whether bioenergy from SE US wood pellets is achieving desired goals [94]. In addition, state and federal regulations, best management practices (BMPs), forest and fiber-sourcing certification programs, nonprofit conservation organizations, land trusts, and logger training programs provide a network of support and accountability for efficient management and protection of US forest lands [37].

SDG targets designed to support monitoring of progress toward development goals are limited in their ability to capture local, negative impacts, such as the noise and traffic associated with transporting biomass. There is also overlap and confusion about where to report some effects, e.g., supply chain GHG reductions could fall under SDG 9 (more sustainable industries) or SDG 13 (combat climate change). Several SDGs have limited direct linkages with bioenergy supply chains, such as SDG 14 (life below water), and SDG 16 (peace, justice, and strong institutions). Therefore, a process should be followed to develop indicators with stakeholders that are aligned with local needs and priorities [95].

5. Conclusions

The SE US pellet supply chain is important for forestry activities and investments in communities and ports servicing pellet processing mills [59]. While the supply chain represents a tiny share of the total biomass processed by SE US forest industries, sustainability requirements for pellets influence wider forestry practices and contribute to increased conservation investments in regions where feedstocks are harvested, e.g., [96]. The SDGs and their targets provide broad goals for nations; however, context-specific objectives are more useful for considering effects on particular industries and regions. This specificity is particularly valid for the SE US pellet supply chain, which must adapt to site-specific social and environmental sensitivities as it responds to opportunities presented by high volumes of low-value forest resources lacking other markets.

Close cooperation between regional and local stakeholders—including small forest landowners, forest sector industries and service providers, and local communities—are critical for building the trust required to reap social, economic, and environmental benefits from the pellet supply chain. Reliable and timely data on forest conditions, including how pellet supply chains can be managed to increasingly support healthy and resilient forest ecosystems, are also important for marking progress toward the SDGs and local development priorities. Working with stakeholders, future research and investment can target initiatives designed to mitigate weaknesses and threats and to optimize the benefits from the strengths and opportunities provided by the woody biomass energy supply chain in the SE US.

Author Contributions: Conceptualization, K.L.K.; Analysis, K.L.K., V.H.D., E.R. and B.T.; Investigation, K.L.K., V.H.D., E.R. and B.T.; Writing—original draft preparation and organization V.H.D. with contributions from K.L.K., E.R. and B.T.; Project administration, E.R. and K.L.K.; Funding acquisition, E.R. and K.L.K. All authors have read and agreed to the published version of the manuscript.

Funding: K.L.K.'s contribution was supported by the US Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), Bioenergy Technologies Office (BETO), under award number EE0007088 to ORNL. ORNL is managed by the UT-Battelle, LLC, for DOE under contract DE-AC05-00OR22725. The contribution of V.H.D., E.R. and B.T. was funded by International Energy Agency (IEA) Bioenergy Technology Collaboration Programme, Task 43: Sustainable Biomass Supply Integration for Bioenergy within the Broader Bioeconomy. The University of the Sunshine Coast (ABN 28 441 859 157), Sippy Downs, Queensland, Australia, manages and administers funding on behalf of IEA Bioenergy Task 43.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created in this study. Data analyzed and presented in this study are available in publicly accessible repositories listed in the References.

Acknowledgments: We thank Matthew Langholtz, Thomas Schuler, and three anonymous reviewers for helpful comments on prior versions of this manuscript. We thank collaborators in IEA Bioenergy—particularly Jim Spaeth, Bruno Gagnon, Jean Blair, Mark Brown, and Thomas Schuler—for support and guidance.

Conflicts of Interest: The authors declare no conflict of interest. The funders had a role in design and approval of the IEA Bioenergy case study but not in the collection, analyses, or interpretation of data; nor in the writing of the manuscript, nor in the decision to publish the results.

References

1. O'Connell, B.M.; LaPoint, E.B.; Turner, J.A.; Ridley, T.; Pugh, S.A.; Wilson, A.M.; Waddell, K.L.; Conkling, B.L. *The Forest Inventory and Analysis Database: Database Description and User Guide Version 6.0.1 for Phase 2*; U.S. Department of Agriculture, Forest Service: Washington, DC, USA, 2014; 748p. Available online: https://www.fia.fs.fed.us/library/database-documentation/historic/ver6/FIADB_user%20guide_6-0_p2_5-6-2014.pdf (accessed on 14 December 2020).
2. Mann, C.C. *1491: New Revelations of the Americas Before Columbus*; Knopf: New York, NY, USA, 2005.
3. Delcourt, H.R.; Delcourt, P.A. Pre-Columbian Native American use of fire on Southern Appalachian landscapes. *Conserv. Biol.* **1997**, *11*, 1010–1014. [CrossRef]
4. Cowell, M.C. Historical change in vegetation and disturbance on the Georgia Piedmont. *Am. Midl. Nat.* **1998**, *140*, 78–89. [CrossRef]
5. Flatley, W.T.; Lafon, C.W.; Grossino-Mayer, H.D.; LaForest, L.B. Fire history, related to climate and land use in three southern Appalachian landscapes in the eastern United States. *Ecol. Adapt.* **2013**, *23*, 1250–1266. [CrossRef]
6. Klein Goldewijk, K.; Beusen, A.; Doelman, J.; Stehfest, E. Anthropogenic land use estimates for the Holocene—HYDE 3.2. *Earth Syst. Sci. Data* **2017**, *9*, 927–953. [CrossRef]

7. Oswalt, S.N.; Smith, W.B.; Miles, P.D.; Pugh, S.A. Forest Resources of the United States, 2017. A Technical Document Supporting the Forest Service 2020 RPA Assessment (WO-97); 2019. Available online: https://www.fs.usda.gov/treesearch/pubs/57903 (accessed on 19 December 2020).
8. Hurtt, G.C.; Frolking, S.; Fearon, M.G.; Moore, B.; Shevliakova, E.; Malyshev, S.; Pacala, S.W.; Houghton, R.A. The underpinnings of land-use history: Three centuries of global gridded land-use transitions, wood harvest activity, and resulting secondary lands. *Glob. Change Biol.* **2006**, *12*, 1208–1229. [CrossRef]
9. Schweizer, P.E.; Matlack, G.R. Factors driving land use change and forest distribution on the coastal plain of Mississippi, USA. *Landsc. Urban Plan.* **2014**, *121*, 55–64. [CrossRef]
10. Gragson, T.L.; Bolstad, P.V. Land use legacies and the future of Southern Appalachia. *Soc. Nat. Res.* **2006**, *19*, 175–190. [CrossRef]
11. Wear, D.N.; Greis, J.G. *The Southern Forest Futures Project: Summary Report*; Technical Report SRS-178; USDA-Forest Service, Southern Research Station: Asheville, NC, USA, 2012; p. 552. Available online: https://www.srs.fs.usda.gov/pubs/42526 (accessed on 19 December 2020).
12. Wear, D.N.; Gries, J.G. *Southern Forest Resource Assessment*; Gen. Technical Report SRS–53; U.S. Department of Agriculture, Forest Service, Southern Research Station: Asheville, NC, USA, 2002; 635p.
13. Wear, D.N.; Carter, D.R.; Prestemon, J. *The U.S. South's Timber Sector in 2005: A Prospective Analysis of Recent Change*; General Technical Report SRS-99; USDA Forest Service Southern Research Station: Ashville, NC, USA, 2012; 44p. Available online: https://www.srs.fs.usda.gov/sustain/report/pdf/gtr-srs-99.pdf (accessed on 19 December 2020).
14. Sun, X.; Zhang, D.; Butler, B.J. Timberland ownerships and reforestation in the Southern United States. *For. Sci.* **2015**, *61*, 336–343. [CrossRef]
15. Dale, V.H.; Joyce, L.A.; McNulty, S.; Neilson, R.P.; Ayres, M.P.; Flannigan, M.D.; Hanson, P.J.; Irland, L.C.; Lugo, A.E.; Peterson, C.J.; et al. Forest disturbances and climate change. *BioScience* **2001**, *51*, 723–734. [CrossRef]
16. United Nations General Assembly. Transforming Our World: The 2030 Agenda for Sustainable Development (adopted on 25 September 2015) A/RES/70/1 2015. Available online: https://www.refworld.org/docid/57b6e3e44.html (accessed on 16 November 2020).
17. United Nations. The Sustainable Development Goals Report 2019 Database 2019. Available online: https://unstats.un.org/sdgs/indicators/database/ (accessed on 31 May 2020).
18. United Nations. SDG Indicators. Global Indicator Framework for the Sustainable Development Goals and Targets of the 2030 Agenda for Sustainable Development. 2020. Available online: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed on 18 November 2020).
19. United Nations. SDG #15, Why It Matters—Life on Land, Facts and Figures. Available online: https://www.un.org/sustainabledevelopment/wp-content/uploads/2019/07/15_Why-It-Matters-2020.pdf (accessed on 16 November 2020).
20. International Energy Agency. Uneven Progress on Achieving Access to Sustainable Energy for All. 2017. Available online: https://www.iea.org/newsroom/news/2017/april/uneven-progress-on-achieving-access-to-sustainable-energy-for-all.html (accessed on 31 May 2020).
21. Eggers, J.; Melin, Y.; Lundström, J.; Bergström, D.; Öhman, K. Management strategies for wood fuel harvesting—Trade-offs with biodiversity and forest ecosystem services. *Sustainability* **2020**, *12*, 4089. [CrossRef]
22. Intergovernmental Panel on Climate Change (IPCC). *Summary for Policymakers, Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group 3 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014.
23. Efroymson, R.A.; Dale, V.H.; Bielicki, J.; McBride, A.; Smith, R.; Parish, E.; Schweizer, P.; Kline, K.L.; Shaw, D. Environmental indicators of biofuel sustainability: What about context? *Environ. Manag.* **2013**, *51*, 291–306. [CrossRef]
24. Creutzig, F.; Ravindranath, N.H.; Berndes, G.; Bolwig, S.; Bright, R.; Cherubini, F.; Chum, H.; Corbera, E.; Delucchi, M.; Faaij, A.; et al. Bioenergy and climate change mitigation: An assessment. *Glob. Change Biol. Bioenergy* **2015**, *7*, 916–944. [CrossRef]
25. IEA Bioenergy Technology Collaboration Programme. Inter-Task Projects for 2019–2022 Triennium. 2020. Available online: https://www.ieabioenergy.com/blog/task/inter-task-projects/ (accessed on 16 November 2020).
26. Kittler, B.; Stupak, I.; Smith, C.T. Assessing the wood sourcing practices of the U.S. industrial wood pellet industry supplying European energy demand. *Sustain. Soc.* **2020**, *10*. [CrossRef]
27. Favero, A.; Daigneault, A.; Sohngen, B. Forests: Carbon sequestration, biomass energy, or both? *Sci. Adv.* **2020**, *6*. [CrossRef] [PubMed]
28. Parish, E.S.; Dale, V.H.; Kline, K.L.; Abt, R.C. Reference scenarios for evaluating wood pellet production in the Southeastern United States. *WIREs Energy Environ.* **2017**, *6*, e259. [CrossRef]
29. Hoefnagels, R.; Junginger, M.; Faaij, A. The economic potential of wood pellet production from alternative, low-value wood sources in the southeast of the US. *Biomass Bioenergy* **2014**, *71*, 443–454. [CrossRef]
30. U.S. Energy Information Administration. In *Monthly Densified Biomass Fuel Report, Data Archive Form EIA-63C*. Available online: https://www.eia.gov/biofuels/biomass/ (accessed on 16 November 2020).
31. Visser, L.; Hoefnagels, R.; Junginger, M. Wood pellet supply chain costs—A review and cost optimization analysis. *Renew. Sustain. Energy Rev.* **2020**, 118. [CrossRef]

32. Barrette, J.; Durocher, C.; Mansuy, N.; Béland, M.; Thiffault, E. From Unloved Woods to Desirable Renewable Biofuels: Policy Brief. *Can. J. For. Res.* **2017**, *48*, 1470–1481. Available online: https://biofuelnet.ca/wp-content/uploads/2017/09/2017.07.03_BFN_Policy-Brief_Unloved-Wood.pdf (accessed on 16 November 2020). [CrossRef]
33. USDA Forest Inventory Analysis Timber Products Output Studies, TPO Interactive Reporting Tool. Available online: https://www.fia.fs.fed.us/program-features/tpo/ (accessed on 16 November 2020).
34. Brandeis, C.; Guo, Z. Decline in the pulp and paper industry: Effects on backward-linked forest industries and local economies. *For. Prod. J.* **2016**, *66*, 113–118. [CrossRef]
35. Hodges, D.G.; Hartsell, A.J.; Brandeis, C.; Brandeis, T.J.; Bentley, J.W. Recession effects on the forests and forest products industries of the south. *For. Prod. J.* **2012**, *61*, 614–624. [CrossRef]
36. Brandeis, C.; Abt, K.L. Roundwood use by southern wood pellet mills: Findings from Timber Product Output mill surveys. *J. For.* **2019**, *117*, 427–434. [CrossRef]
37. National Association of State Foresters. *Protecting Water Quality through State For. Best Management Practices*; National Association of State Foresters: Washington, DC, USA, 2015. Available online: http://www.stateforesters.org/sites/default/files/issues-and-policies-document-attachments/Protecting_Water_Quality_through_State_For._BMPs_FINAL.pdf (accessed on 18 November 2020).
38. Dale, V.H.; Kline, K.L.; Parish, E.S.; Cowie, A.L.; Emory, R.; Malmsheimer, R.W.; Slade, R.; Smith, C.T.; Wigley, T.B.; Bentsen, N.S.; et al. Status and prospects for renewable energy using wood pellets from the southeastern United States. *Glob. Change Biol. Bioenergy* **2017**, 1296–1305. [CrossRef]
39. Hodges, D.G.; Chapagain, B.; Watcharaanantapong, P.; Poudyal, N.C.; Kline, K.L.; Dale, V.H. Opportunities and attitudes of private forest landowners in supplying woody biomass for renewable energy. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109205. [CrossRef]
40. Cornwall, W. Is wood a green source of energy? Scientists are divided. *Science* **2017**, *355*, 18–21. [CrossRef] [PubMed]
41. German Wood Fuel and Pellet Association. *Recommendations for Storage of Wood Pellets*; UK Pellet Council: Chippenham, UK, 2012. Available online: https://www.intricoproducts.com/user_uploads/wood-pellet-storage-guide.pdf (accessed on 16 December 2020).
42. European Commission Renewable Energy Directive (RED). Available online: https://ec.europa.eu/energy/topics/renewable-energy/renewable-energy-directive/overview_en (accessed on 16 November 2020).
43. Abt, K.L.; Abt, R.C.; Galik, C.S.; Skog, K.E. *Effect of Policies on Pellet Production and Forests in the US South*; USDA Forest Service Southern Research Station: Asheville, NC, USA, 2014.
44. U.S. Department of Agriculture. USDA Foreign Agricultural Service Searchable Database. 2019. Available online: https://apps.fas.usda.gov/Gats/default.aspx (accessed on 31 May 2020).
45. Lowenthal-Savy, D. UK's Renewable Energy Targets Drive Increases in U.S. Wood Pellet Exports; 2015. Available online: https://www.eia.gov/todayinenergy/detail.php?id=20912 (accessed on 31 May 2020).
46. Parish, E.S.; Herzberger, A.; Phifer, C.; Dale, V.H. Transatlantic wood pellet trade demonstrates telecoupled benefits. *Ecology Society* **2018**, *23*, 28. [CrossRef]
47. Galik, C.S.; Abt, R.C. Sustainability guidelines and forest market response: An assessment of European Union pellet demand in the southeastern United States. *Glob. Change Biol. Bioenergy* **2015**, *8*, 658–669. [CrossRef]
48. Butler, B.J.; Hewes, J.H.; Dickinson, B.J.; Andrejczyk, K.; Butler, S.M.; Markowski-Lindsay, M. Family forest ownerships of the United States: Findings from the U.S. Department of Agriculture forest service's National woodland owner survey. *J. For.* **2016**, *114*, 638–647. [CrossRef]
49. Butler, B.J.; Ma, Z.; Kittredge, D.B.; Catanzaro, P. Social versus biophysical availability of wood in the northern United States. *North. J. Appl. For.* **2010**, *27*, 151–159. [CrossRef]
50. Galik, C.S.; Abt, R.; Wu, Y. Forest biomass supply in the Southeastern United States—Implications for industrial roundwood and bioenergy production. *J. For.* **2009**, *107*, 69–77. [CrossRef]
51. Gruchy, S.R.; Grebner, D.L.; Munn, I.A.; Joshi, O.; Hussain, A. An assessment of nonindustrial private forest landowner willingness to harvest woody biomass in support of bioenergy production in Mississippi: A contingent rating approach. *For. Policy Econ.* **2012**, *15*, 140–145. [CrossRef]
52. Joshi, O.; Mehmood, S.R. Factors affecting nonindustrial private forest landowners' willingness to supply woody biomass for bioenergy. *Biomass Bioenergy* **2011**, *35*, 186–192. [CrossRef]
53. Joshi, O.; Grebner, D.L.; Hussain, A.; Grado, S.C. Landowner knowledge and willingness to supply woody biomass for wood-based bioenergy: Sample selection approach. *J. For. Econ.* **2013**, *19*, 97–109. [CrossRef]
54. Butler, S.M.; Butler, B.J.; Markowski-Lindsay, M. Family forest owner characteristics shaped by life cycle, cohort, and period effects. *Small Scale For.* **2017**, *16*, 1–18. [CrossRef]
55. Koester, S.; Davis, S. Siting of wood pellet production facilities in environmental justice communities in the Southeastern United States. *Environ. Justice* **2018**, *11*. [CrossRef]
56. Ramseth, L. *World's Largest Pellet Mill Could Boost Mississippi's Economy. But will it Hurt Environment, Residents?* Mississippi Clarion Ledger: Jackson, MS, USA, 2019. Available online: https://www.clarionledger.com/story/news/politics/2019/07/08/mississippi-pellet-mill-economic-boon-environmental-threat/1351677001/ (accessed on 19 December 2020).

57. Hamilton, D.S.; Quinlan, J.P. *The Transatlantic Economy 2017: Annual Survey of Jobs, Trade and Investment between the United States and Europe*; American Chamber of Commerce to the European Union: Brussels, Belgium, 2017. Available online: http://www.amchameu.eu/sites/default/files/170227_full-book.pdf (accessed on 17 November 2020).
58. International Renewable Energy Agency (IRENA). Renewable Energy Highlights (July 2020). Available online: https://www.irena.org/publications/2020/Jul/Renewable-energy-statistics-2020 (accessed on 17 November 2020).
59. Dahal, R.P.; Aguilar, F.X.; McGarvey, R.G.; Becker, D.; Abt, K.L. Localized economic contributions to renewable wood-based biopower generation. *Energy Econ.* **2020**, *91*. [CrossRef]
60. Henderson, J.E.; Joshi, O.; Parajuli, R.; Hubbard, W.G. A regional assessment of wood resource sustainability and potential economic impact of the wood pellet market in the U.S. south. *Biomass Bioenergy* **2017**, *105*, 421–427. [CrossRef]
61. Cowie, A.; Brandão, M.; Soimakallio, S. Quantifying the climate effects of forest-based bioenergy. In *Managing Global Warming: An Interface of Technology and Human Issues*, 1st ed.; Letcher, T.M., Ed.; Elsevier Academic Press: Cambridge, MA, USA, 2019; Chapter 13; pp. 399–418. [CrossRef]
62. Visser, L.; Hoefnagels, R.; Junginger, M. The potential contribution of imported biomass to renewable energy targets in the EU—The trade-off between ambitious greenhouse gas emission reduction targets and cost thresholds. *Energies* **2020**, *13*, 1761. [CrossRef]
63. Dwivedi, P.; Khanna, M.; Bailis, R.; Ghilardi, A. Potential greenhouse gas benefits of transatlantic wood pellet trade. *Environ. Res. Lett.* **2014**, *9*, 024007. [CrossRef]
64. Malmsheimer, R.W.; Fernholz, K. How laws, practices, and markets ensure sustainable forest biomass feedstocks from the southeast US. In *World Biomass 2015–2016*; DCM Productions: York, UK, 2015; pp. 8–12. Available online: http://dcm-productions.co.uk/world-biomass-2015-2016/ (accessed on 17 November 2020).
65. Coppoletta, M.; Merriam, K.E.; Collins, B.M. Post-fire vegetation and fuel development influences fire severity patterns in reburns. *Ecol. Appl.* **2016**, *26*, 686–699. [CrossRef]
66. Fox, T.R.; Jokela, E.J.; Allen, H.L. The development of pine plantation silviculture in the southern United States. *J. For.* **2007**, *105*, 337–347.
67. Evans, A.M.; Perschel, R.T.; Kittler, B.A. Overview of forest biomass harvesting guidelines. *J. Sustain. For.* **2013**, *32*, 89–107. [CrossRef]
68. Poudyal, N.C.; Joshi, O.; Hodges, D.G.; Hoyt, K. Factors related with nonindustrial private forest landowners' forest conversion decisions in Cumberland Plateau, Tennessee. *For. Sci.* **2014**, *60*, 988–993. [CrossRef]
69. Kline, K.L.; Dale, V.H. Protecting biodiversity through forest management: Lessons learned and strategies for success. *Int. J. Environ. Sci. Nat. Res.* **2020**, *26*, 556194. [CrossRef]
70. Joly, C.A.; Huntley, B.J.; Verdade, L.M.; Dale, V.H.; Mace, G.; Muok, B.; Ravindranath, N.H. Biofuel Impacts on Biodiversity and Ecosystem Services. In *Scientific Committee on Problems of the Environment (SCOPE) Rapid Assessment Process on Bioenergy and Sustainability*; Souza, G.M., Joly, C.A., Eds.; SCOPE: Paris, France, 2015; Chapter 16; pp. 555–580.
71. Aguilar, F.X.; Mirzaee, A.; McGarvey, R.G.; Shifley, S.R.; Burtraw, D. Expansion of US wood pellet industry points to positive trends but the need for continued monitoring. *Sci. Rep.* **2020**, *10*, 18607. [CrossRef] [PubMed]
72. Varner, J.M.; Gordon, D.R.; Putz, E.; Hiers, J.K. Restoring fire to long-unburned *Pinus palustris* ecosystems: Novel fire effects and consequences for long-unburned ecosystems. *Restor. Ecol.* **2005**, *13*, 536–544. [CrossRef]
73. Greene, R.E.; Iglay, R.B.; Evans, K.O.; Miller, D.A.; Wigley, T.B.; Riffell, S.K. A meta-analysis of biodiversity responses to management of southeastern pine forests—Opportunities for open pine conservation. *For. Ecol. Manag.* **2016**, *360*, 30–39. [CrossRef]
74. Costanza, J.K.; Abt, R.C.; McKerro, A.J.; Collazo, J.A. Bioenergy production and forest landscape change in the southeastern United States. *Glob. Change Biol. Bioenergy* **2017**, *9*, 924–939. [CrossRef]
75. Olesen, A.S.; Kittler, B.; Price, W.; Aguilar, F.X. *Environmental Implications of Increased Reliance of the EU on Biomass from the South East US. European Commission Report ENV.B.1/ETU/2014/0043*; Publications Office of the European Union: Brussels, Belgium, 2016. [CrossRef]
76. Parish, E.S.; Baskaran, L.; Dale, V.H. Framework for assessing land management effects on species of concern: An example using wood pellet production and the gopher tortoise. *WIRES Wiley Interdiscip. Rev.* **2020**. [CrossRef]
77. Dale, V.H.; Parish, E.; Kline, K.L.; Tobin, E. How is wood-based pellet production affecting forest conditions in the southeastern United States? *For. Ecol. Manag.* **2017**, *396*, 143–149. [CrossRef]
78. Kline, K.L.; Mayer, A.L.; Martinelli, F.S.; Medeiros, R.; Oliveira, C.O.F.; Sparovek, G.; Walter, A.; Venier, L. Bioenergy and biodiversity: Key lessons from the Pan America Region. *Environ. Manag.* **2015**, *56*, 1377–1396. [CrossRef]
79. Berndes, G.; Cowie, A.; Pelkmans, L. IEA Bioenergy Bulletin: The Use of Forest Biomass for Climate Change Mitigation: Dispelling Some Misconceptions. 2020. Available online: https://www.ieabioenergy.com/wp-content/uploads/2020/08/The-use-of-biomass-for-climate-change-mitigation-dispelling-some-misconceptions-August-2020-Rev1.pdf (accessed on 17 November 2020).
80. Matthews, R.; Hogan, G.; Mackie, E. Carbon Impacts of Biomass Consumed in the EU: Supplementary Analysis and Interpretation for the European Climate Foundation. 2018. Available online: https://www.drax.com/wp-content/uploads/2019/10/CIB-Summary-report-for-ECF-v10.5-May-20181.pdf (accessed on 17 November 2020).

81. Jonker, J.G.G.; Junginger, M.; Faaij, A. Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States. *Glob. Change Biol. Bioenergy* **2014**, *6*, 371–389. [CrossRef]
82. Rolls, W.; Forster, P.M. Quantifying forest growth uncertainty on carbon payback times in a simple biomass carbon model. *Environ. Res. Commun.* **2020**, *2*, 045001. [CrossRef]
83. Anderson, P.; Powell, K. Dirty deception: How the wood biomass industry skirts the Clean Air Act. Reports sponsored by the Environmental Integrity Project (April 26). 2018. Available online: https://www.environmentalintegrity.org/wp-content/uploads/2017/02/Biomass-Report.pdf (accessed on 17 November 2020).
84. Schelhas, J.; Hitchner, S.; Brosius, J.P. Envisioning and implementing wood-based bioenergy systems in the southern United States: Imaginaries in everyday talk. *Energy Res. Soc. Sci.* **2018**, *35*, 182–192. [CrossRef]
85. International Labour Organization. Guidelines for a Just Transition towards Environmentally Sustainable Economies and Societies for All. 2015. Available online: https://www.ilo.org/global/topics/green-jobs/publications/WCMS_432859/lang--en/index.htm (accessed on 18 November 2020).
86. Duden, A.S.; Verweij, P.A.; Junginger, H.M.; Abt, R.C.; Henderson, J.D.; Dale, V.H.; Kline, K.L.; Karssenberg, D.; Verstegen, J.A.; Faaij, A.P.C.; et al. Modeling the impacts of wood pellet demand on forest dynamics in southeastern United States. *Biofuels Bioprod. Biorefin.* **2017**. [CrossRef]
87. Nepal, P.; Abt, K.L.; Skog, K.E.; Prestemon, J.P.; Abt, R.C. Projected market competition for wood biomass between traditional products and energy: A simulated interaction of US regional, national, and global forest product markets. *For. Sci.* **2018**, *65*, 14–26. [CrossRef]
88. Dezember, R. Man Who Steered Timber Subsidy Program Calls It His Biggest Regret. The Wall Street Journal. 2018. Available online: https://www.wsj.com/articles/man-who-steered-timber-subsidy-program-calls-it-his-biggest-regret-1539946801 (accessed on 19 December 2020).
89. King, J.S.; Ceulemans, R.; Albaugh, J.M.; Dillen, S.Y.; Domec, J.C.; Fichot, R.; Fischer, M.; Leggett, Z.; Sucre, E.; Trnka, M.; et al. The challenge of lignocellulosic bioenergy in a water-limited world. *BioScience* **2013**, *63*, 102–117. [CrossRef]
90. Gagnon, B.; Kline, K.L. Personal Communications in Regular Meetings of the WB2-SDG Inter-Task Case Study Team, May–November. 2020. Updates will be Available online: https://www.ieabioenergy.com/blog/task/inter-task-projects/ (accessed on 14 January 2021).
91. Kline, K.L.; Parish, E.S.; Dale, V.H. The importance of reference conditions in assessing effects of bioenergy wood pellets produced in the southeastern United States. In *World Biomass 2018–2019*; DCM Productions: York, UK, 2018; pp. 82–87. Available online: http://dcm-productions.co.uk/world-biomass-2018-2019/ (accessed on 17 November 2020).
92. Koponen, K.; Soimakallio, S.; Kline, K.L.; Cowie, A.; Brandão, M. Quantifying the climate effects of bioenergy—Choice of reference system. *Renew. Sustain. Energy Rev.* **2018**, *81*, 2271–2280. [CrossRef]
93. Norman, S.P.; Hargrove, W.W.; Spruce, J.P.; Christie, W.M.; Schroeder, S.W. *Highlights of Satellite-Based Forest Change Recognition and Tracking Using the for Warn System. Gen. Tech. Rep. SRS-GTR-180*; USDA-Forest Service, Southern Research Station: Asheville, NC, USA, 2012; 30p. Available online: http://www.srs.fs.usda.gov/pubs/44239 (accessed on 31 May 2020).
94. Parish, E.S.; Dale, V.H.; Tobin, E.; Kline, K.L. Dataset of timberland variables used to assess forest conditions in two Southeastern United States' fuelsheds. *Data Brief* **2017**, *13*, 278–290. [CrossRef]
95. Dale, V.H.; Kline, K.L.; Parish, E.S.; Eichler, S.E. Engaging stakeholders to assess landscape sustainability. *Landsc. Ecol.* **2019**, *34*, 1199–1218. [CrossRef]
96. Enviva Forest Conservation Fund. Available online: https://envivaforestfund.org/ (accessed on 18 November 2020).