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Investigating the Sustainability of Southeastern United States' Wood Pellet Production for Use in European Biopower Facilities

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To the Graduate Council:

I am submitting herewith a dissertation written by Esther Sullivan Parish entitled "Investigating the Sustainability of Southeastern United States' Wood Pellet Production for Use in European Biopower Facilities." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Energy Science and Engineering.

Virginia Dale, Major Professor

We have read this dissertation and recommend its acceptance:

Keith Kline, Nicholas Nagle, Adam Taylor

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Investigating the Sustainability of Southeastern United States' Wood Pellet Production for Use in European Biopower Facilities

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Esther Sullivan Parish
December 2017

DEDICATION

This work is dedicated to my husband, Brad Parish, and my in-laws, Joan and Eddie Parish. Without their loving support, I would not have been able to juggle the multiple demands of my job, graduate school, and two excellent kids.

ACKNOWLEDGEMENTS

Thank you to Kristen Johnson of the United States Department of Energy (DOE) BioEnergy Technologies Office for funding much of this research through Oak Ridge National Laboratory (ORNL) Task 4.2.2.40, “Bioenergy Sustainability: How to define and measure it.” ORNL Center for BioEnergy Sustainability scientists Dr. Virginia Dale and Keith Kline both contributed significantly to this research through that task. Deeper understanding of Southeastern US forest management and wood pellet production was gained through participation in an April 10-14, 2016 Bioenergy Study Tour with over 30 international researchers hosted by DOE and ORNL. PhD students Anna Herzberger of Michigan State University and Colin Phifer of Michigan Technological University both contributed to Chapter I of this dissertation as a result of a collaboration forged during the April 2016 Telecoupling Workshop hosted by Dr. Jack Liu and his Michigan State University Center for Systems Integration and Sustainability at the US Regional Association of the International Association for Landscape Ecology Annual Meeting in Asheville. Professor Bob Abt of North Carolina State University graciously contributed his expertise to the wood industry definitions and reference scenarios described in Chapter II via multiple phone calls and email exchanges. Staff at the US Forest Service Southern Research Station in Knoxville provided invaluable assistance with understanding and querying the Forest Inventory and Analysis (FIA) data used in Chapters III and IV—especially Jeff Turner, Helen Beresford, Tom Brandeis, Consuelo Brandeis, and Sam Lambert. University of Tennessee (UT) undergraduate Emma Tobin assisted with the FIA data analyses described in Chapters III and IV during her summer at ORNL as a 2015 SouthEast Energy Development (SEED) Fellow funded through the Southeastern Partnership for Integrated Biomass Supply Systems. UT Professors Nicholas Nagle and Adam Taylor provided dissertation oversight and thoughtful suggestions of ways to extend this research. Thank you to UT-Battelle, LLC for providing graduate coursework tuition reimbursement through the ORNL Educational Assistance Program. Thank you to the staff and students of The Bredesen Center for Interdisciplinary Research and Graduate Education for providing a unique and rewarding learning experience at both the UT and ORNL campuses. Special thanks to Dr. Virginia Dale for a decade of invaluable scientific mentorship.

ABSTRACT

Although transition to renewable energy resources like bioenergy is being promoted as a way to mitigate global climate change, it is not always clear what potential tradeoffs stakeholders might encounter as these new energy resources reach commercial scale. Holistic consideration of a variety of potential effects on environmental and socioeconomic factors valued by human societies will be an essential component of meeting the world's energy needs without compromising the quality of life available to future generations. This dissertation is therefore intended to advance understanding of the potential benefits and tradeoffs associated with the production of industrial wood pellets from Southeastern United States' (SE US) forests for use in European biopower facilities.

Although SE US global industrial wood pellet exports have developed in response to European Union goals to mitigate climate change, groups on both sides of the Atlantic Ocean have expressed concerns that the trade arrangement will lead to negative impacts on SE US forests. Concerns include potential loss of old growth and bottomland forests and associated ecosystem services and species, as well as heavily debated potential effects on global greenhouse gas emissions. These claims of adverse impacts need to be tested with empirical data associated with key environmental and socioeconomic indicators of sustainability.

Four collaborative research manuscripts developed for this dissertation are presented as four chapters following an Introduction. In Chapter 1, a telecoupling framework is used to qualitatively analyze the sustainability of the transatlantic wood pellet trade system. Chapter 2 proposes a set of definitions and reference scenarios to improve cross-cultural understanding of the new pellet industry within the context of the pre-existing SE US timber industry, as well as guidelines for future quantitative modeling efforts. Chapters 3 and 4 describe a quantitative analysis of timberland changes in two case study SE US fuelsheds that have been supplying industrial wood pellets to Europe since 2009. The Conclusion synthesizes the main findings from the four chapters and discusses opportunities to use the research to improve future policy decisions related to this renewable bioenergy system.

PREFACE

"My view is that sustainability is a moral imperative that requires the current generation to consider the effects of their actions on future generations and to give future well-being equal weight to their own. The actions of our generation do affect future generations who currently neither participate in markets nor in public policy decisions. It is also clear that the scale of human activity has reached the level at which it threatens vital global systems not just for the current generation but for future generations, and it is also clear that energy supply and use play major roles."

—David Greene, "Energy Policy:
Where are the boundaries?" (2014)

"The demand for ecosystem services is now so great that trade-offs among services have become the rule."

— Millennium Ecosystem Assessment (2005)

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INTRODUCTION

Holistic consideration of a variety of potential effects on environmental and socioeconomic factors valued by human societies will be an essential component of meeting the world's energy needs without compromising the quality of life available to future generations (Greene 2014, MEA 2005). This need for 'sustainability' has been an explicit global concern since the "Brundtland Report" was commissioned by the United Nations in 1983 (Wilbanks 2012). In 1999, the U.S. National Academy of Sciences (NAS) asked the question, "How can basic needs of a global population at least half again as large as present be met in 50 years without undermining environmental services on which development depends in the longer run?" The report concluded that increasing energy and materials services while simultaneously reducing environmental impacts would be one of the major five challenges to achieving sustainability (NAS 1999). Nearly two decades later, the challenge of increasing energy availability without adverse consequences is still a pressing issue.

Modeling the sustainability of future energy pathways necessitates understanding connections to global and regional climate, technology options and strategies, and broader aspects of socioeconomic development, including population migration, regional economics, and competing demands for energy, water, and land resources (Sovacool and Sovacool 2009a,b; DOE 2014). Although transition to renewable energy resources such as bioenergy, wind, solar and hydropower are being promoted as a way to mitigate climate change (IPCC 2014), it is not always clear what potential tradeoffs stakeholders might encounter as these new energy resources reach commercial scale. Policy makers need unbiased information and tools to make evidence-based decisions about which energy pathways can minimize negative impacts to—or even improve—ecosystems and the services they provide (MEA 2005), including clean air and water, nutrient-rich soil for agricultural production, recreation, and flood protection.

Few empirical data are available to effectively characterize the commercial-scale impacts of newer renewable energy resources like cellulosic bioenergy, particularly given the significant regional variation found across the United States. But new and cheaper techniques for collecting data and modeling and visualizing future outcomes are developing rapidly. Ultimately, researchers hope to provide decision makers with adaptive management frameworks that will help them evaluate potential tradeoffs and synergies associated with multiple (and potentially conflicting) stakeholder goals, set targets and baselines for working on established priorities within a given context, and iteratively track progress toward (or away from) those goals as new knowledge and information becomes available (or as circumstances change).

This dissertation is designed to advance understanding of the potential tradeoffs associated with a new renewable energy pathway: production of industrial wood pellets from forests of the Southeastern United States (SE US) for use as biopower. Currently all of these pellets are being sent abroad, and most are being shipped to Europe to serve as a substitute for coal in their electric power plants (Dale et al. 2017a). Although this global exchange has developed in response to proactive European Union (EU) goals to mitigate climate change through reduced greenhouse gas emissions (European Parliament 2009), groups on both sides of the Atlantic Ocean have expressed concerns that the trade arrangement has led (or will lead) to negative impacts on SE US forests (Olesen 2016, NRDC 2015). As discussed by Dale et al. (2017) in an opinion piece written with over 30 international collaborators, concerns include potential loss of old growth and bottomland forests and associated ecosystem services and species as well as heavily debated potential effects on global climate change. These claims of adverse impacts need to be tested with empirical data associated with key environmental and socioeconomic indicators of sustainability recommended for US bioenergy systems (Dale et al. 2013, McBride et al. 2011), and possibly with ecosystem services-based Sustainable Forest Management (SFM) criteria that are being promoted across Europe (EASAC 2017).

Four collaborative research manuscripts developed for this dissertation are presented as four chapters. In Chapter 1, a telecoupling framework is used to qualitatively analyze the sustainability of the transatlantic wood pellet trade system. Chapter 2 proposes a set of definitions and reference scenarios to improve cross-cultural understanding of the new pellet industry within the context of the pre-existing SE US timber industry, as well as guidelines for future quantitative modeling efforts. Chapters 3 and 4 describe a quantitative analysis of timberland changes in two case study SE US fuelsheds that have been supplying industrial wood pellets to Europe since 2009. The Conclusion synthesizes the main findings from the four chapters and discusses opportunities to use the research to improve future policy decisions related to this renewable bioenergy system.

Chapter 1 presents the telecoupling framework that Dr. Jack Liu et al. (2013) have developed to evaluate environmental and socioeconomic sustainability of processes occurring across large distances and uses it to qualitatively examine the assertions that the intended benefits of the wood pellet trade for Europe are being offset by negative consequences in SE US. The results of this analysis conducted with Anna Herzberger, a PhD student in Dr. Jack Liu's Center for Systems Integration and Sustainability at Michigan State University, Colin Phifer, a PhD student from Michigan Technological University's School of Forest Resources and Environmental Science, and Dr. Virginia Dale of Oak Ridge National Lab (ORNL), show that the assumption of negative impacts is currently unsupported by observations. At this time, positive environmental and socioeconomic effects from the wood pellet trade seem to be occurring on both sides of the Atlantic Ocean.

Sustainability assessment of an energy supply chain necessitates an understanding of the system's trajectory compared to alternative scenarios. The counterfactual, i.e., the scenario of what would have happened in the absence of industrial wood pellet production, is critical when evaluating the effects of pellet production on future conditions and should be defined based on an analysis of historical and current conditions. The assumptions and counterfactual scenarios used in recent evaluations have often been unrealistic (e.g., Stephenson and McKay 2015) and have led to disagreements over the transatlantic wood pellet trade's potential impacts on global climate change and on ecological, social and economic factors affecting the SE US forests. Therefore, Chapter 2 presents a set of definitions and realistic scenarios for understanding past, current and future conditions associated with SE US timberland management based on expertise from SE US researchers Dr. Virginia Dale and Keith Kline of ORNL in collaboration with Professor Bob Abt of North Carolina State University's Department of Forestry and Environmental Resources. The manuscript was published in a journal with an international audience in the hopes of improving European understanding of SE US timberland management and future quantitative modeling of wood pellet production scenarios within that preexisting context.

The second half of this dissertation describes a quantitative analysis designed to test for effects of the wood pellet production within two case study SE US fuelsheds. Focusing on the forested landscapes contributing biomass to pellets shipped from Savannah, Georgia, and Chesapeake, Virginia, Chapter 3 presents the data analysis techniques used to assess changes to ten timberland characteristics gleaned from USDA Forest Inventory and Analysis (FIA) data (O'Connell et al. 2014) for each fuelshed for years 2002-2014. Chapter 4 summarizes the findings of the companion research article by Dale, Parish, Kline and Tobin (2017). The trend analysis showed no significant changes in the timberland characteristics following the initiation of export pellet production in 2009. The FIA data processing and analysis techniques were developed through consultation with staff at the US Forest Service (USFS) Southern Research Station (SRS) in Knoxville.

A system's current state and sustainability trajectory may be evaluated through a carefully selected combination of environmental and socioeconomic indicators, such as the 35 indicators in 12 categories proposed by McBride et al. (2011) and Dale et al. (2013) to evaluate bioenergy systems. The Conclusion discusses the need to integrate spatial data for many of these indicators and produce a quantitative model that can be used to evaluate potential sustainability tradeoffs and synergies under future fuelshed scenarios.

Together these four chapters demonstrate an understanding of the full context of this new renewable bioenergy pathway, including its current and potential effects on environmental and socioeconomic factors within the sending system (SE US) and receiving system (Europe). The qualitative and preliminary quantitative assessment of current and realistic future changes to SE US forest management resulting from this new wood product will be need to be verified through future empirical quantitative assessment to ensure that forest health is maintained—or improved—as a result of transatlantic trade.

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Thank you to Kristen Johnson of the US Department of Energy (DOE) BioEnergy Technologies Office for funding research for this dissertation through ORNL Task 4.2.2.40, “Bioenergy Sustainability: How to define and measure it.” ORNL is managed by the UT-Battelle, LLC, for DOE under contract DE-AC05-00OR22725. Thank you to Dr. Virginia Dale for her helpful comments on an earlier version of this Introduction.

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CHAPTER I

TRANSATLANTIC WOOD PELLET TRADE DEMONSTRATES TELECOUPLED BENEFITS

A version of this chapter has been accepted for publication in *Ecology and Society* pending minor revisions. The article was prepared by Esther Parish, Anna Herzberger, Colin Phifer, and Dr. Virginia Dale inclusion in a special feature on “Telecoupling: A New Frontier for Global Sustainability” edited by Drs. Jack Liu and Vanessa Hull:

Esther S. Parish, Anna J. Herzberger, Colin C. Phifer, Virginia H. Dale. “Transatlantic wood pellet trade demonstrates telecoupled benefits”. *Ecology and Society* (in revision)

The article is presented in its original form, formatted for this dissertation including renumbering tables and figures. Author was lead author and lead investigator on study. Coauthors Anna Herzberger of Michigan State University and Colin Phifer of Michigan Technological University both contributed to this manuscript as PhD students following joint participation with the author in the April 2016 Telecoupling Workshop hosted by Dr. Jack Liu during the US Regional Association of the International Association for Landscape Ecology Annual Meeting. As a researcher in Dr. Liu’s Center for Systems Integration and Sustainability, Anna Herzberger ensured correct application of the telecoupling framework. Coauthor Dr. Virginia Dale’s guidance and revisions were instrumental in understanding the international issues involved in wood pellet trade.

Abstract

European demand for renewable energy resources has led to rapidly increasing transatlantic exports of wood pellets from the Southeastern United States (SE US) since 2009. Disagreements have risen over the global greenhouse gas reductions associated with replacing coal with wood, and groups on both sides of the Atlantic Ocean have raised concerns that increasing biomass exports might negatively impact SE US forests and the ecosystem services they provide. We use the telecoupling framework to test assertions that the intended benefits of the wood pellet trade for Europe might be offset by negative consequences in the SE US. Through review of current literature and available datasets, we characterize observed and potential changes in the environmental, social, and economic components of the sending and receiving regions in order to assess the overall sustainability of this renewable energy system. We conclude that the observed transatlantic wood pellet trade is an example of a mutually beneficial telecoupled system with the potential to provide environmental as well as socioeconomic benefits in both the SE US and Europe despite some negative impacts on the coal industry. We recommend continued monitoring of this telecoupled system in order to quantify the environmental, social, and economic interactions and effects in the sending, receiving and spillover systems over time so that evidence-based policy decisions can be made with regard to the sustainability of this renewable energy pathway.

Introduction

Integration of multiple disciplinary specifics into a holistic perspective is essential to advance society toward an ultimate goal of sustainable energy production, meaning energy production that can benefit current human populations without adversely impacting future human communities. While many have investigated the potential carbon savings associated with transatlantic wood pellet trade that fuels European biopower facilities, there is little research that considers the combined environmental and socioeconomic costs and benefits of this renewable energy trade on both sides of the Atlantic Ocean. Such a comprehensive perspective is necessary to support evidence-based decisions, monitoring plans, and policies related to this controversial renewable energy pathway (NRDC 2015, Olesen et al. 2015, Cornwall 2017).

Teleconnections refer to causal connections or correlations between environmental phenomena that occur across large distances, and globalization has been used to examine socioeconomic effects across large distances. Building upon both of these concepts, the telecoupling framework proposed by Liu et al. (2013) facilitates identification and characterization of the drivers that connect coupled human and natural systems separated by great distances and their associated environmental and socioeconomic effects. The telecoupling framework therefore offers an ideal lens for examining the connectedness and sustainability of the systems involved in transatlantic wood pellet trade. Previous studies of wood pellet trade have focused on carbon accounting aspects of combusting this renewable fuel resource in place of fossil fuel—an issue that is complicated by the fact that fossil fuels are used at various stages of the wood pellet supply chain (Dwivedi 2011, Dwivedi et al. 2014, Krč et al. 2016). However, we have not found addressing environmental, social, and economic effects of the transatlantic wood pellet trade in a holistic and systematic way.

In this paper, we explore assertions that there will be unintended negative environmental and/or socioeconomic consequences on the Southeastern United States (SE US) sending system as a result of wood pellet trade to Europe (NRDC 2015, Olesen et al. 2015, Cornwall 2017). In addition, we use the telecoupling framework to consider negative consequences that might occur outside the geographic boundaries of either the sending or receiving systems (i.e., within a ‘spillover system’). Through this case study, we seek to improve understanding of the interactions and consequences of the transatlantic wood pellet trade and lay the groundwork for future quantitative modeling of this renewable energy pathway’s sustainability.

Case Study Application of the Telecoupling Framework

Society is increasingly looking to renewable energy production as a way to mitigate global climate change while simultaneously improving local environmental and socioeconomic conditions. To expand their renewable energy portfolios, 27 member states of the European Union (EU) established targets of 20% renewable energy consumption by 2020 and 27% by 2030 (European Parliament 2009, European Commission 2017). Initial EU renewable energy targets became binding in 2009, and a combination of legislation and national incentives spurred several European industrial power plants to begin combusting wood pellets in place of coal.

A confluence of interacting factors has led to rapidly increasing transatlantic exports of wood pellets from the heavily forested Southeastern United States (SE US) to several European nations. These factors include increasing renewable energy demand, limited European forest resources, and controversial greenhouse gas (GHG) accounting practices that have codified biomass energy as carbon neutral in EU member states, effectively allowing energy producers to ignore GHG emissions from wood at the point of combustion (EASAC 2017). As the transatlantic wood pellet trade has increased, concerns have risen over potential impacts to SE US forests and the ecosystem services they provide (Olesen et al. 2016). Apprehensions over forest degradation and loss of bottomland hardwood forests are coupled with concerns about harm to threatened and endangered species (NRDC 2015). Stakeholders on both sides of the Atlantic question whether the desired greenhouse gas reductions are being achieved at a global scale via this international trade arrangement (Cornwall 2017).

For this case study, we first use the telecoupling framework (Liu et al. 2013, 2015) to identify the key players (agents), patterns, flows and processes within this telecoupled trade system to determine if they enhance or compromise progress toward sustainability across distances. After characterizing the sending and receiving systems (including their agents, causes, effects) and the flows between them, we discuss a geographically distinct spillover system that is potentially impacted by the wood pellet trade. We also describe two potential extensions to the telecoupling framework that proved useful during this analysis.

Conceptual model of the transatlantic wood pellet trade system

The telecoupling framework includes five major interrelated components: systems, causes, effects, flows, and agents (Liu et al. 2013). Systems refer to interconnected natural and built environments within specific, non-overlapping geographic areas. The sending system is the donor or exporter, and the receiving system accepts or imports the traded item (which can be raw materials, intellectual property, tourism, etc.). The spillover system is a geographically distinct system impacted by and potentially influencing both the sending and receiving systems. These three systems interact at multiple scales due to a variety of social, political, technological, and environmental factors that can affect and can be affected by social, political, or environmental factors, even over great distances. Connecting these disparate systems are the flows. Flows can be products, species, money, or information transferred within or between the systems (e.g., wood pellets). Agents are the final component of this telecoupled framework and act as the stakeholders that affect the flows within and between the connected systems (e.g., EU member states, SE US forest owners).

We have developed a conceptual model of the transatlantic wood pellet trade system (Figure 1) using the SE US as the sending system, the EU as the receiving system, and the coal industry as the geographically distinct potential spillover system (along with emissions to air and water during transatlantic pellet transport). We have then focused our research on the sending and receiving systems because data availability is greater for these parts of the telecoupling framework, and because the identified spillover system is impacted by additional systems that are beyond the scope of this paper. The flows, systems, causes, agents, and effects identified through our data analyses and literature review are discussed below and summarized in Tables 1-6. The application of the telecoupling framework provides a way to examine multiple aspects of sustainability associated with using wood pellets—i.e., other facets of social and ecological sustainability besides the carbon emissions tracked through life cycle analyses (LCAs).

Sending and receiving systems and the flows between them

Through analysis of recent US International Trade Commission (USITC) data, we evaluate the transatlantic flows of wood pellets and money involved in this rapidly growing telecoupled system and use the results to refine understanding of the geographic boundaries of the sending and receiving systems (Tables 1 and 2).

Europe as a whole is a large wood pellet producer, and its member states initially intended to meet their 2020 biopower production targets through a combination of wood and agricultural residues (Dwivedi et al. 2011, Goh et al. 2013, Beckman 2015). However, by 2014 the SE US was supplying 40% of Europe’s 9 million metric tons (MT) industrial wood pellets (Stewart 2015) and had become the largest external supplier of pellets to the European Union (EU) (Olesen et al. 2016). By 2015, the US was exporting pellet volumes three times greater than Canada and five times greater than the Russian Federation (FAOSTAT 2017).

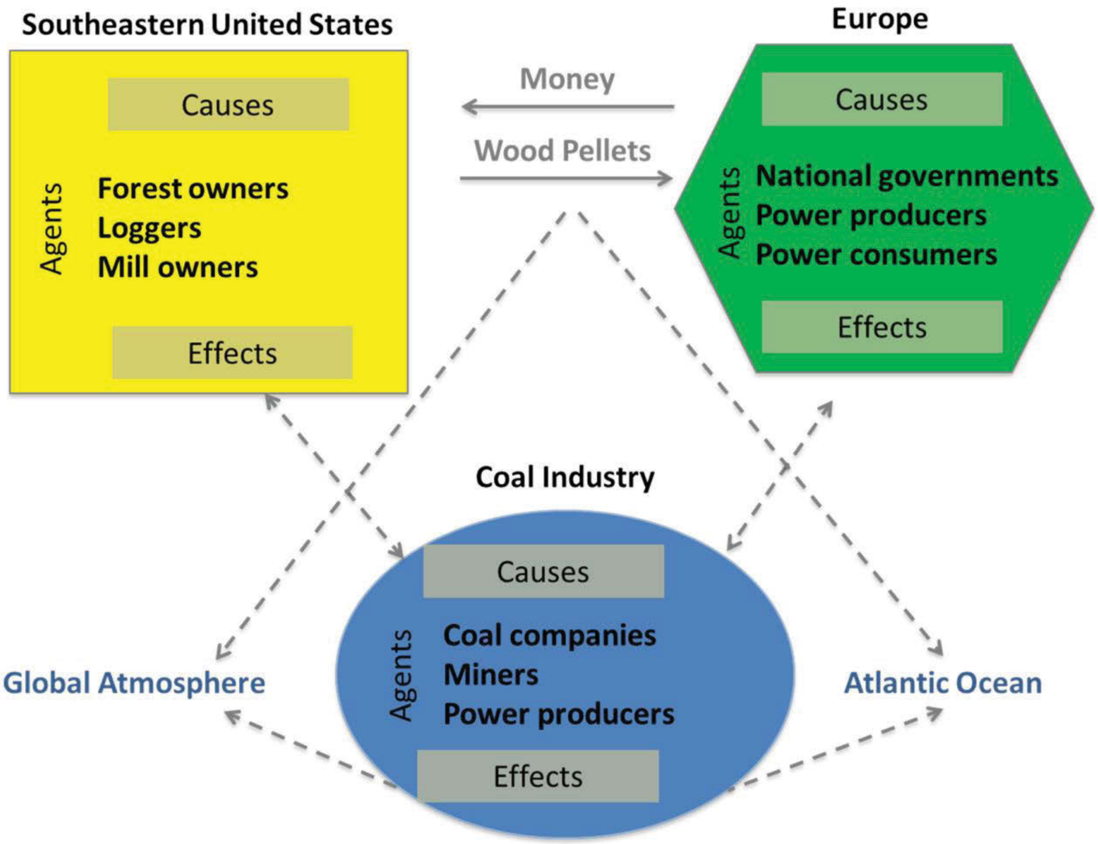

Figure 1. Conceptual model of the transatlantic wood pellet trade system

This conceptual model is based on the telecoupling framework proposed by Liu et al. (2013). Solid arrows indicate direct flows of material (wood pellets) and money between the sending system (SE US) and the receiving system (Europe). Dotted arrows indicate potential connections (influences) on the spillover system (coal industry) as well as emissions of greenhouse gases and waste related to transatlantic shipping between the sending and receiving systems.

Table 1. Interacting subsystems within the telecoupled transatlantic wood pellet trade system

Subsystem	**Description**	**Sources of Information**
Sending system	Southeastern US, including public and private timberland in 9 states bordering the Atlantic Ocean and Gulf of Mexico (AL, FL, GA, LA, MS, NC, SC, VA, TX), 6 shipping ports, 16 export pellet mills, a variety of wood processing mills, and related transportation infrastructure (roads, rails and barges)	Abt et al. (2014), O'Connell et al. (2014), Stewart (2015), Olesen et al. (2016), analysis of US International Trade Commission data (USITC 2017)
Receiving system	Pellet importing nations of Europe (UK, the Netherlands, Belgium), the power producers, EU government, and electricity consumers	European Parliament (2009), Goh et al. (2013), Dwivedi et al. (2014), Beckman (2015), analysis of US International Trade Commission data (USITC 2017)
Spillover system	Coal industry	Drax (2016b), Voegele (2016), analysis of US International Trade Commission data (USITC 2017)
Spillover system	Atlantic ocean (barge traffic)	Dwivedi et al. (2014)
Spillover system	Global atmosphere (carbon emissions)	Dwived et al. (2014), Morrison and Golden (2016)

Table 2. Flow components of the telecoupled transatlantic wood pellet trade system

The three columns at the right of the table indicate the systems (Table 1) that are most closely related to each component attribute: S = sending system, R = receiving system and Sp = spillover system.

Flow components	**Attributes**	**Source(s) of information**	**Related system(s)**		
			S	**R**	**Sp**
Wood pellets	Directly harvested biomass (e.g., forest thinnings, cull trees, trees for which there is no other market)	Stewart (2015), Anderson and Mitchell (2016), Morrison and Golden (2016),	X	X	
Wood pellets	Indirectly obtained woody biomass (e.g., sawmill residues)	Stewart (2015), Anderson and Mitchell (2016), Morrison and Golden (2016)	X	X	
Money	Pellet purchase price	Goh et al. (2013), Stewart (2015), analysis of international trade data (FAOSTAT 2017)	X	X	
Money	EU renewable energy credits	Dwivedi et al. (2014), Stewart (2015)	X	X	X
Money	Forest owner income from bioenergy product sales	Malmsheimer and Ferhnolz (2015)	X		

Table 3. Causal components of the telecoupled transatlantic wood pellet trade system

The three columns at the right of the table indicate the systems (Table 1) that are most closely related to each component attribute: S = sending system, R = receiving system and Sp = spillover system.

Causal components	**Attributes**	**Source(s) of information**	**Related system(s)**		
			S	**R**	**Sp**
Socioeconomic	US housing market collapse c.2008	Malmsheimer and Ferhnolz (2015), Stewart (2015)	X		
Socioeconomic	Decline in US pulp and paper industries	Goh et al. (2013), Stewart (2015), World Biomass (2015), Brandeis and Guo (2016)	X		
Socioeconomic	Lack of a US biopower market	Personal communication to E.S. Parish from attendees of the Appalachian Wood Energy Innovations Conference on August 24, 2016	X		
Socioeconomic	Availability of low-cost natural gas	Breen and Koehler (2017)	X		
Socioeconomic	Low cost of transatlantic shipments and dedicated shipping lanes	Rodrique (2016), Dwivedi et al. (2014)	X	X	X
Socioeconomic	European demand for high-grade (e.g., low ash content), low-cost wood pellets	Olesen et al. (2016), Beckman (2015), Abt et al. (2014),	X	X	
Socioeconomic	Relatively low cost of retrofitting coal plants to enable biomass co-firing	Morrison and Golden (2016)		X	
Political	EU climate and renewable energy goals	Directive 2009/28/EC of the European Parliament (EC 2009), European Commission (2017)		X	

Table 3 (continued)

Causal components	**Attributes**	**Source(s) of information**	**Related system(s)**		
			S	**R**	**Sp**
Political	Wood energy plans and subsidies by EU member states	Dwivedi et al. (2014), EASAC (2017)	X	X	X
Political	US coal industry opposition to proposed US Clean Power Plan	Personal communication to E.S. Parish from attendees of the Appalachian Wood Energy Innovations Conference on August 24, 2016	X		X
Environmental	Downed wood available following insect outbreaks, tornadoes, ice storms, and other extreme events	Greenberg and Collins (2016), Wear et al. (2013)	X		X
Geographic	Temperate SE US climate, allowing for rapid forest growth and regeneration	Goh et al. (2013)	X	X	
Geographic	SE US forests' proximity to Atlantic Ocean enabling direct shipping to EU	Goh et al. (2013), Hamilton and Quinlan (2017)	X	X	X

Table 4. Agents within the telecoupled transatlantic wood pellet trade system

Primary agents are the system's key decision makers, facilitating agents tend to increase flows within the system, and constraining agents tend to decrease flows within the system.

Agent Type	Sending System	Receiving System
Primary agents	Family forest owners, Institutional forest owners, Loggers, Mill owners	Governments of European nations and EU member states, Power producers (e.g., Drax), Power consumers
Facilitating agents	Port operators & shipping companies, Railroad operators, Truckers, Owners of mothballed pulp mills, Industrial Pellet Association, Investors, USDA Forest Service (USFS), Forestry extension agents from land grant universities, Forestry associations	European Commission, Pellet supply chain operators, Investors
Constraining agents	State governments, Municipalities, Environmental Nongovernmental Organizations, Citizens' Alliances, Land Trusts	Environmental Nongovernmental Organizations (eNGOs)
Facilitating or constraining agents?	US Environmental Protection Agency (EPA), US Fish and Wildlife Service (USFWS), Forest certification programs	Certification programs specific to wood pellet industry (e.g., Sustainable Biomass Partnership)

Table 5. Observed effects within the telecoupled transatlantic wood pellet trade system

The three columns at the right of the table indicate systems (Table 1) that are most closely related to each component attribute: S = sending system, R = receiving system and Sp = spillover system. Positive (+), negative (-) and uncertain (o) effects are indicated for each subsystem.

Observed Effect Category	**Attributes**	**Source(s) of information**	**Related system(s)**		
			S	**R**	**Sp**
Environmental	Enhanced management of SE US forest systems through extra income from bioenergy products with resulting benefits to water quality, biodiversity, carbon sequestration, and forest productivity	Malmsheimer and Fernholz (2015), Dale et al. (2017*a*),	+		
Environmental	Conservation of sensitive SE US forest ecosystems through funds established by large pellet producers	Drax (2016*a*), Enviva Forestry Funds (2016)	+		
Environmental	Reduction in toxic air emissions related to coal combustion	Rudie et al. (2016)		+	
Environmental	Reduction in greenhouse gas emissions from energy production	Goh et al. (2013), Dwived et al. (2014), Drax (2016*b*), Morrison and Golden (2016)		o	o
Environmental	Reduction in air pollution due to reduced burning of woody debris in the open	Evans et al. (2013)	+		
Environmental	Preservation of EU forested land and associated ecosystem services	Solberg et al. (2014)		+	
Socioeconomic	Increased fuel costs for European power producers (relative to coal)	Green (2015)		-	

Table 5 (continued)

Observed Effect Category	Attributes	Source(s) of information	Related system(s)		
			S	R	Sp
Socioeconomic	Boiler conversion costs	Green (2015)		-	
Socioeconomic	Additional market opportunity for woody biomass helps SE US land remain in forest (rather than succumbing to urbanization pressures)	World Biomass (2015), Dale et al. (2017a)	+		
Socioeconomic	Avoided job losses in rural SE US	World Biomass (2015)	+		
Socioeconomic	Reduced risk of wildfires due to increased forest management	Neary and Zieroth (2007), Anderson and Mitchell (2016)	+		
Socioeconomic	Development of international sustainability certification schemes	Buchholz et al (2009), Scott et al. (2013), Barnett (2015) Olesen et al. (2016)	o	o	

Table 6. Potential effects of the transatlantic wood pellet trade system

The three columns at the right of the table indicate systems (Table 1) that are most closely related to each component attribute: S = sending system, R = receiving system and Sp = spillover system. Positive (+), negative (-) and neutral (o) effects are indicated for each subsystem.

Potential Effect Category	**Attributes**	**Source(s) of information**	**Related system(s)**		
			S	**R**	**Sp**
Environmental (Potential)	Increased pressure on threatened and endangered SE US forest species, either directly through changes to forest habitat (e.g., conversion of hardwood to pine plantations) or indirectly through altered management practices (e.g., removal of debris or snags, altered rotation intervals)	Fritts et al. (2015), Hanula et al. (2015), NRDC (2015), Olesen et al. (2016)	-		
Environmental (Potential)	Loss of ecosystem services from SE US forests (e.g., flood protection, soil stabilization, carbon sequestration)	Janowiak and Webster (2010), NRDC (2015), Tarvainer et al. (2015)	-		
Environmental (Potential)	Changes in SE US forest structure and composition	Olesen et al. (2016)	-		
Socioeconomic (Potential)	Local competition for low-cost biomass as domestic and international markets fluctuate	Galik et al. (2009), Spelter and Toth (2009), Stasko et al. (2011), Stewart (2015),	-	-	
Socioeconomic (Potential)	Growth in sustainable green economy jobs relative to boom/bust cycle of extractive nonrenewable energy alternatives	Parish et al. (2013)	+		-
Socioeconomic (Potential)	Changes in SE US forest management practices (e.g., rotation length, thinnings, residue removal rates)	Dwivedi et. al. (2014), Fritts et al. (2015),	o		

Table 6 (continued)

Potential Effect Category	Attributes	Source(s) of information	Related system(s)		
			S	R	Sp
Socioeconomic (Potential)	Impacts on recreation and hunting during harvests	Personal communication to E.S. Parish from attendees of the Appalachian Wood Energy Innovations Conference on August 24, 2016	o		

During 2015, the SE US sent 4.6 million metric tons (MT) of wood pellets to 34 countries (Figure 2). Most (84%) of these pellets were delivered to the UK, 13% went to Belgium, 1% went to both the Netherlands and France, and the remaining 1% of the wood pellet exports went to the 30 other countries around the globe (USITC 2016). Although the top importers of US wood pellets have fluctuated during each year of record, the UK has been the dominant importer since 2011 and is currently the world's largest importer of wood pellets, while the Netherlands and Belgium have been important importers since 2008 (FAO 2017). USITC (2016) data also show that (1) these three countries initiated significant imports of this US material after 2007, when the EU pledged to increase its use of renewable energy resources, and (2) the large increase in US wood pellet exports after 2011 has been primarily attributable to the demands of the UK, the Netherlands, and Belgium. Even though the UK has voted to leave the EU, it continues to import pellets in accordance with the long-term contracts established by several large power producers and achieved record pellet imports of 4.2 MT from the US in 2016 (USITC 2017). The Netherlands has recently stopped importing US pellets while deciding on new sustainability requirements (Figure 2) but is expected to resume shipments once certification programs are implemented (Kotrba 2017).We therefore designate these three European countries (UK, Netherlands and Belgium) as the primary receiving system.

Nearly all US wood pellet exports to Europe are shipped from six SE US ports (Figure 3). Total wood pellet exports from these six SE US ports more than doubled from 1.9 million metric tons (MT) in 2012 to 4.7 MT in 2015 (USITC 2016). These industrial-grade pellets were composed of wood material processed by dedicated export pellet mills after being obtained from surrounding timberland and saw timber mills. Timberland is a subset of US forestland that is "producing or is capable of producing crops of industrial wood and not withdrawn from timber utilization by statute or administrative regulation" (O'Connell et al. 2014). We therefore define the SE US sending system as the timberlands, saw timber mills, export pellets mills, and transportation systems in the nine states bordering the Atlantic Ocean that provide wood pellets to Europe: Alabama, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Virginia, and eastern Texas (Figure 3). The transportation infrastructure within the sending system includes road networks, railroads, river barges, and shipping ports.

The first two SE US export wood pellet mills began operating in 2008, and there were 16 operational export wood pellet mills with three more under construction in 2016 (Stewart 2015). Generally these mills obtain biomass for the wood pellets from sawmill residues and other leftovers from higher value wood products (Morrison and Golden 2016). However, biomass for wood pellet production is also obtained directly from forests via thinning of tops, cull trees and brush, downed woody debris, and roundwood (logs) obtained from forests stranded from the market after pulp mill closures (Parish et al. in press, Dale et

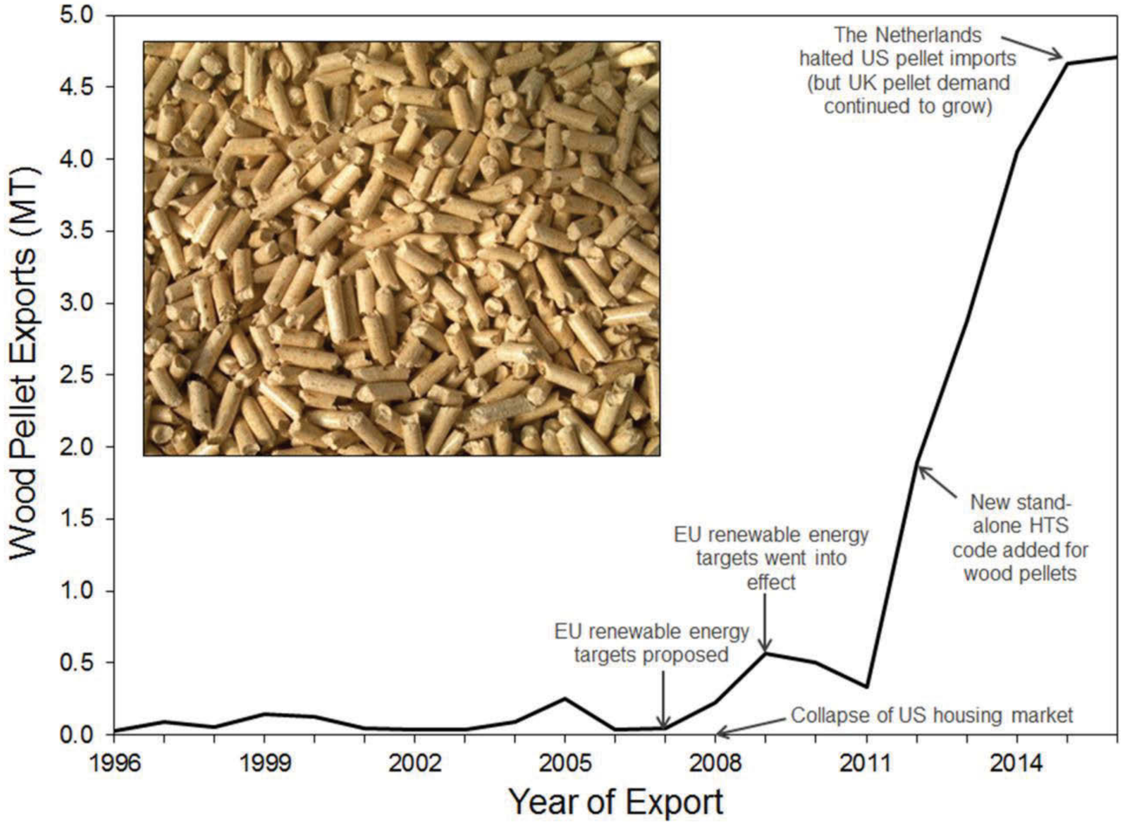

Figure 2. Annual total US wood pellet exports to all countries from 1996 to 2016

Data were obtained from the US International Trade Commission (USITC 2017). In 2012, a new stand-alone Harmonized Trade Schedule (HTS) code 4401310000 was introduced for "Wood Pellets," but previously wood pellets were included in HTS code 4401300000, "Sawdust and wood waste or scrap, whether or not agglomerated in logs, briquettes, pellets or similar forms." The graph shows changes in HTS code 4401300000 before 2012 and in HTS code 4401310000 for 2012 and years thereafter.

Figure 3. Map of the Southeastern US sending system

Nearly all 2015 US industrial wood pellet exports were shipped to Europe from six ports located on the coasts of Virginia (28%), Georgia (28%), Florida (14%), Alabama (13%), Texas (10%), and Louisiana (5%) (USITC 2016). The wood pellets were delivered to these ports from 16 export pellet mills, which obtained their woody material from forests and saw timber mills within a 75-mile radius (Stewart 2015). The majority of SE US forests are privately owned by families (Forest Service Research Data Archive ownership data layer accessed November 26, 2016).

al. 2017b). Through their interviews with SE US pellet industry representatives, Morrison and Golden (2016) found that SE US pellet production scenarios range anywhere from 100% sawmill residues to 100% roundwood, fluctuating with available supply and demand.

The reported total export value of the SE US wood pellets was $258M in 2012, $371M in 2013, $519M in 2014, and $683M in 2015 (FAOSTAT 2017). Industrial pellets are mostly traded with European nations under long-term bilateral fixed contracts (Goh et al. 2013). In the short term, pellet prices may be influenced by general wood market supply and demand trends, currency exchange rates, and disruptive events—such as the heavy winter rains of 2009 and 2013 that prevented planned SE US tree harvests (Stewart 2015). Export wood pellet demand has not yet caused any significant price changes for other US wood products, but bioenergy production has caused some local competition for pulpwood (Stewart 2015). It is possible that this local competition will diminish as the saw timber market continues to rebound from the 2008 US housing market crash.

Causes of recent growth in wood pellet trade

Transatlantic wood pellet trade has accelerated due to a variety of causes (Table 3). The EU government is the main driver of the trade through both its Renewable Energy Directive and its incentive programs (Dwivedi et al. 2014). European nations look to renewable biomass resources as an opportunity to mitigate climate change through reduction of greenhouse gas emissions (IPCC 2014), and the European Commission identified wood pellets as the most economical way to convert biomass materials to fuel to help meet these goals (Beckman 2015). Because they are produced through compression, wood pellets have a higher BTU content than typical biomass sources (ITA 2016). As a response to EU's 2020 climate and renewable energy targets, national legislations and regulations provided monetary incentives to owners of biomass-based power plants (Dwivedi et al. 2011, Goh et al. 2013, EASAC 2017). The engineering necessary to retrofit an existing coal power plant to use biomass, either alone or through co-firing, is relatively simple, and the low cost of plant conversion helps make biomass an important bridge fuel for European power supplies (Morrison and Golden 2016).

Industrial wood-pellet trade flows are influenced by European power plant specifications for size and quality (e.g., low ash content), which affect wood inputs as well as processing techniques (Anderson and Mitchell 2016). Although EU member states increasingly have opportunities to purchase wood pellets from nearby countries, the high quality of US wood pellets coupled with their relatively lower cost of transportation over water (relative to land) make US wood pellets an attractive import commodity (Beckman 2015).

Although the rise in US wood pellet exports has been primarily driven by increased European demand, geography, economics, and other factors within the SE US system have contributed. The temperate climate of the SE US supports plentiful forests that regenerate quickly. Known as the nation's 'woodbasket,' the SE US region contains 40% of the 521 million acres of timberland found across the US and has supplied about 63% of US timber harvests since 1996 (Oswalt and Smith 2014, DOE 2016). The proximity of large amounts of this forested land to the Atlantic Ocean (Figure 3) enables low-cost transportation of woody biomass to Europe via well-established maritime shipping routes (Rodrique 2016, Hamilton and Quinlan 2017). Forest disturbances from insect outbreaks, windstorms, ice storms, and other extreme events yield immediate sources of low-grade biomass that may be burned or left to decompose without a market outlet (Wear et al. 2013, Greenberg and Collins 2016).

The rise of the digital age around the turn of the century led to the general decline of the pulp/paper market worldwide, and following the crash of the over-built US housing market in December 2007, nearly 1,000 US wood-processing mills were closed (Oswalt and Smith 2014). By 2009, sawmills across the SE US were operating at only 60% capacity (Stewart 2015), and losses of SE US mills led to a significant loss of jobs throughout the SE region (World Biomass 2015). Alternative wood product pathways are therefore critical to keeping SE US land in forest (Dale et al. 2017a).

At this time, there are no policies in place that specifically inhibit or encourage the use of wood pellets within the US (DOE 2016). Although woody biomass could theoretically be used for local biopower production, the recent drop in US natural gas prices coupled with the lobbying strength of the US coal industry have prevented the development of a SE US market for wood pellets (personal communication to E.S. Parish from attendees of the Appalachian Wood Energy Innovations Conference on August 24, 2016) . Bagged wood pellets have been used for home heating in the Northeastern US since the 1930s (Spelter and Toth 2009), but opposition to the US Environmental Protection Agency's (EPA's) Clean Power Plan proposal and lack of incentives have hampered growth of wood-based biopower at an industrial scale. Thus, US wood pellet exports have far outstripped domestic use over the past several years.

Agents: Primary, facilitating and constraining

A complex variety of decision-makers are involved in both the sending and receiving systems. We have therefore divided the 'agents' into three subtypes based on the way(s) they can affect flows within and between the sending, receiving, and spill-over systems (Table 4). We define 'primary agents' to be the central decision-makers within each system that drive flows based on actions and information received from facilitating and constraining agents. ‘Facilitating agents’ are entities within the system that increase or speed up the flow of material from the system. Lastly, ‘constraining agents’ slow down or reduce the flow of material. Because of the many uncertainties related to future growth and expansion of international wood pellet trade, we thought it important to integrate these layered agents into the conceptual model.

Industrial-grade wood pellets for bioenergy are a new commodity within a preexisting US forest sector that is driven by local demand for the highest value timber product, which is often saw timber but can be pulp—as influenced by location and types of mill (Parish et al. in press). The primary agents within the SE US sending system include the forest owners and land managers who make key decisions about timberland management and harvests. The decisions include choices in harvest/rotation length, residue removal rates, and ownership transfer, which affect forest area, quality and composition over space and time for many decades.

Recent divestiture of industry land ownership to private ownership (e.g., International Paper’s sale of 4.7 million acres of SE US timberland in 2006) has led to more stand-level management and more flexibility to market conditions (Stewart 2015). The majority (i.e., 87%) of SE US forests are now privately owned by families (Weir and Greis 2013), many of whom choose when and how to harvest based on personal values and financial considerations coupled with life events, such as education or health needs (Butler, Butler and Markowski-Lindsay 2017). Family owners generally have the goal of growing larger, higher value trees and frequently delay harvests until the price of saw timber looks favorable (Stewart 2015) or life events instigate a need for cash (Butler et al. 2017). Hunting and recreation leases also supplement incomes (Malmsheimer and Fernholz 2015) and influence the type of harvest selected or avoided (e.g., clearcutting, controlled burning).

Loggers and mill owners are also primary agents within the SE US sending system. Certified pellet, pulp, and saw mills require special documentation of logger training and certification from their suppliers to ensure sustainable practices. Both mill operators and forest managers help make decisions regarding when to supply biomass to different portions of the wood products market, including pellet production facility operators.

Getting wood material transferred from SE US forest landings to other parts of the supply chain is facilitated by a well-developed infrastructure of railways, road networks, and barges. The Industrial Pellet Association, mothballed paper/pulp mills, and the available workforce through the SE US are additional facilitating agents that encourage the production of wood pellets by making the supply chain components accessible and cost efficient.

Additional facilitating agents within the sending system include US Department of Agriculture Forest Service (USFS) personnel and Forestry Extension Agents from Land Grant Universities. These entities are charged with educating forest owners concerning best forest management practices and the potential (and often variable) outlets for wood. Forestry associations such as the Society of American Foresters (SAF) and the National Council for Air and Stream Improvement (NCASI) have a primary responsibility is to help implement decisions that will promote a sustainable wood industry over multiple decades and are also currently supportive of the pellet industry. If these entities were to gain new information about the wood pellet industry causing negative impacts on forests, they would alter their advice to forest managers accordingly.

A variety of federal, state, county, and municipal regulations apply to forest management in the SE US (Olesen et al. 2016) and may either directly or indirectly impact the supply of biomass available for the pellet industry. The US Energy Independence and Security Act (EISA) of 2007 sets renewable fuel specifications for the US and may begin to affect pellet production if woody biomass starts being used for domestic energy generation (DOE 2016). EPA and the US Fish and Wildlife Service (USFWS) are the primary federal regulatory agents in charge of enforcing the Clean Water Act, the Endangered Species Act, Migratory Bird Treaty Act, Coastal Zone Management Act, and Lacey Act (USIPA 2013). EPA and USFWS often delegate oversight to individual state governments, which also support a variety of forestry best management practices (BMPs) (Cristan et al. 2016) related to water quality management, soil quality and erosion, wetlands protection, zoning issues and landscaping ordinances. All of these regulations and BMPs have the potential to constrain pellet production (e.g., through residue removal rate requirements). Land trusts and citizens' alliances are additional constraining agents, for they may convert timberland to protected forestland through the establishment of conservation easements (Davis 1996). Some alliances exert political and social pressure to not use wood for energy.

It is currently unclear whether potential new requirements to get all pellet feedstock certified through programs such as the Roundtable on Sustainable Bioproducts (RSB) or the Sustainable Biomass Program (SBP) will increase or decrease SE US export pellet volumes. A recent Dutch study (Kotrba 2017) found that only 5% of small forest owners in the US are currently certified by one of the four primary US forest certification programs, namely the Forest Stewardship Council, The American Tree Farm System, the Sustainable Forestry Initiative, and the Programme for the Endorsement of Forest Certification. Although certification programs can help SE US pellet mills satisfy the legal requirements of receiving EU countries, getting formally certified under one or more of these programs may end up proving too costly or time-consuming for many of the small family forest owners who manage over 80% of SE US timberland (Malmsheimer and Fernholz 2015, Poudyal et al. 2015, Olesen 2016). A recent survey of Georgia residents found that they are more supportive of environmental management incentives than requirements (Poudyal et al. 2015).

Primary agents within the European receiving system include individual governments which support the increased use of biomass as a substitute for coal in response to renewable energy targets set by the European commission (Table 4). Primary agents also include the biomass-using power producers and the power consumers who collectively determine the amount of electricity that needs to be generated as well as fuel types used.

Facilitating agents include the European Commission, which has the power to establish and revise energy legislation and incentives, as well as the individuals who operate within the pre-existing pellet supply chain originally set up to receive pellets from within Europe. Constraining agents include environmental Nongovernmental Organizations (eNGOs) on both sides of the Atlantic that oppose wood pellet trade due to potential harm to SE US forest biodiversity and ecosystem services (e.g., NRDC 2015).

Within the European receiving system there are also agents that may be either facilitating or constraining depending on the turn of events. For instance, the Sustainable Biomass Partnership (SBP) formed in 2013 in conjunction with European utilities intends to facilitate wood pellet trade via standardized sustainability protocols—but making that program a requirement for doing business with SE US mills may become a hindrance for reasons already discussed. This example demonstrates that agents within the telecoupled system can have impacts across system boundaries and large distances. If and when governmental subsidies for renewable energy are removed, private investors may facilitate or hinder new market development for the wood pellet trade

Effects: Observed versus potential

Both the recentness and the relatively small size of wood pellet production within a preexisting wood market system make it difficult to determine actual effects of this new trade commodity on SE US forest management and related ecosystem services. While US wood pellet exports have been growing rapidly during recent years (Figure 2), they still constitute a relatively small proportion of total SE US timberland removals (Figure 4). NGOs are particularly vocal about potential environmental problems that might arise from a growing wood pellet industry (hence their designation as constraining agents in Table 4), but evidence of actual observed impacts is difficult to find—particularly at this early stage of the industry's development. We have therefore distinguished between wood pellet industry effects that have been observed (Table 5) and those that have only been

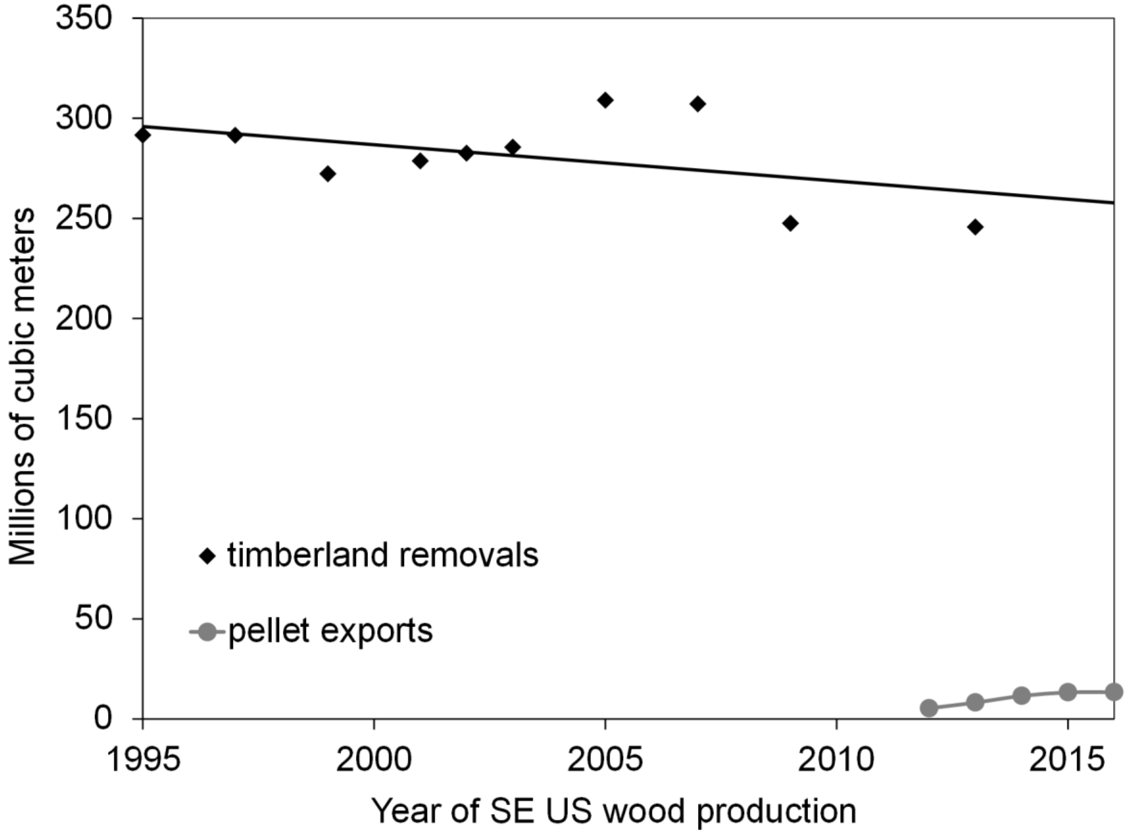

Figure 4. Overall decline in Southeast US timberland removal volumes (1995 to 2013) shown relative to wood volumes used to produce pellet exports (2012 to 2013)

Timberland removal volumes (TPO 2017) have been totaled for the nine states contained in the SE US sending system (Fig. 3). Wood volumes used for export pellets are based on the export kg values (USITC 2017) converted using a factor of 0.7 tonne/m3 (Lamers 2013) and the knowledge that 2 tonnes of woody biomass is used to produce 1 tonne of dry pellets (Dale et al. 2017a). In 2013, the 8 million cubic meters of woody biomass used to make pellets comprised only 3% of the total SE US timberland removal volume of 246 million cubic meters.

speculated (i.e., potential effects) (Table 6). Both types of effects are discussed in this section.

Potential effects on the environment have been raised by the European Commission regarding transatlantic wood pellet trade, including: (1) deforestation and forest degradation within the SE US, (2) losses of biodiversity and ecosystem services in SE US forests, and (3) the EU not achieving desired net greenhouse gas emissions reductions through substitution of wood pellets for coal. Each of these concerns is addressed below.

There is no evidence that recent pellet production has been responsible for deforestation or forest degradation in the SE US (Dale et al. 2017b). Instead, changes in the amount of SE US land retained in forest as well as the quality and composition of the forest continues to be driven largely by development, urban encroachment, natural disturbances, and climate change (Wear and Greis 2013). While some NGOs argue that species-rich mixed hardwood stands are being replaced by pine plantations due to increased wood demand for energy (NRDC 2015, Olesen et al. 2016), recent analysis of total SE US sawtimber and pulpwood inventory from 2000-2014 showed a 0.1% annual increase in hardwoods in the Atlantic Region and a 1.3% annual increase in hardwoods in the Gulf Region (Stewart 2015).

Assessing effects of the transatlantic wood pellet trade on SE US biodiversity is difficult because of the small role of pellet production within the larger US wood products system (Figure 4) and because effects on biodiversity are highly context-specific and depend on particular species and their habitats, forest management practices (e.g., rotation intervals, residue removal rates), and forest conditions prior to harvest (Constanza et al. 2016). The same set of conditions may cause some species to decline while other species may benefit (e.g., some species thrive in younger forests while others depend upon mature trees). It is important to recognize the SE US region is a mosaic landscape of different forests (in terms of age, stand structure, and species composition) that are managed for multiple objectives with overlapping state and federal guidelines. Negative effects of bioenergy on biodiversity can be avoided or reduced by conservation of priority areas (Joly et al. 2015), and two of the largest SE US pellet producers have recently established conservation funds to help preserve and restore sensitive bottomland forests (Drax 2016a, Enviva 2016).

Ecosystem services are now considered to be essential forest ‘products’ alongside timber and pulp resources (Anderson and Mitchell 2016). Growing biomass exports do have the potential to affect additional SE US ecosystem services such as flood control, soil quality, and water purification (NRDC 2015)—as well as recreational opportunities for hikers, boaters, and hunters (Malmsheimer and Fernholz 2015)—by changing forest management and harvest practices (Webster 2010, Achat et al. 2015, Tarvainen et al. 201). Soil carbon can be impacted by forest harvesting, but the degree of effect is highly site dependent with complex interactions (Achat et al. 2015, Coulston et al 2015). Thinned forests for biomass can also improve carbon sequestration in maturing trees by increasing stand growth rates (Jandl et al. 2007). Most state-managed forestry BMPs throughout the SE US and the requirement by many mills that certified loggers do the harvesting should ensure that water quality and soil quality are maintained, since these system actors are also concerned about these potential effects (Cristan et al. 2016, Olesen et al. 2016). Profits from wood pellet exports have provided SE US land owners with additional income needed to keep their land in forests and manage it properly (Malmsheimer and Fernholz 2015, Dale et al. 2017a). This new revenue source for wood products is especially important given the recent decline in total US wood-based production (Figure 4), which has acute effects in rural US SE communities (World Biomass 2015). Well-managed forests have been shown to improve water quality, carbon sequestration, and biodiversity as well as overall productivity (Anderson and Mitchell 2016, Dale et al. 2017a).

The transatlantic wood pellet trade was initiated to help European nations reduce their GHG emissions from electricity generation relative to traditional fossil fuel combustion. A variety of studies, including one that modeled GHG emissions under 930 different scenarios (Dwivedi et al. 2014), have found that overall GHG emissions may be substantially reduced through use of wood pellets. However, ‘carbon accounting’ continues to be one of the thorniest areas of consternation and debate concerning the transatlantic wood pellet trade due to different assumptions and methods for estimating net GHG emissions (Berndes et al. 2016, EASAC 2017). EU member states that import wood pellets from nations outside of the EU (such as the U.S. and Canada) have reported large reductions in carbon dioxide emissions at least partly because of the controversial accounting practice of assuming that carbon is instantly released to the atmosphere when trees are harvested rather than at the point of combustion (EASAC 2017). In general, the ‘carbon debt’ debate relates to the fact that it takes much longer for trees to regrow and store carbon (i.e., decades) than it does to release carbon from wood via combustion in power plants (Goh et al. 2013). ‘Carbon debt’ often assumes the trees would not be harvested except for pellet demand and does not apply to the wood wastes and residues that are often used for pellet production in the SE US. In the absence of a bioenergy market, woody debris from noncommercial thinnings, harvest residues and some mill residues are more likely to be left in piles to decompose or burned on-site, thereby emitting GHGs with no energy recovery (Evans et al. 2013, Dale et al. 2017a). Forest management through selective thinnings has the potential to increase carbon stored in soils and trees (Dale et al. 2017a) while simultaneously providing low-quality roundwood feedstock to pellet mills located within a reasonable distance. The careful consideration of baselines and realistic counterfactuals in developing future modeling scenarios is essential to solving this debate over carbon accounting (Ricardo 2016, Parish et al. 2017).

Partly due to sustainability concerns from European and US NGOs, a certification program specifically intended for wood for energy was started in 2013. This Sustainable Biomass Partnership (SBP) is industry-led and is supported by European utilities (Olesen et al. 2016). The UK and Belgium have already implemented sustainability regulations for the whole biomass supply chain (Goh et al. 2013), and the Netherlands has been examining this issue (Kotrba 2017).

Negative socioeconomic impacts of the pellet trade on the receiving system include higher costs of wood pellets relative to coal (June 2016 price differences were $165 per tonne of wood pellets versus $58 per tonne of coal) and the costs associated with boiler conversion (Green 2015). Benefits to Europe improved local air quality from the fewer air toxins released during combustion of wood relative to coal (Dwivedi et al. 2014) and the preservation of EU forested lands and their associated ecosystem services (Solberg et al. 2014).

Spillover system: The decline of coal

Britain celebrated its first completely coal-free electricity day since 1881 on April 21, 2017 (BBC News 2017). UK biomass capacity has increased 16-fold since 2010 while coal-fired generation has dropped 88% since 2010 (Voengele 2016). There has been a waning in US coal shipments to the UK and Belgium, and a leveling off of coal shipments to the Netherlands at the same time that wood pellet shipments to the EU have increased for biopower production (Figure 5). US coal production and energy usage declined slightly from nearly 1.2 billion tons in 2008 to approximately 900 million tons in 2015, while US coal exports shifted away from Europe toward China, South Korea and other countries (EIA 2016). While we cannot definitively attribute the recent drop in European coal imports to the coincident increases in wood pellet imports, we think that the US coal industry is a likely spillover system (Figure 1). This impression is supported by a recent news article stating that Europe decreased its imports of coal from the US region of Appalachia by 50% over the past five years due, in part, to a growing market of renewables (Breen and Koehler 2017).

Additional spillover effects from wood pellet trade include pollutant emissions to the global atmosphere and the Atlantic Ocean during shipments of the pellets to Europe (Figure 1). Dwivedi et al. (2011) calculated that transportation across the ocean is the largest source of greenhouse gas emissions from the supply chain, amounting to 71,750 metric tons of carbon

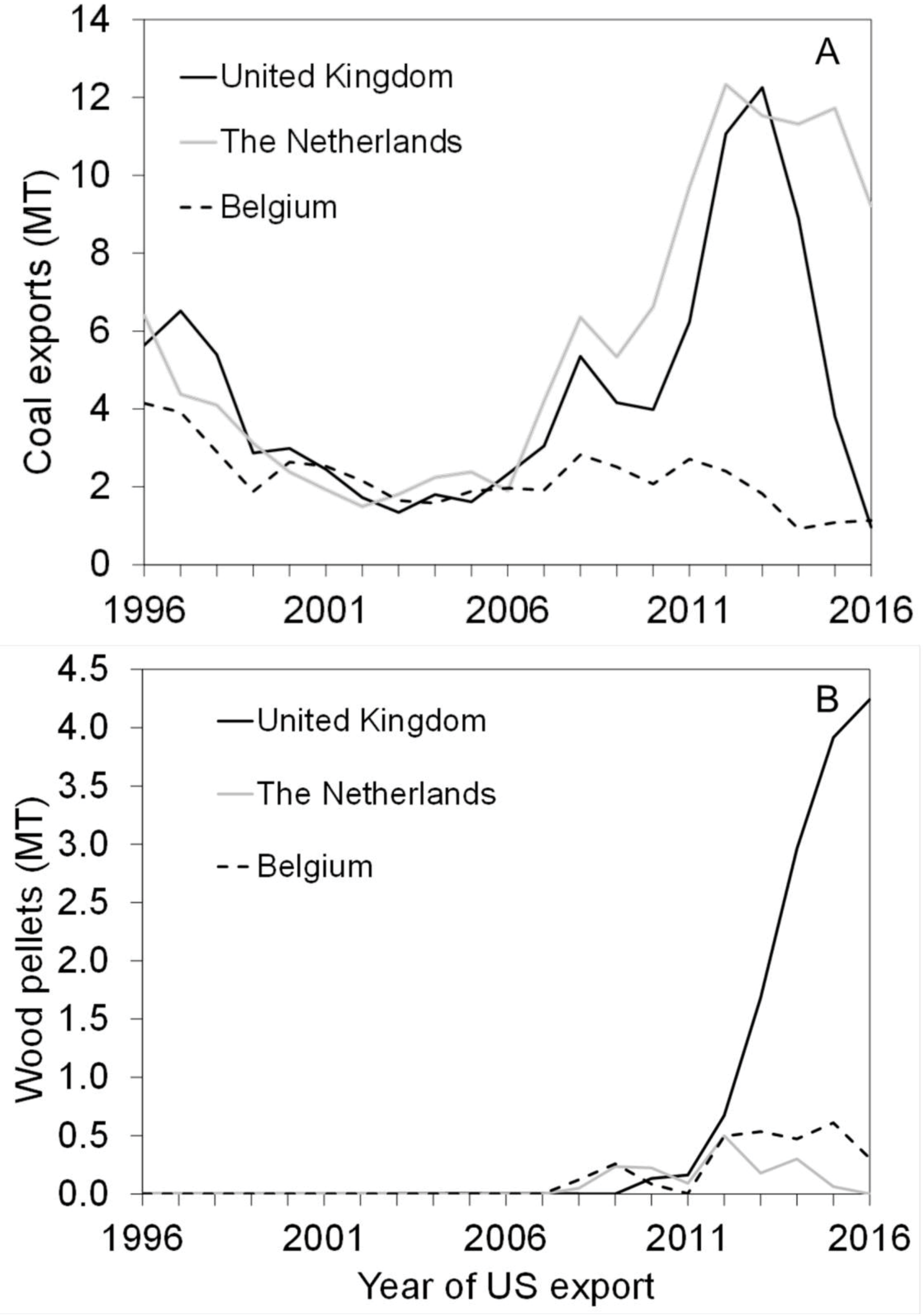

Figure 5. Comparison of US coal and wood pellet exports to three European nations

US coal exports (A) and wood pellet exports (B) to the three largest European importers of SE US wood pellets (USITC 2017). Note that SE US wood pellet exports (b) to these three EU member states (USITC 2017) accelerated at about the same time that US coal exports began to slow down or decline.

dioxide (CO2) equivalent per shipment from Florida to the Netherlands, or 44% of the CO2 equivalent emissions generated from tree production through power plant combustion. However, it is unclear whether transatlantic shipments have increased due to the wood pellet trade or if the tankers are simply transporting the pellets in place of something else (e.g., coal).

Knowledge Gaps and Future Uncertainties

Uncertainty in energy markets is a key concern for the SE US wood pellet industry, and a range of future decisions have significant potential to affect the overall system. Many European power plants have already made the necessary conversions from coal to biomass and have long-term contracts with wood suppliers in the SE US, suggesting this telecoupling trade will continue. The European Commission has recently proposed an increase in its renewable energy target to 27% by 2030, making it possible that the EU will need to import more wood pellets from the US (Olesen et al. 2016). On the other hand, some NGO actors are pushing to end EU subsidies for wood energy. Recent austerity measures by the EU and its member states have capped subsides for all renewables making it harder for new export pellet mills to secure long-term contracts with European customers (Stewart 2015). The recent “Brexit” decision by the UK to depart the EU has many wondering if the UK, the largest importer of SE US pellets, will begin to decrease its demand of wood for energy. And President Trump’s recent decision to remove the US from the Paris Agreement complicates US pellet exports since the EU is not allowed to accept pellets from nations which are not part of that international climate agreement (Murray 2017). During the remainder of 2017, EU member states will likely be debating the proposed Renewable Energy Directive (RED II) and whether it will allow the US to continue exporting wood pellets to the EU if suppliers meet a set of sustainability requirements (Ginter 2017).

Biomass suppliers report in trade industry journals that they anticipate continued growth in wood pellet trade with the UK and EU through 2020 (e.g., Wood Pellet Association of Canada 2017). Total production capacity of existing SE US export pellet mills is 7.4 MT (Stewart 2015), so there is room to grow beyond the 4.6 MT of pellets exported in 2015. If the EU market for SE US wood pellet does decline, there are other potential markets available, both locally and abroad, including China, which is phasing out or canceling many planned coal plants (Arnold 2016). Meanwhile, other renewable energy resources such as solar and wind power will continue to develop commerically and may eventually compete with biopower.

Forest management concerns raised by rapid growth of the wood pellet export industry are similar to the issues raised when a large number of chip mills began to proliferate across the SE US during the years 1985-2000 (Stewart 2015). Despite the fears expressed by NGOs, clearcutting did not become widespread and harvest rotation lengths did not shorten during the chip mill boom (Shaberg et al. 2005, Stewart 2015). An integrated assessment of wood chip production in North Carolina found that chip mills should be viewed as “a processing technology rather than an independent cause of timber harvesting” (Schaberg at al. 2005:17). We envision a similar outcome for the transatlantic export wood pellet market given its small share of the overall SE US wood market and the multitude of regulations and state-based BMPs in place to ensure sustainable forest management at regional and local scales.

Conclusion

Based on this analysis using the telecoupled framework, we conclude that assertions of negative ecological impacts on SE US forests are not currently substantiated (as demonstrated by the observed effects listed in Table 5). We also find that the transatlantic wood pellet trade is an example of a mutually beneficial telecoupled system with the potential to provide environmental as well as socioeconomic benefits in both the SE US and Europe despite some negative impacts on the coal industry. Given that biomass for wood pellets comprises only ~3% of SE US timberland removals, however, it is profoundly difficult to isolate the effects of wood pellet production from those of the SE US wood industry as a whole. And against the current backdrop of plentiful natural gas (in the US) and increasing renewable energy use (worldwide), it is extremely difficult to isolate the effects of wood pellets on the coal industry’s downward trajectory.

Some of the controversy surrounding this renewable energy pathway has been due to the large number of agents involved in the transatlantic wood pellet trade, many of whom have different definitions of the alternative (or reference) case of forest management in the absence of pellet trade (Parish et al. in press). During this case study, we extended the telecoupling framework by subdividing agents. We delineated between decision-making (primary) agents who operate in this connected system and those that facilitate, but are not essential to, the magnitude of the flow between the sending and receiving systems. We also found it useful to highlight those constraining agents that can inhibit or slow the telecoupled relationships in either the sending or receiving systems. This refined understanding of agents helps to identify stakeholders who influence the telecoupled relationships found within this complex system. Agents’ roles can cross system boundaries and be time- or case-specific, evolving as the systems reacts to feedbacks.

Previous studies of the transatlantic wood pellet trade have typically focused on LCA of GHG emissions, but using the telecoupling framework helped us to integrate information from across many disciplines to holistically address transatlantic wood pellet trade and reveal environmental, social, and economic benefits in both the sending and receiving systems. Further research is needed to quantify all of the interactions and effects identified through this analysis so that a model can be developed for evidence-based decision-making with regard to the sustainability of this bioenergy pathway. Continued monitoring of SE US forests will be essential for determining whether the potential environmental and socioeconomic effects (Table 6) of wood pellet trade are realized at some point in the future.

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CHAPTER II

REFERENCE SCENARIOS FOR EVALUATING WOOD PELLET PRODUCTION IN THE SOUTHEASTERN UNITED STATES

A version of this chapter was originally published by Esther Parish, Virginia Dale, Keith Kline and Bob Abt as:
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The article is presented in its original form, formatted for this dissertation including renumbering tables and figures. Author was lead author and lead investigator on study. Coauthors Virginia Dale and Keith Kline of the ORNL provided guidance, revisions, and photos that were instrumental in its publication. Coauthor Bob Abt of North Carolina State University contributed significantly to the discussion, provided references, and authored portions of the text.

Abstract

Wood pellet exports from the Southeastern United States (SE US) to Europe have been increasing in response to European Union member state policies to displace coal with renewable biomass for electricity generation. An understanding of the interactions among SE US forest markets, forest management, and forest ecosystem services is required to quantify the effects of pellet production compared to what would be expected under a reference case or “counterfactual scenario” without pellet production. Inconsistent methods to define and justify the counterfactual scenario result in conflicting estimates and large uncertainties about the impacts of pellet production on the SE US forests. Guidelines to support more consistent and transparent counterfactual scenarios are proposed. The guidelines include identifying major influences on current SE US forest conditions, developing potential futures that clearly document underlying assumptions and associated uncertainties, identifying the most likely alternative feedstock fates, and estimating the effects of no pellet demand on future forest conditions. The guidelines can help modelers to more accurately reflect the past and current forest dynamics and to consider the implications for SE US forest landscapes of future scenarios with and without pellet production.

Introduction

Exports of wood pellets from the Southeastern United States (SE US) to Europe have been growing rapidly over the past decade. Several European nations have been importing pellets as a renewable energy resource to burn in place of coal to reduce emissions of greenhouse gases (GHGs) and support climate change goals (European Parliament 2009, European Commission 2017). However, groups within Europe and the SE US are concerned that an expanding pellet industry may inadvertently impact the overall sustainability of SE US forest landscapes (NRDC 2015, Olesen et al. 2015, Cornwall 2017).

The extensive debate about the potential effects of transatlantic wood pellet trade on GHG emissions (Lamers and Junginger 2013, Dwivedi et al. 2014, Olesen et al. 2015, Cornwall 2017, Cowie et al. 2017) has generally omitted broader aspects of sustainability, meaning the capacity for pellet production to continue while maintaining options for future generations. In addition to GHG emissions, important social and environmental indicators that may be affected by the pellet industry include soil and water quality, biodiversity, and jobs (McBride et al. 2011, Dale et al. 2013). Assessing potential trade-offs and synergies involving aspects of bioenergy sustainability within the pellet trade system necessitates the creation of a conceptual model detailing a set of hypotheses about the way the system works given realistic assumptions and context (Dale and Van Winkle 1998).

This synthesis article is intended to inform future assessment and modelling of the sustainability of SE US wood pellet production and trade. This article presents an overview of the interactions among SE US forested landscapes and management for wood pellet production developed by researchers from the locale. We synthesize a literature review, on-the-ground observations, and discussions with a variety of stakeholders (Kline and Coleman 2010, Abt et al. 2014, Dale et al. 2016, Butler et al. 2017, Dale et al. 2017). An examination of recent peer-reviewed and grey literature reveals that a variety of definitions for terminology has been used to discuss the potential effects of the export wood pellet trade, and diverse interpretations of the words used to describe feedstock and system characteristics further confound an already complex issue. Therefore, this article carefully defines key terms (e.g., baseline, counterfactual, thinning) and discusses current, historical, and potential future SE US forest landscape conditions. Guidelines for developing reasonable reference scenarios for models related to SE US wood pellet production industry are then proposed.

Baseline Definitions

‘Baseline’ has been defined in several different ways owing to the various research questions asked about the use of woody biomass for energy. The term typically refers to historical trends or conditions documented at a specified time and place in the past, but ‘baseline’ has sometimes been used interchangeably with ‘reference case,’ ‘counterfactual,’ and ‘business as usual.’ In this paper, we focus on evaluating the SE US wood-pellet production system, and, for that analysis, we define ‘baseline conditions’ as those forest and market conditions existing prior to 2008, the year that SE US wood pellet exports began in response to European commitments to increase the share of renewables in total energy use (European Parliament 2009, Dale et al. 2017, USITC 2017).

While a “baseline” is fundamentally any datum against which change is measured (EPA 2011), different approaches build from the baseline to consider alternative conditions. For bioenergy systems, the US Environmental Protection Agency (EPA) identified three baseline approaches considering different points of view (EPA 2014). A Reference Point Baseline approach determines effects on the forested system by comparing two points in time. For example, this approach would quantify how much more or less carbon is stored in a system at the end of the assessment period compared to a starting point. An Anticipated Future Baseline approach assesses whether there is more or less carbon stored in the system if business-as-usual (BAU) conditions continue for a given length of time through the use of dynamic modelling to simulate the continuation of past trends or statistical analysis and extrapolation of historical trends into the future. The Comparative Baseline approach determines the extent to which net emissions to the atmosphere from the bioenergy system differ from net emissions that might have occurred if another energy resource had been used. The Comparative Baseline is developed from the viewpoint of energy options and their associated GHG emissions.

EPA’s Science Advisory Board rejected the Reference Point Baseline approach because it lacks a clear method to separate the marginal difference made by an actual wood bioenergy system relative to the overall forest system’s total carbon under a dynamic BAU scenario (EPA 2014). The Comparative Baseline Approach involves so many layers of assumptions about the alternative energy resource that would have been used in the absence of bioenergy that it becomes difficult to implement consistently. Therefore, EPA recommends the Anticipated Future Baseline approach be used for evaluating the effects of wood pellet production systems and we focus on this approach throughout the remainder of the paper.

BAU conditions can be extrapolated or simulated with and without the bioenergy system based on historical data and current conditions and by comparing two anticipated futures under the assumption that all other things remain equal. When assessing the effects of bioenergy systems, the EPA refers to the Anticipated Future Baseline without the use of biomass for energy as the “counterfactual” scenario (see next section). In other comparisons of bioenergy alternatives, these two hypothetical cases are typically described as the Bioenergy case and the Reference case.

Spatial and temporal scales are critical components of a sound baseline definition for sustainability analysis. Whereas forest operations are conducted at a stand level at a given point in time, the forest landscape that provides feedstock, or ‘fuelshed’ in the case of wood pellet production, is “the scale at which forest management across a mosaic of forest stands is coordinated to supply a continuous flow of forest products” (Cintas et al. 2016). It is therefore essential to analyze baseline and anticipated future conditions at the scale that considers at least an entire fuelshed It typically takes at least 10-15 years for forest landscapes to develop new characteristics resulting from management changes made in response to changing market conditions (Abt et al. 2014), and a wide variety of intra- and inter-annual conditions and disturbances impact SE forests over different temporal and spatial scales (Joyce et al. 2014, Greenberg and Collins 2015). Therefore, baseline conditions should be assessed over a time frame of at least 10 years—and preferably longer if data are available.

Counterfactual Descriptions

A ‘counterfactual’ (also sometimes called ‘reference case’ or ‘alternative scenario’) is a hypothetical scenario that tries to estimate what would have happened in the absence of what did happen, i.e., the factual. For wood pellet production in the SE US, the factual is represented by management activities and conditions that occur in the fuelsheds supplying wood pellets, and the counterfactual represents what would have happened in those fuelsheds if wood pellet production had not occurred. The conditions in the fuelsheds under the two scenarios can then be compared to assess the net effects (either positive or negative) attributable to wood pellet production. The term ‘counterfactual’ is common in life cycle analysis (LCA) literature (Bowyer et al. 2012) and is used in the EPA’s biogenic carbon accounting framework (EPA 2014) developed to address carbon dioxide emissions from stationary sources combusting biomass comprised of non-fossil materials.

Most counterfactuals for SE wood pellet production have been developed to examine the issue of GHG emissions. When wood pellets are used for energy, carbon that was sequestered with plant growth is released back to the atmosphere. One challenge for the counterfactual is to determine the fate of this same volume of carbon if the biomass had not been used for bioenergy. Typically, a similar amount of total carbon is expected to eventually be released through a variety of processes over time. Therefore, the timing of carbon removal from the atmosphere through photosynthesis and carbon release back to the atmosphere associated with biomass combustion or decay is a critical variable to consider. Forest management affects growth rates and carbon removals and also influences how forest systems are impacted by and respond to disturbance. In addition to the timing of emissions, rates of carbon sequestration, persistence of forest land cover, frequency and intensities of wildfire, decay rate or burning of logging residue, qualities of air and water, and changes in biodiversity are additional variables to consider when comparing the GHG emissions from two alternative scenarios (Dale et al. 2017, Hanssen et al. 2017). Because forest management assumptions and resulting estimates of net emissions can vary widely in counterfactual scenarios, groups such as the Institute for European Environmental Policy (IEEP) have called for a consistent approach to the consideration of counterfactuals for the bioenergy sector to facilitate future decision making (Bowyer et al. 2012).

Constructing counterfactuals is challenging, particularly given that analyses of the effects of bioenergy should consider economic and policy changes in addition to effects on GHG emissions and other environmental factors (EPA 2014). Considering a range of counterfactuals is useful to examine the sensitivity of results to the assumptions, and each selected counterfactual scenario should be justified. Justification begins with documentation of past and present conditions relevant to the SE US forest ecosystems and local wood product markets.

Analyzing and understanding the local context is a prerequisite to defining appropriate counterfactual scenarios. In the SE US it is important to recognize that the initiation of the export wood pellet industry followed widespread closures of pulp and paper mills (Brandeis and Guo 2016) and coincided with the 2008 crash of the US housing market. The housing market crash led to severe economic recession in SE US areas dependent on the forest products industry, as timber prices fell to half of their pre-recession values and over 100,000 jobs disappeared throughout the region (Hodges et al. 2011, Woodall et al. 2011). It is not surprising, therefore, to find that in the SE US, wood pellet mills are frequently built in the procurement area of a recently closed paper mill (Stewart 2015). By locating where paper mills have closed, pellet mills can take advantage of an existing trained workforce, logging and trucking infrastructure, and wood supplies that are otherwise stranded (left without market outlets), leading to lower feedstock prices.

It might seem that developing a counterfactual scenario for the relatively straightforward case of a pellet mill replacing a shuttered SE US pulp mill would be simple because the pellet mill could utilize the same type and quantities of woody feedstock as the paper mill. However, many distinct counterfactuals can be considered when calculating the effects of just one pellet mill. Consider the following examples of potential alternative scenarios that might be selected for comparison to pellet production and note how each scenario affects the overall carbon emissions outcome:

(1) Assume that the pulp mill had not closed and that the forest management and harvesting practices did not differ in any

substantial way from those currently used for pellet production. Using these assumptions, forest carbon stocks end up equivalent under each scenario, but because the wood pellets are used as a substitute for coal in European power production, there is an overall reduction in global GHG emissions under the pellet scenario.

(2) Assume that the pulp mill closed and the forest continued to be managed in anticipation of a new industry arriving to replace the pulp mill. Using these assumptions, forest carbon stocks would be higher than under the case involving biomass removal for pellet production. This loss of SE US forest carbon stocks offsets some of the GHG emissions reductions achieved by avoiding coal combustion in Europe, at least initially.

(3) Assume that the pulp mill closed and that the absence of a wood market removed the incentive to invest in forest management. This scenario could lead to eventual reductions in overall forest area via conversion to other, more lucrative land uses, and lower forest productivity relative to forest managed for pellet production. Forest carbon stocks are lower than under scenarios with management because unmanaged forests typically sequester carbon at slower rates and are more exposed to disturbances such as pest outbreaks and wildfires. Using this counterfactual scenario, it is difficult to determine if pellet production leads to a net difference in global GHG emissions or not.

(4) Assume that the pulp mill closed and was replaced by a new type of wood-product industry. This assumption necessitates an understanding of the timing, scale, and feedstock requirements of the alternative wood industry and a life cycle analysis (LCA) of its effects compared to those of pellet production. The projected net effects of a pellet mill would depend in large part on the characteristics of the new industry and the products that would be displaced by its output.

The net effects of the pellet mill under each of these four counterfactual scenarios will also depend on the length of time considered for the comparison. Trees show diminishing rates of carbon sequestration as they age. Thus, the timing of management interventions, harvests and other costs and benefits under each scenario is paramount. Based on historical land use and ownership in the SE US, it is not reasonable to assume that scenario (2) of managing forests while waiting for a new industry to arrive would be sustained indefinitely. Scenario (2) would eventually transition to scenarios (1), (3) or (4). In the real world, blends of assumed counterfactuals and other unforeseen scenarios could occur simultaneously.

These counterfactual examples illustrate that even an analysis that begins with a clear set of simple assumptions about a single pellet production facility replacing a pulp mill can lead to a wide range of projected impacts depending on the scenario(s) selected for comparison. Because it is impossible to predict the future with certainty, a set of probable counterfactuals should be considered to better understand the potential range of variation in outcomes related to net carbon sequestration and other factors of concern. Careful analysis of both current and historical social, economic, and environmental variables is required in order to define the probable future conditions of the forest and forest products. Thus, we now turn to a discussion of our understanding of current conditions in SE US forests before delving into the less certain past and the even more uncertain future.

Current Conditions

Because current conditions are the one case that can be verified, they should be clearly documented and considered when developing counterfactual scenarios. In the SE US, the availability of forest biomass material to produce wood pellets for export depends on a variety of interacting factors (Figure 6), including the physiographic context, forest conditions, and major uses associated with existing forested areas as well as the current economic conditions driving market potential for different wood products. Rapid growth and establishment of many tree species are facilitated by favorable climate and soil conditions found along the SE US coastline, which includes those US states extending east from Texas and north from Florida to Virginia.

Due to the prevalence of agriculture during previous centuries, forested areas are now scattered across the SE US region in a patchwork pattern that reflects a variety of ownership types and management practices. Productive commercial forests are often found on former agricultural fields and plantation lands. Only small tracts of old-growth forest remain (defined as forests with advanced tree age, minimal human disturbance, and mature successional stage), and these are protected from logging activities through regulations and conservation easements (Davis 1996). In addition to encroachment by expanding urban and suburban areas, SE US forests are subject to a variety of disturbances including pest outbreaks, droughts, fires, and extreme storm events such as hurricanes, tornadoes, and ice storms (Greenberg and Collins 2015). These disturbances can result in large volumes of downed woody material that are often

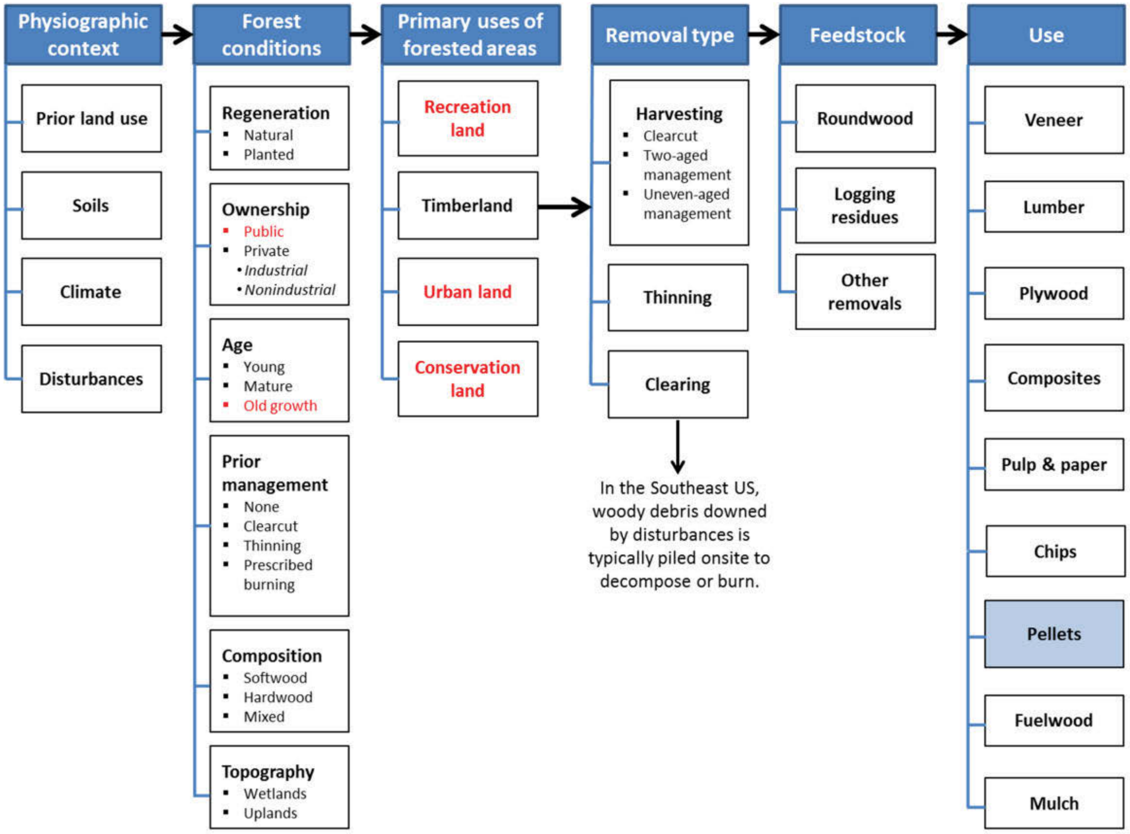


Figure 6. Factors determining availability of biomass material used for export wood pellet production in the Southeastern United States

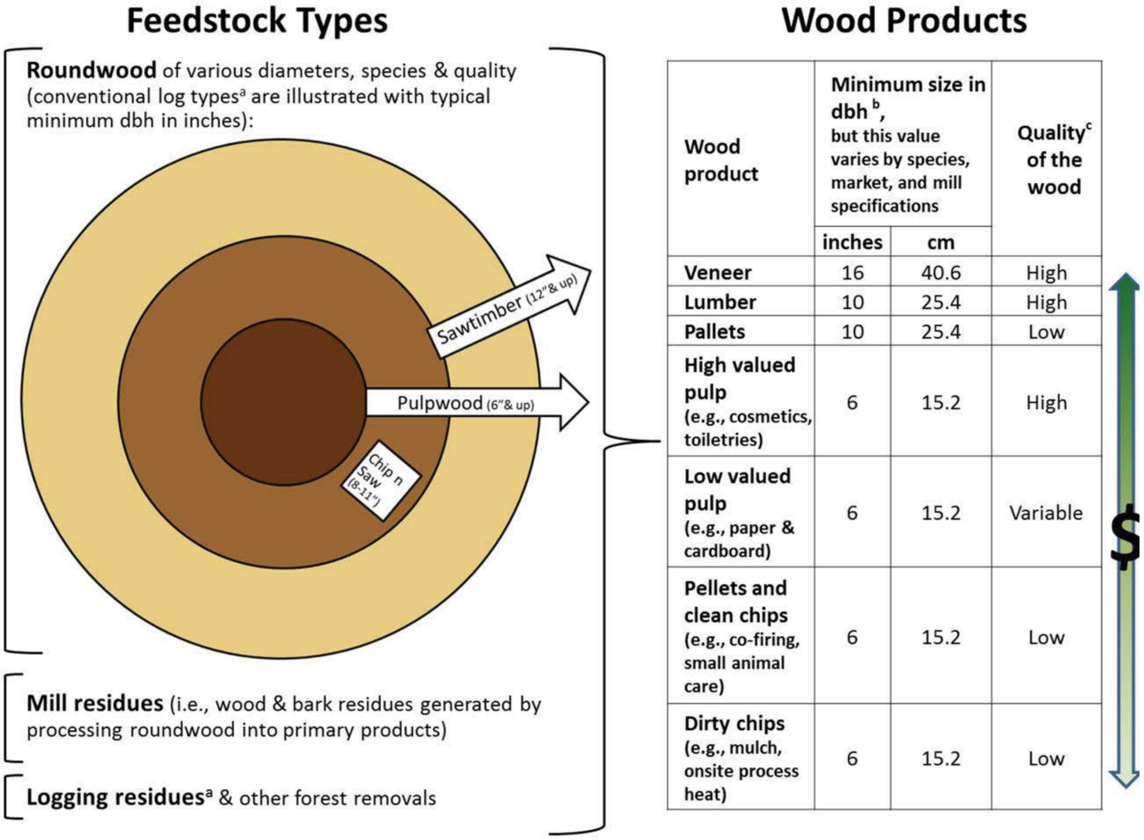
Sources of biomass not used in the manufacture of wood pellets for commercial-scale bioenergy production are shown in red font (e.g., old growth forests). The 'Use' portion of the figure shows common wood products in generally descending order of economic value. Note that mill residues generated during the production of one type of wood product are often used as inputs into other wood products further down the list.

left in place to decompose or sometimes burned in the absence of market demand. In addition, clearing of forest for development is the primary cause of forest loss in the SE US (Wear et al. 2013)—however, that wood is typically not used for pellet production.

The US South is known as the country's 'woodbasket' because of its extensive timber supply (USFS 2014). Long-term data collected by the US Department of Agriculture's Forest Service (USFS) indicate that SE US forested area and associated carbon stocks have increased since the 1920s as forests were planted or allowed to regrow on former agricultural fields (USFS 2014). However, there is considerable variation in forest composition, maturity, regeneration type, management, and topography across the region (Figure 6). Some portions of SE US forested land are reserved and unavailable as sources of pellet feedstock because of conservation agreements or because of their dedicated use as recreation land or urban green space (Figure 6). Timberland, defined by the USFS as "nonreserved forest land capable of producing at least 20 cubic feet of wood volume per acre per year" (O'Connell et al. 2014), is currently the only subset of SE US forested land available for biomass extraction for commercial pellet production. In 2012, timberland made up the biggest proportion of SE US forested land (i.e., 86% by area) and was largely privately owned (USFS 2014). An estimated 60% of SE US timberland is owned by small family forest owners (Oswalt et al. 2014, Stewart 2015).The conditions of SE US forested landscapes therefore depend largely on the accumulation of many stand-level decisions.

Managed SE US forests have harvest cycles of up to 50 years or more for higher-value roundwood (Figure 7). Larger diameter trees take more time to grow but offer higher financial returns, especially if landowners begin thinning the stands when trees are 10 to 15 years old Demers et al. 2016). Harvest decisions by family landowners are often based on the owner's life circumstances (e.g.., the need to raise money for a child's college tuition), market conditions (e.g., a sudden housing market boom), or both (Butler et al. 2017).

Confusion has been generated by terminology used for harvest, thinning, and whole trees. Any removal of standing timber for sale is considered a harvest. If the removal involves nearly an entire stand of trees at once, it is called a 'clearcut.' Since the late 1980s, clearcuts increasingly follow management plans that conserve standing dead trees, shelter belts along roadways and streams, and other 'retention trees' in small patches (Franklin 1989). Clearcuts are the most economically efficient harvest option for commercial forest production and allow land owners to generate another even-aged forest (Kline and Coleman 2010).



Wood product	Minimum size in dbh[b], but this value varies by species, market, and mill specifications		Quality[c] of the wood
	inches	cm	
Veneer	16	40.6	High
Lumber	10	25.4	High
Pallets	10	25.4	Low
High valued pulp (e.g., cosmetics, toiletries)	6	15.2	High
Low valued pulp (e.g., paper & cardboard)	6	15.2	Variable
Pellets and clean chips (e.g., co-firing, small animal care)	6	15.2	Low
Dirty chips (e.g., mulch, onsite process heat)	6	15.2	Low

Figure 7. US timberland removal types and wood products

Terms used for removal types (TPO 2017) are associated with traditional pulp and saw timber industries. One parameter, log diameter at breast height (DBH), is illustrated in the figure. Additional qualities and market opportunities determine if and where a harvested log can be sold.

[a] *Product specifications from Georgia Stump Prices, 1st Quarter 2016, Timber Mart-South*

[b] *South Carolina Forestry Commission. Understanding trees as a commodity. http://www.state.sc.us/forest/lecom.htm*

[c] *Zhang SY. 2003. Wood quality attributes and their impacts of wood utilization. XII World Forestry Congress. Quebec City, Canada. http://www.fao.org/docrep/ARTICLE/WFC/XII/0674-B1.HTM*

Current forest management plans are widely acknowledged as improvements over the antiquated practices that repeatedly removed only the most valuable trees and resulted in ‘high grading’ and degeneration of forest landscapes. Forest management plans may now call for selective thinning and removal of trees aimed at generating higher-value stands for future harvest. When a selective thinning is timed to generate logs that can be sold, it is often described as a ‘commercial thinning’ although additional biomass that has no commercial value is cleared at the same time. Indeed, to complicate matters, commercial thinning generates tree tops, limbs and other harvest residues that have not had commercial value in the past. Qualified commercial thinning logs are traditionally used to supply paper mills or specialized ‘chip n saw mills’ that are designed to take advantage of small diameter logs to extract some lumber and then chip the rest.

By contrast, ‘pre-commercial thinnings’ refer to clearing to reduce competition from underbrush and volunteer trees in plantations, correct stand density, and improve the vigor and quality of remaining trees without attempting to market the woody material being cleared. By definition, pre-commercial thinning involves biomass that lacks commercial value. Small farmers often use a “hack and squirt” approach to pre-commercial thinning, applying herbicide on the stumps of undesired trees. Biomass from pre-commercial thinning is typically left on site to rot or burn. Larger operations may pile biomass from pre-commercial thinning and either burn the piles or allow them to decompose in place. If located nearby, wood pellet mills now offer a potential market for biomass that previously lacked commercial value.

Traditional SE US labels for trees and logs—such as pulpwood and sawtimber—can also lead to confusion since logs may be used to make many different products depending on the species, size, quality, distance from mills, and current market conditions (Figures 7 and 8). Given the general goal to maximize profit, forest owners tend to favor the production of trees with higher value for products such as veneer and dimensional lumber (Figure 7). Trees used for pulp and paper, historically described as pulpwood, used to bring only a fraction of the price of the sawtimber used for higher value products. However, that price differential has diminished since the housing crash of 2008. Owners will seek the highest value, but if biomass cannot be sold to higher-value markets, it may be used to make lower-value products such as wooden stakes, chips, pellets, or mulch, if those types of processing facilities are available within a reasonable distance, typically within 120-km. And if the appropriate processing facilities exist, biomass from a single tree will be used for multiple products, such as the case of chip n saw mills. Mill residues, sawdust, bark, dirty chips and other biomass that does not meet required specifications for other products will often be used for onsite heat or power in processes that produce particle board,

TRADITIONAL TERMINOLOGY USED BY SE US FOREST INDUSTRIES

Saw timber, chip n saw, and pulpwood are terms commonly used to describe harvested logs in the SE US. The ‘roundwood’ feedstock types (Figure 7) are not based exclusively on size as the diameter at breast height (dbh) of pulpwood overlaps with that of chip n saw and sawtimber. ‘Logging residues’ are the residual portions of trees cut for roundwood products and other trees killed in the process of extracting roundwood products (USFS 2017). ‘Other removals’ include trees killed in timber stand improvement activities, like precommercial thinnings, weedings, etc. not directly associated with roundwood product harvests (USFS 2017).

The value of a log is based on the value of the products that can be made from it (Figure 7). Determining the best utilization for a given log is influenced by many factors including size (height and diameter), species, straightness, knottiness, and other qualities of the wood (Zhang 2003) as well as location and accessibility to mills or buyers, and specifications that are defined by each buyer. Regardless of dbh and common labels assigned to logs, sellers seek the best possible market price. Biomass for pellets commands a lower price than several other uses, but pellets may offer the best option for someone selling logs that do not meet quality requirements for other uses and for economically stranded trees.

Figure 8. Traditional terminology used by SE US forest industries

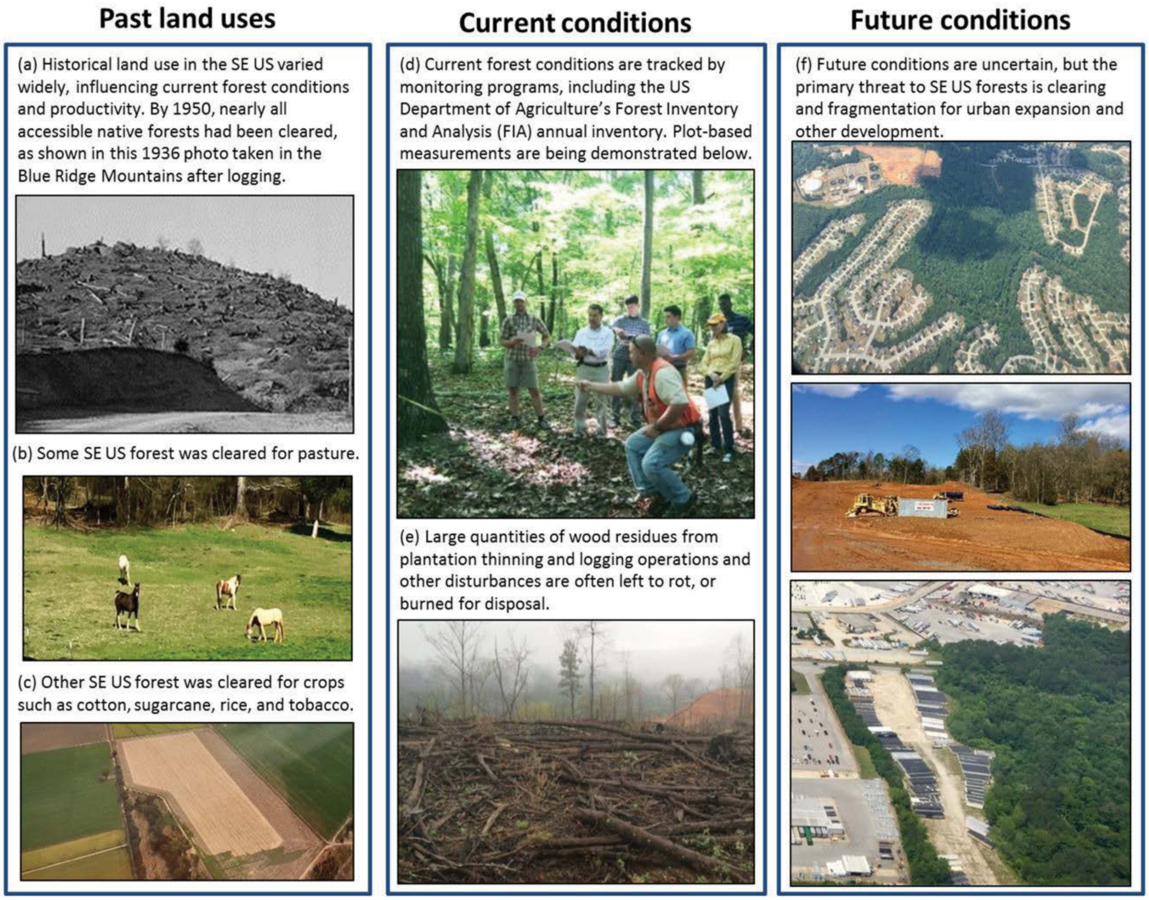
fibreboard, diapers, or pellets. Saw mills often sell excess residues to others, for myriad uses including animal bedding, fuelwood, mulch, and pellets.

Products such as wood pellets are generally found near the end of the SE US wood-products supply chain and have a small market share and low value relative to saw timber (Figure 7). Similar to the wood chip mills that expanded rapidly across the SE US during the 1990s, pellet mills are a new processing technology rather than an independent cause of timber harvest (Schaberg et al. 2005).Thus, pellet production does not currently drive the SE US forest product market nor the landscape-scale forest management decisions in the region (Dale et. 2017b). Pellet mills can and do, however, influence localized markets.

Two large pellet producers (Enviva and Drax) have purchased abandoned mills and nearby timberland to establish dedicated supply chains for European power plants. Although the long-term effects of these integrated supply chains on forested ecosystems remain to be verified, the companies are documenting their wood supply sources and have provided funds and other support for the conservation of nearby ecologically sensitive areas and for forest restoration (Drax 2017, Enviva 2017). Independent data from the US Department of Agriculture Forest Inventory and Analysis (FIA) are available to examine the effects on forests associated with these operations (O'Connell et al. 2014) and, so far, the FIA data for key indicators such as carbon stocks and forest stand conditions in the pellet supply fuelsheds show no significant deviations since pellet production began to ramp up in 2008 (Dale et al. 2017b). Current forest conditions are partially a function of prior land uses and disturbances, and the effects of current management can take years to be reflected in FIA data. Therefore, continued monitoring of the publicly available FIA data is recommended to identify any changes in forest conditions over time.

Past Conditions Influence Current Forest Landscapes

The heterogeneity of SE US forest landscapes in combination with their long history of disturbances offers distinct analytical challenges when it comes to estimating past carbon stocks and other conditions (Figure 9). While forest conditions are often assessed at a regional scale, circumstances do vary across a fuelshed depending on many factors including the land history of each parcel.
Today's forests are the products of centuries of human interventions. Pre-Colombian Native Americans managed the region through extensive use of fire to support agriculture (Mann 2005). Early European settlers established economic development in the region based on cotton plantations, pastures and products derived from pine sap or 'naval stores.' During that period, accessible native forests were degraded and cleared over time. For example, the Great


Past land uses

(a) Historical land use in the SE US varied widely, influencing current forest conditions and productivity. By 1950, nearly all accessible native forests had been cleared, as shown in this 1936 photo taken in the Blue Ridge Mountains after logging.

(b) Some SE US forest was cleared for pasture.

(c) Other SE US forest was cleared for crops such as cotton, sugarcane, rice, and tobacco.

Current conditions

(d) Current forest conditions are tracked by monitoring programs, including the US Department of Agriculture's Forest Inventory and Analysis (FIA) annual inventory. Plot-based measurements are being demonstrated below.

(e) Large quantities of wood residues from plantation thinning and logging operations and other disturbances are often left to rot, or burned for disposal.

Future conditions

(f) Future conditions are uncertain, but the primary threat to SE US forests is clearing and fragmentation for urban expansion and other development.

Figure 9. Past land uses and conditions of forest landscapes in the SE US are heterogeneous and offer distinct challenges to attempts to project future conditions.

Past land uses influence current productivity and vary with time and place. Current forest conditions within fuelsheds can be verified more easily than historical conditions. Future conditions are highly uncertain. Photo credits: Keith Kline and Virginia Dale except (a): US National Archives and Record Administration (NARA) Photo 280115.

Smoky Mountain National Park, the region's largest and most visited conservation unit, was established only after most of the mountains had been clear-cut or high-graded by timber companies.

Timberlands are unevenly scattered across the SE US region in patchwork patterns that reflect the bio-geophysical characteristics of the landscape as well as past ownership types, management practices, and disturbance. The composition and age classes of today's SE timberland reflect the timing of reestablishment of forests on lands previously cleared. US government subsidies drove surges in SE US pine plantation establishment on small holder farm fields, leading to "supply bubbles" that are important to a fuelshed's forest age-structure and influence the timing of potential thinnings and harvests (Abt et al. 2014). SE US forests have also been fragmented by powerline right-of-ways, highways, reservoirs, and persistent urban and suburban expansion, which may continue to occur in the future (Figure 9f).

Potential Future Conditions

From any defined starting point, a large number of different potential future pathways can be defined for land use and management influencing SE forested landscapes (Wear et al. 2013, Wang et al. 2015). It is challenging to make wood-pellet projections due to limited availability of empirical data related to the new pellet markets, forest product market volatility, a lack of long-term stable policies, and the potential for other countries to disrupt global markets (Dale et al. 2017, USITC 2017). Although it is impossible to verify the accuracy of future predictions, some assumptions previously made about the developing pellet industry and SE US forest management are not supported by current expert opinion and should be avoided (Stephenson and MacKay 2014, Ricardo Energy & Environment 2016). We think it is reasonable to assume that federal lands will continue to be excluded from biomass production, that saw timber and pulp will remain higher-value markets for harvested logs, and that historical disturbances and threats to SE forests will increase under changing climate conditions (Dale et al. 2001) and growing population pressures (Wear et al. 2013).

Land-use decisions must be considered in the context of the entire local economy, where forest product markets are linked and changes in rural land cover and management depend on urbanization pressures and agricultural markets as well as potential forest returns. Some studies have assumed that old-growth forests might be used for pellet production or be converted to pine plantations in response to pellet demand. However, old growth forests are extremely rare and mostly protected (Davis 1996). Recent analysis of FIA data for two SE US fuelsheds showed no change in the amount of land dedicated to either plantation forest or naturally regenerating forest during the period of expanding pellet production (Dale et al. 2017b), and past experience has shown that increased demand for a low-value forest product (Figure 2) is not likely to become a driver of SE US land-use change (Schaberg et al. 2005). Based on regional trends and market analyses, land-use change affecting the forests is more likely to involve fragmentation and conversion to non-forest uses and development as SE US populations continue to grow (Wear et al. 2013).

Rather than assuming pellet production leads to forest clearing, a more reasonable approach is to consider alternative future scenarios based on historical evidence and probable feedstock fates (i.e., end uses). Competing uses for available forest biomass then becomes a key topic of analysis (Hanssen et al. 2017). This type of future scenario considers wood pellets within the larger wood products market and recognizes that the decline in demand for one product (e.g., paper) may be offset by demand for other products. Pellet mills are typically omnivorous—meaning that they can convert biomass derived from either hardwoods or softwoods (Stewart 2015). Thus, studies that focus only on one region, species, or forest type ignore the interactions of the bioeconomy described above. Assumptions related to rotation length and planting frequency can affect size class distribution and have longstanding consequences on carbon storage and forest health. Timber price and supply inelasticity both influence the amount of biomass available for wood pellet production, and it is important to recognize that local demand and supply conditions vary across the SE US. Transparently documenting counterfactual assumptions is essential for proper interpretation of bioenergy assessments given that assessment outcomes are determined by the choices associated with many different variables and assumptions (Kopenen et al. 2017).

Assuming that SE US pellet exports will continue to grow modestly over the next decade seems reasonable given existing infrastructure investments and multi-year supply contracts as well as the EU's 2030 goals for renewable energy use (European Commission 2017). If the pellet market continues to grow, there may be opportunities to source adequate biomass from existing timberland management and other sources without adversely impacting other markets (Figure 10). Removal of dead wood and thinning is an effective means to manage all lands to proactively reduce the risk of destructive wildfires, insect outbreaks, or storm damage (Coppoletta et al. 2016). Biomass residues may also be collected while managing recreation and conservation lands impacted by invasive species, disturbances, or required treatments for biodiversity protection (e.g., hardwood understory removal for red cockaded woodpecker habitat). Eventually, biomass for wood pellets could be also procured from urban and developed land through power line right-of-way maintenance, tree removal during construction, and trees downed by storms. All such wood could be used for pellets if a production facility or chipper was located nearby (Kline and Coleman

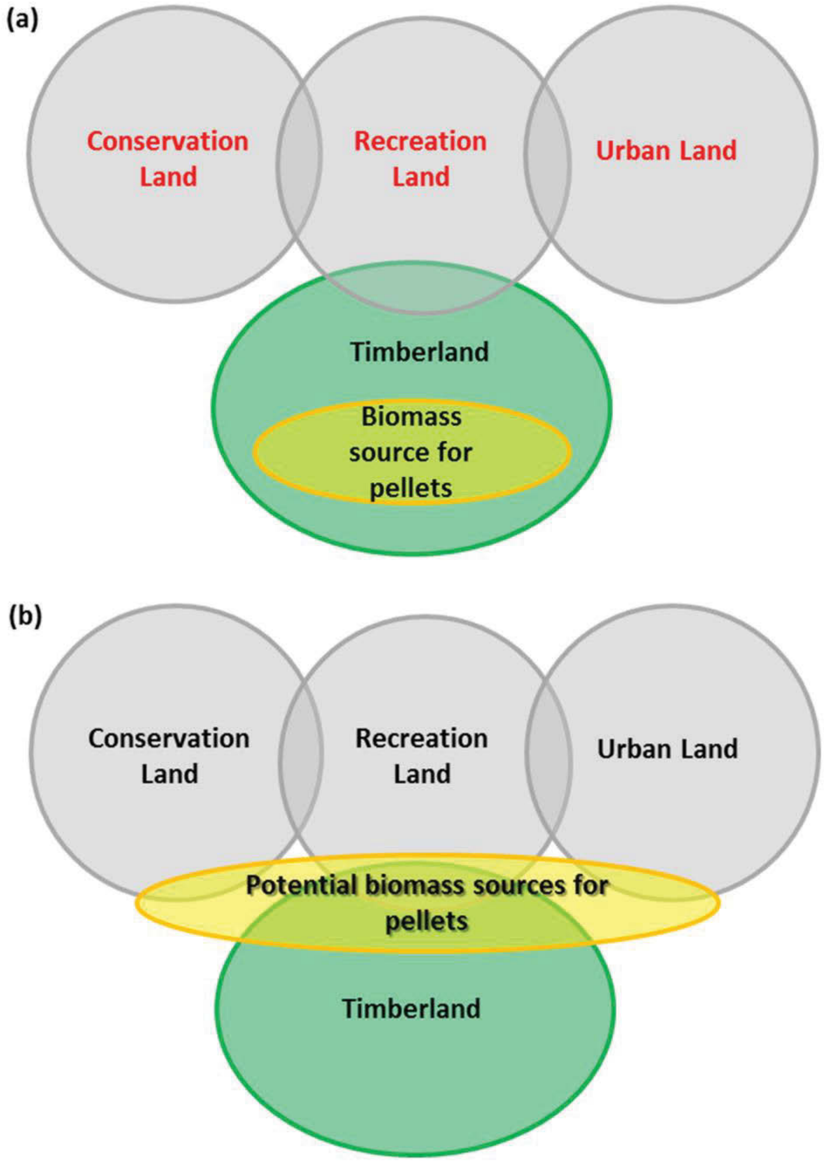


Figure 10. Forests are found across many lands-use types in the SE US

The top three circles represent land uses that currently do NOT supply wood for pellets. The yellow ovals illustrate that (a) at present, biomass for wood pellet exports is obtained only from commercially harvested timberland. However, significant potential supplies for pellet production could be sourced from other areas (b) in the future due to wood wastes requiring disposal after disturbances (storms, insect outbreaks), reduction of fuel loads to reduce risk of devastating wildfire, clearing for urban development, construction debris, removal of invasive species and underbrush to maintain habitat for species of concern, and other human activities. Thus, the biomass resources available for pellets may expand over time beyond timberland operations.

2010). Wood pellet mills may therefore offer an additional disposal option for wood that does not meet size or quality standards for other markets. Although some of these potential biomass sources might not meet sustainability requirements for EU member states, they could potentially be used for pellet production within the US.

Uncertainty is inherent in future projections about wood pellet markets and exports. Uncertainty regarding changing policies and requirements for the use of wood pellets as renewable energy, and the fact that requirements vary by receiving country, may undermine the confidence of future investors and land managers. European nations that import pellets may continue to revise the “sustainability requirements” for acceptable woody biomass, which currently focus on calculated GHG emissions, carbon stocks, and biodiversity. NGOs are particularly concerned about potential direct and indirect impacts on threatened and endangered species (NRDC 2015, Cornwall 2017). However, several studies find little evidence for biodiversity effects occurring due to pellet production (Fritts et al. 2015, Grodsky et al. 2016). In the interactive forest economy of the SE US, it will be important to continue monitoring for effects that can be attributable to pellet production in terms of biodiversity, forest management, land-use change, and carbon outcomes. Both local and global economic trends will continue to influence future market demand for wood pellets. Therefore, it is important to document assumptions regarding the strength of the US dollar relative to the currencies in nations that import pellets and in those that produce forest products, as the latter are likely to compete for export share and limit the ability to significantly increase prices for SE US pellet exports.

Recommendations

Models of potential effects of wood pellet exports on SE US forests should be developed using assumptions that are based on an analysis of historical trends and documentation of current conditions. Both the ecological context and the economic context must be considered in the development of future scenarios since intervention or lack of intervention in forest landscapes can lead to effects on biodiversity and ecosystem services. The effects of using biomass for pellet production are highly variable, context-specific, and differ across the landscape and over time (Tarr et al. 2016, Costanza et al. 2017).

The following guidelines are recommended to achieve reasonable, consistent and complete counterfactual scenarios when analyzing the effects of wood pellet production in the SE US.

Guideline A. Specify the context, including (1) the geospatial area of analysis, which should incorporate the entire fuelshed area supplying one or more pellet-producing mills, (2) the temporal scale of analysis, which should be a 10-year or longer period, (3) the energy efficiency of the produced wood pellets relative to the fossil fuels they displace, (4) historical and current conditions such as forest age and structure classes, carbon stocks, and sequestration rates in the fuelshed, (5) current and projected supplies of woody wastes and residues including amounts that have been left to decay or burn in the past, (6) current and projected thinning operations, (7) past management activities affecting diversity of organisms in the forest, and (8) prevailing disturbance regimes and their implications for carbon sequestration rates, biodiversity, and other variables of concern.

Guideline B. Consider the potential implications of pellet production in the fuelshed that are associated with (1) relationships to protected areas, reserves, conservation easements and additional areas of high conservation value such as those identified by the Land Conservation Cooperation Network for the SE US (https://lccnetwork.org/), (2) forest management practices (or lack thereof) on neighboring forests and high conservation-value lands, and (3) threats to forests, including land ownership, ownership trends, and how scenario assumptions interact with decisions to retain land in forest versus urbanization and other development pressures.

Guideline C. In making future projections, (1) document underlying assumptions for forests and economic activities; this could involve assuming that all other things remain unchanged from current conditions or, preferably, use a published set of assumptions such as the “A1B mid-range” growth scenario of the Intergovernmental Panel on Climate Change (Nakicenovic and Swart 2000) as developed for the SE US by the Forest Futures Project (Wear and Greis 2013); (2) verify reasonableness of assumptions regarding future forest management, markets, and disturbance regimes using multi-disciplinary experts practitioners with experience working in the landscape; (3) apply sensitivity and uncertainty analysis to counterfactual assumptions; (4) allow alternative future scenarios to refer to different feedstock fates; and (5) use a justified rate of growth in future pellet demand as well as a scenario with no growth (or no pellet demand). If land-cover changes are expected to be significant, additional climate effects that may be relevant include surface albedo, cloud cover, and nitrous oxide and methane emissions associated with altered forest cover and management practices across the landscape.

Collectively, the components included in these guidelines will help modelers to more accurately reflect current conditions, to generate historically-grounded counterfactual scenarios and to document the assumptions underlying future projections about the SE US forest landscapes and the effects of wood pellet production on forest ecosystems.

Conclusion

Since it takes ten or more years to observe impacts of management changes in many forest systems, it will likely be several more years before researchers have enough empirical data to definitively assess the effects of the new export wood pellet industry on forested landscapes of the SE US. Considering the SE US as a region, pellet production is likely play a small role on the margins involving lower valued wood products. Future data may indicate that pellets are an important economic driver within some local fuelsheds. While there are many uncertainties related to future pellet production, what is known for certain is that the lack of a market for wood products in the SE US can lead to unhealthy, unmanaged forests or forest conversion to other uses (Wear and Coulston 2015). Therefore, continued wood pellet demand may contribute marginally to maintaining forest landscapes and certainly provides options for the use of SE US woody biomass that could otherwise decay or burn lacking a commercially viable local market. Continued monitoring and analysis should provide insights to guide future forest management practices and pellet production toward increasing ecological, social, and economic benefits for SE forested landscapes (Dale et al. 2017).

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CHAPTER III

DATASET OF TIMBERLAND VARIABLES USED TO ASSESS FOREST CONDITIONS IN TWO SOUTHEASTERN UNITED STATES′ FUELSHEDS

A version of this chapter was originally published by Esther Parish, Virginia Dale, Emma Tobin and Keith Kline as:
E. S. Parish, V. H. Dale, E. Tobin, K. L. Kline, “Dataset of timberland variables used to assess forest conditions in two Southeastern United States′ fuelsheds”, *Data in Brief* 13:278-290 (2017).

The article is presented in its original form, formatted for this dissertation including renumbering tables and figures. Author was lead author and lead investigator for generating this dataset of timberland variables. Coauthors Virginia Dale and Keith Kline of the ORNL Center for BioEnergy Sustainability provided guidance and revisions that were instrumental in its publication. Coauthor Emma Tobin contributed to earlier versions of this analysis as a 2015 undergraduate SouthEast Energy Development (SEED) Fellow funded through the Southeastern Partnership for Integrated Biomass Supply Systems.

Abstract

The data presented in this article are related to the research article entitled “How is wood-based pellet production affecting forest conditions in the southeastern United States?” (Dale et al., 2017). This article describes how United States Forest Service Forest Inventory and Analysis data from multiple state inventories were aggregated and used to extract ten annual timberland variables for trend analysis in two case study bioenergy fuelshed areas. This dataset is made publically available to enable critical or extended analyses of changes in forest conditions, either for the fuelshed areas supplying the ports of Savannah, Georgia and Chesapeake, Virginia, or for other southeastern US forested areas contributing biomass to the export wood pellet industry.

Value of the Data

- The dataset presents ten landscape-scale characteristics of timberland health that can be used by other researchers for multiple purposes.

- The methods used to aggregate USDA Forest Service (USFS) Forest Inventory and Analysis (FIA) data across US state lines for fuelshed-scale change detection can be used to extend the statistical analyses to other locations (e.g., other southeastern US fuelsheds).

- These data and methods will allow other researchers to extend the statistical analyses into the future as more annual FIA data become available.

The Data

Annual timberland characteristics and associated uncertainty values derived from USDA Forest Service (USFS) Forest Inventory and Analysis (FIA) annual inventory data (O'Connell et al. 2014) for years 2002–2014 are provided for two forested areas supplying bioenergy wood pellets shipped out of the ports of Savannah, Georgia, and Chesapeake, Virginia, in the southeastern United States (Table 7). The annual estimates provided for each fuelshed include timberland volume of naturally regenerating stands ('natural stands') and plantations (Tables 8 & 9), timberland area by stand-size class (Tables 10 & 11), number of standing dead trees per hectare of timberland for natural stands and plantations (Tables 12 & 13), and millions of metric tons of carbon calculated for three carbon pools (Tables 14 & 15). A summary of all ten annual timberland variables (Table 16) and outlier values is provided for the Chesapeake Fuelshed (Table 17) and the Savannah fuelshed (Table 18).

Experimental Design, Materials and Methods

Fuelshed delineation

Two southeast US (SE US) case study fuelsheds were defined and used to extract and aggregate the annual FIA data (Tables 8-15). First, the locations of existing export wood pellet mills in the vicinity of the ports of Savannah, Georgia, and Chesapeake, Virginia, were identified by way of data purchased from Forisk Consulting (Table 19). These ten pellet mill locations were then used to identify counties located within a radius of 120 km (75 miles), the industry standard biomass sourcing distance (Stewart 2015). Finally, the selected counties were used to define two SE US biomass supply areas (Figure 11) known as the Chesapeake fuelshed (Figure 12) and the Savannah fuelshed (Figure 13).

FIA data queries

Freely available USFS FIA annual inventory data (O'Connell et al. 2014) were queried for the two SE US case study fuelshed areas (Figures 11-13) using the online USFS EVALIDator tool, Version 1.6.0.03 (Miles 2016). A list of specific state inventory data evaluation identification numbers (EVALIDs) and years used to generate the annual estimates (Tables 8-15) is shown in Tables 20 & 21 and discussed in subsequent sections. When multiple EVALIDs were available for the same year, the estimates with the lowest sampling error percent values were selected.

Table 7. Timberland dataset specifications

Specification	**Dataset details**
Subject area	Forestry, Ecology, Renewable energy
More specific subject area	Effect of bioenergy wood pellet production on forest conditions
Type of data	Tables, Figures
How data were acquired	USDA Forest Service (USFS) Forest Inventory and Analysis (FIA) annual inventory data and associated uncertainty values were obtained using the online USFS EVALIDator tool in conjunction with custom queries.
Data format	Raw, Analyzed
Experimental factors	Two Southeastern US case study fuelshed areas were defined and used to test for changes in ten timberland variables derived from annual FIA estimates (2002-2014) extracted and aggregated across multiple state inventories.
Experimental features	A hypothesis of no change was used to evaluate trends in timberland characteristics for each fuelshed pre- and post-2009 pellet production
Data source location	Southeastern United States. Two fuelshed regions centered on ports in Savannah, Georgia, 32°1′N; 81°7′W and Norfolk, Virginia, 36°55′N; 76°12′W
Data accessibility	The data are available with this chapter

Table 8. Net volume of live trees, Chesapeake fuelshed

Annual estimates (2002-2014) of the net volume of live trees at least 5 inches in diameter at breast height on timberland. The sampling error percent (S.E. %) is shown at the 95% confidence level. The estimates for years 2004 and 2008 are not provided due to missing Virginia inventory.

	Natural Stands			Plantations		
Year	millions of cubic meters	S.E. %	# of plots	millions of cubic meters	S.E. %	# of plots
2002	121.95	11.8	421	22.12	24.9	113
2003	113.17	12.4	378	29.09	23.4	108
2004						
2005	144.01	10.8	464	32.06	21.9	123
2006	125.80	11.5	412	28.36	23.1	119
2007	135.26	11.2	449	21.95	26.3	110
2008						
2009	121.89	11.7	388	27.46	22.8	124
2010	119.97	12.0	388	31.11	23.2	116
2011	126.57	11.6	406	29.93	22.4	135
2012	117.45	12.0	380	35.20	22.6	128
2013	140.67	11.5	401	35.03	23.8	129
2014	135.15	11.9	385	39.09	20.8	134

Table 9. Net volume of live trees, Savannah fuelshed

Annual estimates (2002-2014) of the net volume of live trees at least 5 inches in diameter at breast height on timberland. The sampling error percent (S.E. %) is shown at the 95% confidence level.

	Natural Stands			**Plantations**		
Year	**millions of cubic meters**	**S.E. %**	**# of plots**	**millions of cubic meters**	**S.E. %**	**# of plots**
2002	85.09	13.6	359	36.58	18.6	184
2003	91.98	13.6	374	33.30	19.1	190
2004	99.60	13.0	376	42.12	18.0	212
2005	104.66	12.7	424	47.47	16.4	247
2006	124.01	12.2	487	47.95	16.7	238
2007	112.59	12.1	458	46.58	15.8	257
2008	106.81	13.0	403	42.10	17.1	225
2009	124.53	11.7	464	51.58	15.6	260
2010	115.77	12.0	460	55.20	15.7	274
2011	125.57	12.4	472	53.21	15.8	252
2012	129.71	10.8	520	52.64	15.1	262
2013	132.79	11.7	484	54.53	14.8	277
2014	135.88	11.1	507	53.58	15.3	251

Table 10. Timberland area, Chesapeake fuelshed

Annual estimates (2002-2014) of timberland area by stand-size class. The sampling error percent (S.E. %) is shown at the 95% confidence level. The estimates for years 2004 and 2008 are not provided due to missing Virginia inventory.

	Small Diameter			Medium Diameter		
Year	thousands of hectares	S.E. %	# of plots	thousands of hectares	S.E. %	# of plots
2002	331.48	15.5	176	258.86	17.3	144
2003	244.21	18.0	139	239.40	17.7	138
2004						
2005	124.79	25.0	73	194.90	19.9	108
2006	129.39	24.3	76	178.75	20.5	101
2007	221.08	18.6	133	219.07	18.6	128
2008						
2009	221.72	18.5	135	259.05	17.1	153
2010	235.51	18.1	133	209.04	18.8	130
2011	213.59	19.0	126	256.77	17.3	146
2012	153.91	21.7	99	249.57	17.6	143
2013	163.70	21.4	99	253.23	17.5	146
2014	153.76	21.9	102	248.17	17.2	151

Table 10 (continued)

	Large Diameter		
Year	thousands of hectares	S.E. %	# of plots
2002	554.85	11.6	307
2003	555.71	11.7	293
2004			
2005	528.78	11.7	272
2006	426.77	13.3	218
2007	544.58	11.7	297
2008			
2009	558.56	11.4	305
2010	603.06	11.1	318
2011	601.64	11.0	339
2012	578.98	11.3	311
2013	617.49	10.9	326
2014	622.16	10.7	338

Table 11. Timberland area, Savannah fuelshed

Annual estimates (2002-2014) of timberland area by stand-size class. The sampling error percent (S.E. %) is shown at the 95% confidence level.

	Small Diameter			Medium Diameter		
Year	**thousands of hectares**	**S.E. %**	**# of plots**	**thousands of hectares**	**S.E. %**	**# of plots**
2002	194.16	20.3	108	196.03	19.9	107
2003	364.49	14.8	194	326.44	15.4	182
2004	333.73	15.1	193	372.98	14.5	206
2005	379.63	14.2	216	421.20	13.3	245
2006	427.22	13.4	243	498.42	12.5	275
2007	446.22	13.3	247	470.11	12.9	250
2008	317.20	15.7	176	406.70	13.8	225
2009	399.83	13.9	226	414.73	13.6	234
2010	387.65	14.0	217	401.98	13.7	238
2011	397.02	13.9	226	443.08	13.2	250
2012	349.67	14.8	202	492.33	12.4	289
2013	352.87	14.6	202	388.06	13.9	236
2014	372.30	14.3	221	400.62	13.7	243

Table 11 (continued)

	Large Diameter		
Year	**thousands of hectares**	**S.E. %**	**# of plots**
2002	292.74	16.4	151
2003	476.60	12.7	263
2004	528.23	12.1	275
2005	560.81	11.7	294
2006	593.69	11.3	318
2007	613.13	11.2	325
2008	585.43	11.3	317
2009	703.90	10.4	375
2010	692.12	10.3	390
2011	642.43	10.9	342
2012	718.35	10.1	399
2013	732.60	10.0	416
2014	720.91	10.0	419

Table 12. Standing-dead tree density, Chesapeake fuelshed

Annual estimates (2002-2014) of standing-dead tree density for timberland in the Chesapeake fuelshed The sampling error percent (S.E. %) is shown at the 95% confidence level. The estimates for years 2004 and 2008 are not provided due to missing Virginia inventory.

	Natural Stands			**Plantations**		
Year	**standing dead trees (# per ha)**	**S.E. %**	**# of plots**	**standing dead trees (# per ha)**	**S.E. %**	**# of plots**
2002	24.35	13.9	231	9.71	46.6	29
2003	22.43	15.8	215	13.24	36.6	40
2004						
2005	24.33	11.9	288	19.49	34.2	55
2006	25.57	15.2	156	12.10	34.9	29
2007	25.35	15.2	214	13.92	41.1	35
2008						
2009	25.23	14.9	221	5.17	51.5	21
2010	24.00	12.3	233	9.36	35.2	38
2011	24.25	12.5	232	7.74	42.6	33
2012	25.41	14.5	203	10.28	37.7	39
2013	23.17	13.8	218	11.28	39.1	42
2014	25.08	14.5	230	11.33	38.5	40

Table 13. Standing-dead tree density, Savannah fuelshed

Annual estimates (2002-2014) of standing-dead tree density for timberland in the Savannah fuelshed. The sampling error percent (S.E. %) is shown at the 95% confidence level.

	Natural Stands			Plantations		
Year	**standing dead trees (# per ha)**	**S.E. %**	**# of plots**	**standing dead trees (# per ha)**	**S. E. %**	**# of plots**
2002	13.32	20.0	136	10.06	32.7	56
2003	12.22	17.1	143	7.98	31.4	56
2004	15.44	16.0	163	10.66	28.3	67
2005	13.62	15.1	181	11.36	28.5	74
2006	14.30	14.9	181	11.48	23.6	81
2007	12.67	15.8	175	9.64	24.4	89
2008	18.15	19.7	176	9.13	28.8	61
2009	16.10	18.6	206	8.58	29.6	66
2010	15.27	15.4	203	7.76	27.5	66
2011	16.96	18.1	199	8.58	24.9	84
2012	16.88	15.4	240	7.66	32.0	73
2013	18.63	22.3	219	7.36	25.5	75
2014	19.75	15.5	255	8.27	27.4	72

Table 14. Carbon storage, Chesapeake fuelshed

Annual estimates (2002-2014) of timberland carbon storage. The sampling error percent (S.E. %) is shown at the 95% confidence level. Years 2004 and 2008 are not provided due to missing Virginia inventory.

	Organic Soil & Leaf Litter			Harvestable Material		
Year	stored carbon (millions of metric tons)	S.E. %	# of plots	stored carbon (millions of metric tons)	S.E. %	# of plots
2002	89.00	8.8	554	70.95	10.1	526
2003	81.12	9.1	511	70.95	10.4	483
2004						
2005	57.32	9.8	405	66.35	10.7	397
2006	49.60	10.7	349	51.94	11.8	341
2007	72.86	9.5	483	68.23	10.4	470
2008						
2009	78.80	9.1	508	72.90	9.9	496
2010	79.07	9.1	508	74.81	10.0	495
2011	80.31	8.9	521	78.09	9.9	510
2012	76.30	9.3	486	71.64	10.3	477
2013	78.48	9.1	506	83.60	10.0	491
2014	77.56	9.1	509	82.54	9.9	498

Table 14 (continued)

	Non-Harvestable Material		
Year	stored carbon (millions of metric tons)	S.E. %	# of plots
2002	13.70	8.7	541
2003	12.79	9.2	499
2004			
2005	10.89	9.7	400
2006	9.13	10.6	343
2007	11.99	9.3	475
2008			
2009	13.04	9.0	500
2010	13.01	9.0	499
2011	13.54	8.9	514
2012	12.47	9.2	480
2013	13.65	8.9	500
2014	13.45	9.0	503

Table 15. Carbon storage, Savannah fuelshed

Annual estimates (2002-2014) of timberland carbon storage. The sampling error percent (S.E. %) is shown at the 95% confidence level.

	Organic Soil & Leaf Litter			Harvestable Material		
Year	stored carbon (millions of metric tons)	S.E. %	# of plots	stored carbon (millions of metric tons)	S.E. %	# of plots
2002	120.04	8.6	563	32.88	14.4	304
2003	122.70	8.8	556	59.46	10.6	523
2004	128.53	8.5	572	69.16	9.9	548
2005	142.05	7.9	641	74.39	9.4	625
2006	159.79	7.6	711	83.89	9.2	690
2007	155.09	7.6	712	78.67	9.1	684
2008	135.97	8.2	608	71.91	9.8	591
2009	156.76	7.6	700	85.36	8.9	681
2010	156.00	7.6	714	83.02	9.0	687
2011	155.17	7.6	718	85.32	9.2	690
2012	160.82	7.4	757	88.24	8.4	727
2013	155.81	7.5	728	89.19	8.8	699
2014	154.31	7.5	736	90.51	8.7	704

Table 15 (continued)

	Non-Harvestable Material		
Year	stored carbon (millions of metric tons)	S.E. %	# of plots
2002	13.58	8.8	549
2003	13.12	9.0	544
2004	13.92	8.7	560
2005	15.18	8.2	627
2006	17.07	7.8	696
2007	16.96	7.7	695
2008	14.50	8.4	595
2009	16.94	7.8	686
2010	16.34	7.8	701
2011	16.59	7.9	702
2012	17.23	7.5	742
2013	16.66	7.8	713
2014	16.90	7.7	723

Table 16. Ten timberland variables

Variable Name	**Variable Description**
Vol Nat	Volume of Natural stands (millions of cubic meters)
Vol Plan	Volume of Plantations (millions of cubic meters)
Area LD	Area of Large Diameter stands (thousands of hectares)
Area MD	Area of Medium Diameter stands (thousands of hectares)
Area SD	Area of Small Diameter stands (thousands of hectares)
StDead Nat	Standing Dead trees in Natural stands (number per hectare)
StDead Plan	Standing Dead trees in Plantations (number per hectare)
Carbon SLL	Carbon stored in Soil & Leaf Litter (millions of metric tons)
Carbon HM	Carbon stored in Harvestable (live) woody Material (millions of metric tons)
Carbon NHM	Carbon stored in NonHarvestable (dead) woody Material (millions of metric tons)

Table 17. Timberland variables and outlier values calculated for the Chesapeake fuelshed

Variable names are listed in Table 16, St Dev = standard deviation, OT A = outlier threshold using method A (i.e., 2 standard deviations below the mean), OT B = outlier threshold using method B (i.e., 1.5 times the interquartile range). Highlighted values are outliers.

Year	Vol Nat	Vol Plan	Area LD	Area MD	Area SD	StDead Nat	StDead Plan
2002	121.95	22.12	554.85	258.86	331.48	24.35	9.71
2003	113.17	29.09	555.71	239.40	244.21	22.43	13.24
2005	144.01	32.06	528.78	194.90	124.79	24.33	19.49
2006	125.80	28.36	426.77	178.75	129.39	25.57	12.10
2007	135.26	21.95	544.58	219.07	221.08	25.35	13.92
2009	121.89	27.46	558.56	259.05	221.72	25.23	5.17
2010	119.97	31.11	603.06	209.04	235.51	24.00	9.36
2011	126.57	29.93	601.64	256.77	213.59	24.25	7.74
2012	117.45	35.20	578.98	249.57	153.91	25.41	10.28
2013	140.67	35.03	617.49	253.23	163.70	23.17	11.28
2014	135.15	39.09	622.16	248.17	153.76	25.08	11.33
Mean	127.44	30.13	562.96	233.35	199.38	24.47	11.24
St Dev	9.97	5.26	54.80	28.34	61.50	1.00	3.69
OT A	107.51	19.60	453.36	176.68	76.38	22.47	3.87
OT B	97.04	16.10	456.87	137.45	31.14	21.99	3.55

Table 17 (continued)

Year	Carbon SLL	Carbon HM	Carbon NHM
2002	89.00	70.95	13.70
2003	81.12	70.95	12.79
2005	57.32	66.35	10.89
2006	49.60	51.94	9.13
2007	72.86	68.23	11.99
2009	78.80	72.90	13.04
2010	79.07	74.81	13.01
2011	80.31	78.09	13.54
2012	76.30	71.64	12.47
2013	78.48	83.60	13.65
2014	77.56	82.54	13.45
Mean	74.58	72.00	12.51
St Dev	11.29	8.62	1.40
OT A	52.01	54.77	9.71
OT B	61.69	53.43	9.66

Table 18. Timberland variables and outlier values calculated for the Savannah fuelshed

Variable names are listed in Table 16, St Dev = standard deviation, OT A = outlier threshold using method A (i.e., 2 standard deviations below the mean), OT B = outlier threshold using method B (i.e., 1.5 times the interquartile range). Highlighted values are outliers.

Year	Vol Nat	Vol Plan	Acres LD	Acres MD	Acres SD
2002	85.09	36.58	292.74	196.03	194.16
2003	91.98	33.30	476.60	326.44	364.49
2004	99.60	42.12	528.23	372.98	333.73
2005	104.66	47.47	560.81	421.20	379.63
2006	124.01	47.95	593.69	498.42	427.22
2007	112.59	46.58	613.13	470.11	446.22
2008	106.81	42.10	585.43	406.70	317.20
2009	124.53	51.58	703.90	414.73	399.83
2010	115.77	55.20	692.12	401.98	387.65
2011	125.57	53.21	642.43	443.08	397.02
2012	129.71	52.64	718.35	492.33	349.67
2013	132.79	54.53	732.60	388.06	352.87
2014	135.88	53.58	720.91	400.62	372.30
Mean	114.54	47.45	604.69	402.51	363.23
St Dev	16.05	7.08	123.75	78.26	62.10
OT 1	82.43	33.29	357.20	245.98	239.03
OT 2	63.87	25.18	294.61	266.41	256.61

Table 18 (continued)

Year	StDead Nat	StDead Plan	Carbon SLL	Carbon HM	Carbon NHM
2002	13.32	10.06	120.04	32.88	13.58
2003	12.22	7.98	122.70	59.46	13.12
2004	15.44	10.66	128.53	69.16	13.92
2005	13.62	11.36	142.05	74.39	15.18
2006	14.30	11.48	159.79	83.89	17.07
2007	12.67	9.64	155.09	78.67	16.96
2008	18.15	9.13	135.97	71.91	14.50
2009	16.10	8.58	156.76	85.36	16.94
2010	15.27	7.76	156.00	83.02	16.34
2011	16.96	8.58	155.17	85.32	16.59
2012	16.88	7.66	160.82	88.24	17.23
2013	18.63	7.36	155.81	89.19	16.66
2014	19.75	8.27	154.31	90.51	16.90
Mean	15.64	9.12	146.39	76.31	15.77
St Dev	2.37	1.41	14.70	15.88	1.50
OT 1	10.89	6.30	116.98	44.55	12.77
OT 2	7.34	4.14	96.06	46.14	10.10

Table 19. SE US pellet mills operating in the vicinity of the ports of Savannah, Georgia and Chesapeake, Virginia [a]

Port	Pellet Mill Name	City	State	Long	Lat
Chesapeake	Equustock LLC Equustock	Chester	Virginia	-77.31	37.35
Chesapeake	Potomac Supply LLC	Kinsale	Virginia	-76.60	38.02
Chesapeake	Trae Fuels Ltd	Bumpass	Virginia	-77.78	37.96
Chesapeake	Enviva Ahoskie	Ahoskie	North Carolina	-76.97	36.27
Chesapeake	Enviva Northampton	Garysburg	North Carolina	-77.56	36.45
Chesapeake	Enviva Southampton	Courtland	Virginia	-77.07	36.72
Chesapeake	Wood Fuel Developers	Waverly	Virginia	-77.10	37.04
Savannah	Georgia Biomass	Waycross	Georgia	-82.41	31.26
Savannah	ATP-SC LLC	Allendale	South Carolina	-81.18	33.00
Savannah	Low Country BioMass	Ridgeland	South Carolina	-81.02	32.48

---

[a] List of operating industrial pellet mills was current as of September 2014.

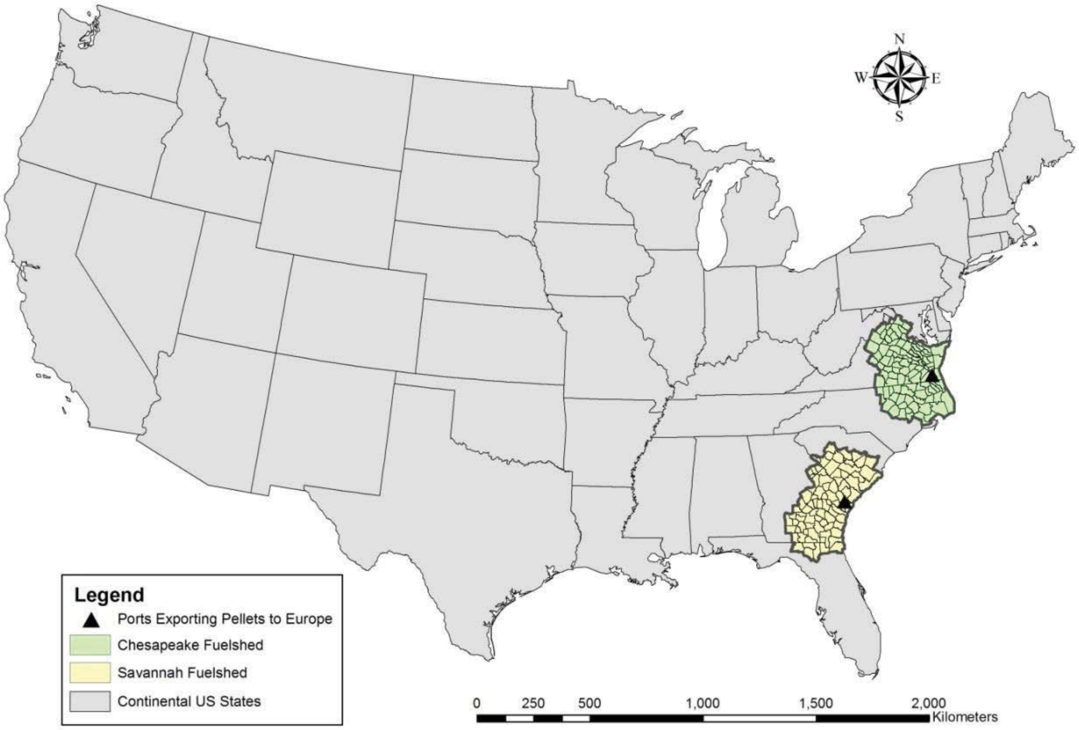

Figure 11. Map of the two SE case study fuelsheds used to extract the FIA data

The two fuelsheds are centered on the ports of Savannah, Georgia and Chesapeake, Virginia. Timberland located in counties within a haul distance of 75 miles (Stewart 2015) of active pellet mills (Table 19) was considered in the FIA data analyses.

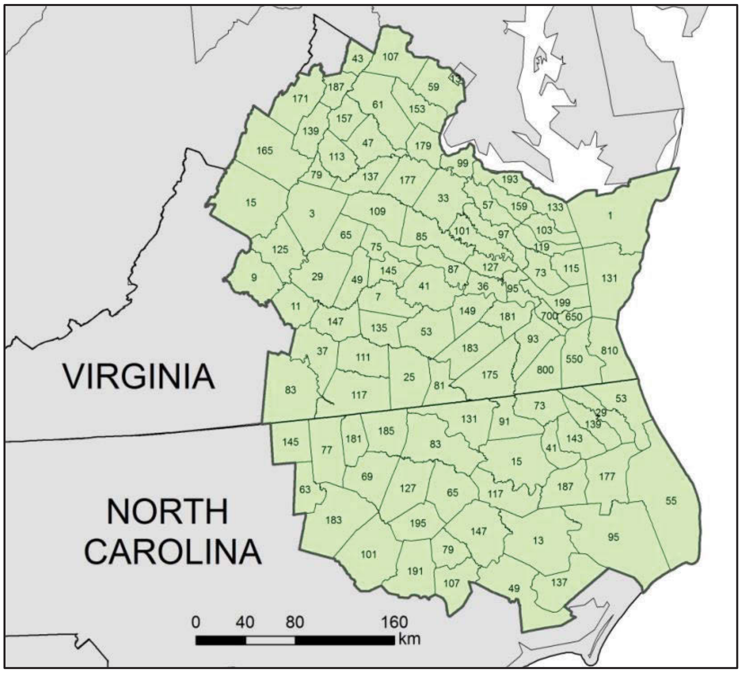

Figure 12. Counties used to extract FIA data for the Chesapeake fuelshed

The Chesapeake fuelshed encompasses 12 million ha across 33 North Carolina counties and 69 Virginia counties. County-level Federal Information Processing Standard (FIPS) codes are indicated.

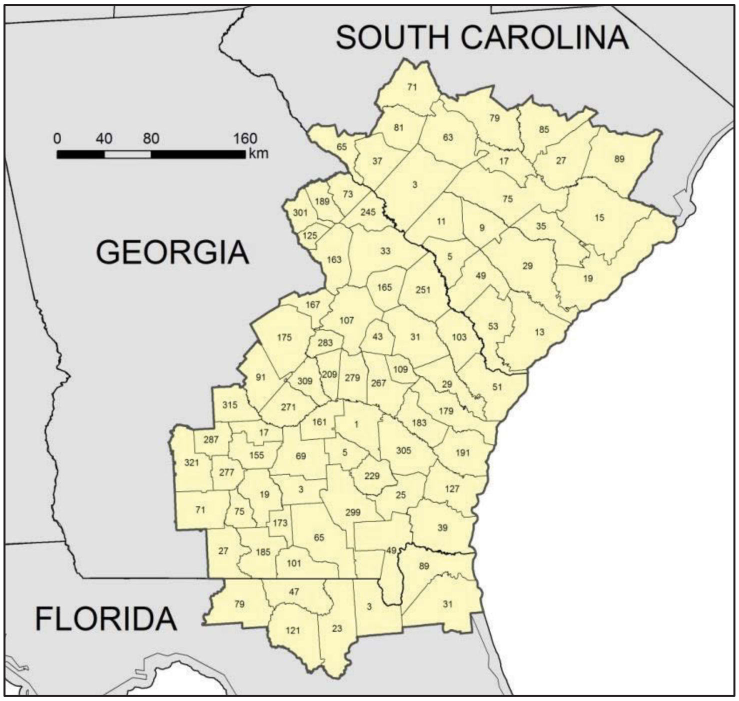

Figure 13. Counties used to extract FIA data for the Savannah fuelshed

The Savannah fuelshed encompasses 12 million ha across 22 South Carolina counties, 54 Georgia counties, and 7 Florida counties. County FIPS codes are indicated.

Table 20. List of FIA state inventory combinations used in data queries for the Chesapeake fuelshed

Group ID	Inventory Years Used	State Inventory Groups Combined
A	2002-2005	RSCD=33 EVALID=370601 NORTH CAROLINA 2002;2003;2004;2005;2006
		RSCD=33 EVALID=510701 VIRGINIA 2002;2003;2005;2006;2007
B	2005-2007	RSCD=33 EVALID=370701 NORTH CAROLINA 2003;2004;2005;2006;2007
		RSCD=33 EVALID=510801 VIRGINIA 2002;2003;2005;2006;2007;2008
C	2009	RSCD=33 EVALID=371401 NORTH CAROLINA 2003;2005;2006;2007;2009;2010;2011;2012;2013;2014
		RSCD=33 EVALID=511301 VIRGINIA 2008;2009;2010;2011;2012;2013
D	2005-2013	RSCD=33 EVALID=371401 NORTH CAROLINA 2003;2005;2006;2007;2009;2010;2011;2012;2013;2014
		RSCD=33 EVALID=510701 VIRGINIA 2002;2003;2005;2006;2007
		RSCD=33 EVALID=511301 VIRGINIA 2008;2009;2010;2011;2012;2013
E	2010-2014	RSCD=33 EVALID=371501 NORTH CAROLINA 2009;2010;2011;2012;2013;2014;2015
		RSCD=33 EVALID=511401 VIRGINIA 2009;2010;2011;2012;2013;2014
F	2002, 2003, 2014	RSCD=33 EVALID=370601 NORTH CAROLINA 2002;2003;2004;2005;2006
		RSCD=33 EVALID=371501 NORTH CAROLINA 2009;2010;2011;2012;2013;2014;2015
		RSCD=33 EVALID=510701 VIRGINIA 2002;2003;2005;2006;2007
		RSCD=33 EVALID=511401 VIRGINIA 2009;2010;2011;2012;2013;2014

Table 21. List of FIA state inventory combinations used in data queries for the Savannah fuelshed

Group ID	Inventory Years Used	State Inventory Groups Combined
G	2002-2004	RSCD=33 EVALID=120701 FLORIDA 2002;2003;2004;2006;2007
		RSCD=33 EVALID=130501 GEORGIA 1998;1999;2000;2001;2002;2003;2004;2005
		RSCD=33 EVALID=450601 SOUTH CAROLINA 2002;2003;2004;2005;2006
H	2005-2009	RSCD=33 EVALID=120901 FLORIDA 2002;2003;2004;2006;2007;2009
		RSCD=33 EVALID=130901 GEORGIA 2005;2006;2007;2008;2009
		RSCD=33 EVALID=450901 SOUTH CAROLINA 2002;2003;2004;2005;2006;2007;2008;2009
I	2010-2014	RSCD=33 EVALID=121401 FLORIDA 2010;2011;2012;2013;2014
		RSCD=33 EVALID=131401 GEORGIA 2010;2011;2012;2013;2014
		RSCD=33 EVALID=451401 SOUTH CAROLINA 2009;2010;2011;2012;2013;2014

To facilitate the aggregation and uncertainty analysis of FIA data across multiple state inventories, the following two custom SQL codes (one for each fuelshed area) were provided by USFS Southern Research Station IT Specialist Helen Beresford on February 3, 2016:

Port: Chesapeake

1. Choose the evalid of interest for VA, NC

2. ADD THIS FILTER in the filter textbox:

   ```
   and (plot.cty_cn) in (select cty_cn from
   ANL_SRS_FIA_DATA_REQUESTS.ORNL_FUELSHED_CO where
   port=′Chesapeake′)
   ```

Port: Savannah

1. Choose the evalid of interest for FL, GA, SC

2. ADD THIS FILTER in the filter textbox:

   ```
   and (plot.cty_cn) in (select cty_cn from
   ANL_SRS_FIA_DATA_REQUESTS.ORNL_FUELSHED_CO where
   port=′Savannah′)
   ```

To input these filters, the option to “Add Filter” was selected during the final step of each EVALIDator query request form found at https://www.fia.fs.fed.us/tools-data.

The timberland subset of forested land was used for all of queries, and a “stand origin” row variable was sometimes used in order to examine changes separately for naturally regenerating forest stands (‘natural stands’) and plantations (i.e., forest showing "clear evidence of artificial regeneration”) (O’Connell et al. 2014, Dale et al. 2017)]. Results from multiple EVALIDator queries were aggregated within Excel spreadsheets to get annual variable sequences. Because sampling error was provided by the EVALIDator tool at a 67% confidence level, we multiplied each “sampling error percent” by 1.94 to determine the 95% confidence level (Tables 8-15). The number of plots included in each year′’s estimate is based on the “Number of non-zero plots in estimate” provided by the EVALIDator tool (Tables 8-15).

Timberland volume estimates

For the timberland volume estimates (Tables 8 & 9), the FIA estimate called "Net volume of live trees (at least 5 in. d.b.h./d.r.c.), in cubic feet, on timberland" was selected, and no denominator was used. Evaluation Group A (years 2002 and 2003 only), B, C, and E were picked for the Chesapeake fuelshed (Table 20), and Groups G, H, and I were used for the Savannah fuelshed (Table 21). The "Page variable" was set to "None", the "Row variable" was set to "Stand origin", and the "Column variable" was set to "Inventory year." Volume estimates were provided by the EVALIDator tool in cubic feet and converted to millions of cubic meters using the standard conversion factor of 0.028 m^3 per cubic foot.

Timberland area estimates

For the timberland area values (Tables 10 & 11), the FIA estimate called "Area of timberland, in acres" was selected and no denominator was used. Evaluation groups were then picked according to Groups A (2002 and 2003 only), D, and E (2014 only) for the Chesapeake fuelshed (Table 20) and Groups G, H, and I for the Savannah fuelshed (Table 21). The "Page variable" was set to "Stand-size class", the "Row variable" was set to "Stand origin", and the "Column variable" was set to "Inventory year." The FIA stand-size classes of large, medium, and small diameter trees were used as proxies for the relative ages of each stand. According to the USFS (O'Connell et al. 2014)], large trees are at least 27.9 cm (11 in.) in diameter for hardwoods and at least 22.8 cm (9 in.) in diameter for softwoods. Medium trees are at least 12.7 cm (5 in.) in diameter for all trees, and smaller than large trees. Small trees are less than 12.7 cm (5 in.) in diameter. EVALIDator area estimates were converted from acres to thousands of hectares by using the standard conversion factor of 1 acre=0.40468564 ha.

Standing-dead tree estimates

For the standing dead tree estimates (Tables 12 & 13), the FIA estimate called "Number of standing-dead trees (at least 5 in. d.b.h./d.r.c.), in trees, on timberland" was selected along with a denominator of "Area of timberland, in acres." Combined state inventory evaluation Groups A (2005), D (2006–2013) and E (2014) were used for the Chesapeake fuelshed (Table 20), and Groups G, H, and I were used for the Savannah fuelshed (Table 21). The "Page variable" was set to "None", the "Row variable" was set to "Stand origin", and the "Column variable" was set to "Inventory year." EVALIDator estimates were converted from number of trees per acre to number of trees per hectare by dividing the returned values by 0.40468564 ha per acre.

Carbon pool estimates

To calculate timberland carbon storage levels (Tables 14 & 15), seven EVALIDator queries were combined to assess three primary carbon pools:

(1) "Harvestable material" was quantified using the timberland estimate for "Above and belowground carbon in live trees (at least 1 in. d.b.h./d.r.c)."

(2) "Nonharvestable material" was defined as a composite of standing-dead trees, understory, and downed material and required adding together timberland estimates for "Aboveground carbon in live seedlings, shrubs, and bushes," "Belowground carbon in live seedlings, shrubs, and bushes," "Above and belowground carbon in standing-dead trees (at least 1 in. d.b.h./d.r.c.)," and "Carbon in stumps, coarse roots, and coarse woody debris."

(3) "Organic soil and leaf litter" was obtained by summing estimates of "Carbon in organic soil" and "Carbon in litter."

State inventories from Groups D and F were used for the Chesapeake fuelshed (Table 20), and EVALIDs from Groups G, H, and I were used for the Savannah fuelshed (Table 21). All carbon estimates were converted from short tons to millions of metric tons using the conversion factor of 0.90718474 metric tons per short ton. In Tables 14 & 15, the presented sampling error percentages and included plot totals for "Nonharvestable material" are means of the individual estimates that were summed to get the carbon values.

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CHAPTER IV
HAS PELLET PRODUCTION AFFECTED SOUTHEASTERN US FORESTS?

This chapter summarizes findings described in the recent publication:
V. H. Dale, E. S. Parish, K. L. Kline, E. Tobin, “How is wood-based pellet production affecting forest conditions in the southeastern United States?”, *Forest Ecology and Management* 396:143-149.

A version of this chapter was originally published by Esther Parish, Virginia Dale, and Keith Kline as:
E. S. Parish, V. H. Dale, K. L. Kline, “Has pellet production affected Southeastern US forests?”, *World Biomass* (in press).

The article is presented in its original form, formatted for this dissertation including renumbering tables and figures. Author was lead author for the article, and ORNL coauthors Virginia Dale and Keith Kline provided guidance, revisions, and photographs that were instrumental in its publication. Because *World Biomass* is a trade magazine written for a broad audience including members of US Congress, industry representatives, foresters, etc., this chapter does not include an abstract, section divisions or references.

Has pellet production affected Southeastern US forests?

Wood pellet export volumes from the Southeastern United States (SE US) to Europe have been growing since 2009, leading to concerns about potential environmental effects. Biomass pellets are intended to reduce carbon emissions and slow global warming by replacing coal in European power plants. Yet, stakeholders on both sides of the Atlantic Ocean worry that increased pellet production might lead to changes in SE US forests that harm water and soil quality, or endanger sensitive species—such as birds, tortoises, and snakes—and their habitats. Stakeholders have also expressed concern that increasing pellet demand might accelerate a fifty-year trend in which naturally regenerating mixed hardwood and pine forests native to the SE US are being replaced by plantation pine forests.

Oak Ridge National Laboratory (ORNL) researchers recently collaborated with the US Department of Agriculture Forest Service to examine data relevant to concerns about pellet exports harming SE US forests. The researchers conducted an analysis of two forested landscapes that produce a large share of US wood pellets being shipped to Europe. These two bioenergy supply areas, referred to as the Savannah and Chesapeake fuelsheds, include timberland within a 120-km radius of the pellet mills supplying the ports of Savannah, Georgia, and Norfolk, Virginia. US International Trade Commission data for wood pellets show that over half of all US pellet exports to Europe have been shipped from these two SE US ports.

Timberland is defined by the US Forest Service as “the nonreserved forest land capable of producing at least 20 cubic feet of commercial wood volume per acre per year” (i.e., 1.4 cubic meters of commercial wood volume per hectare per year). The reserved forest land excluded from the timberland designation includes land set aside for parks and conservation, where forest harvesting activities are not allowed. The majority of productive timberland in the SE US is privately owned and managed by a variety of interests ranging from family land owners to large real estate investment corporations.

The Savannah fuelshed contains some of the most intensively managed pine plantations in the United States, while the Chesapeake fuelshed area contains both pine plantations and mixed hardwood stands. The Savannah fuelshed includes 22 South Carolina counties, 54 Georgia counties, and 7 Florida counties. The Chesapeake fuelshed area includes 33 North Carolina counties and 69 Virginia counties. Each fuelshed has an area of 12 million hectares, and each has supported a large increase in wood pellet production and export since 2009.

The US Forest Service conducts field measurements to support annual surveys of forest conditions. The data are entered into the Forest Inventory and Analysis (FIA) database, which is accessible to the public on the US Forest Service website. FIA data for 2002 to 2014, the most recent complete data for the states included in the two study areas, were used to analyze timberland conditions in the Savannah and Chesapeake fuelsheds. The study focused on observable changes since 2009, the year that pellet exports to Europe began in response to European Commission renewable energy directives.

Timberland characteristics examined by ORNL included:

- total volume of wood inventory in naturally regenerating stands and plantations;
- number of standing dead trees per hectare of natural stands and plantations—since snags are the preferred habitat of some species;
- hectares of trees with small, medium and large diameters— since this roughly corresponds with stand age composition; and
- carbon stocks comprised of carbon content in soil and leaf litter, live harvestable material, and dead nonharvestable material.

Detailed analysis, published in the journal *Forest Ecology and Management*, found no evidence of detrimental effects on stored carbon or conditions of growing timberland in either of the two fuelshed areas supplying wood pellets for export to Europe. In fact, the total amount of carbon stored in each fuelshed increased after 2009. Plantation inventory volumes also increased in both fuelsheds after 2009, and natural stand volumes remained constant in the Chesapeake fuelshed and increased in the Savannah fuelshed. Hectares of large diameter (older) trees increased within both fuelsheds, probably resulting from a slowdown in timber removals following the 2008 US housing market crash. There were no significant changes in the hectares of small- or medium-diameter (younger) trees, suggesting that biomass removals are being offset by regrowth and new tree planting. The persistent increases in carbon in the two fuelsheds during periods of increasing removals for pellets provides empirical support to prior studies describing how forest management that incorporates the production of wood pellets can enhance greenhouse gas sequestration in SE forests while displacing fossil fuels at the point of use.

While both fuelsheds retained more natural stands than plantations, the number of standing dead trees per hectare increased in Savannah's natural stands and decreased in its plantations. There was no change in the standing dead tree density in the Chesapeake fuelshed however. Standing dead tree density can be influenced by many factors including historical disturbance events such as drought, flood, hurricanes and ice storms. Management practices are applied to forests located in both fuelsheds in order to conserve standing dead trees and other wildlife habitat. The reduced density of standing dead trees in the Savannah fuelshed plantations after 2009 warrants further research, both to determine probable causes and to measure its effects on biodiversity. Standing dead trees—even if retained in plantations—eventually fall over and contribute to dead woody material carbon stocks. And dead nonharvestable material in the Savannah fuelshed as a whole did increase after 2009.

One of the priority endangered species in the SE US forests is the red-cockaded woodpecker, which relies on large, living long-leaf pine trees with minimal hardwood wood understory. Having understory trees allows snakes and other predators to access the nests and eat the young birds. Hence researchers recommend low-level burns or thinning hardwood mid-story within long-leaf pine plantations to provide high-quality nesting habitat for the red-cockaded woodpecker. Markets that offer a use for the wood being thinned can provide incentives to achieve these wildlife management goals while also reducing impacts on air quality that result from burning.

Incentives for thinning forests in the SE US can also reduce the risk of destructive forest fires and outbreaks of pests and diseases, increase site productivity and consequent carbon uptake rates, and promote opportunities for recreation and habitat for wildlife. Benefits of controlling disease, pests, and fires on private forests extend to neighboring forests, public lands, and reserves.

While all energy use affects the environment, the results of ORNL's recent analysis indicate that wood pellets can be used to displace fossil energy sources without adversely impacting SE US forests. In fact, monies received for pellets provide small private forest owners a means to invest in thinning and other forest management activities that lead to healthier, more productive forests. There are also beneficial effects of pellet production on employment rates in rural communities and reduced fuel supply for potentially devastating wildfires. By contrast, urbanization—currently the greatest cause of forest loss in the SE US—is more likely to expand into forest landscapes if forest landowners lack adequate income-generating opportunities for their wood.

Even though US wood pellet exports for European renewable energy have more than doubled since 2009, the wood pellet industry still constitutes a very small proportion of total SE US timberland product removals and production (<3%). Therefore, changes in SE US forest conditions are influenced by other forest products and markets such as saw timber demand for new home construction. While the results of ORNL's study suggest that—thus far—there have been minimal effects on timberland conditions from pellet production, changes in forest management practices can take many years or even decades to manifest themselves in tree measurements. We are fortunate, therefore, that consistent and reliable FIA data are available from the US Forest Service to support continued monitoring and evaluation of forest conditions. Furthermore, as pellet manufacturers are contributing improved data regarding sources of biomass for their pellet mills, more precise analyses can be performed to assess timberland conditions in the source areas for raw materials. Periodic reanalysis of annual FIA data provides a scientifically valid approach for ongoing assessment of potential changes to SE US forest conditions.

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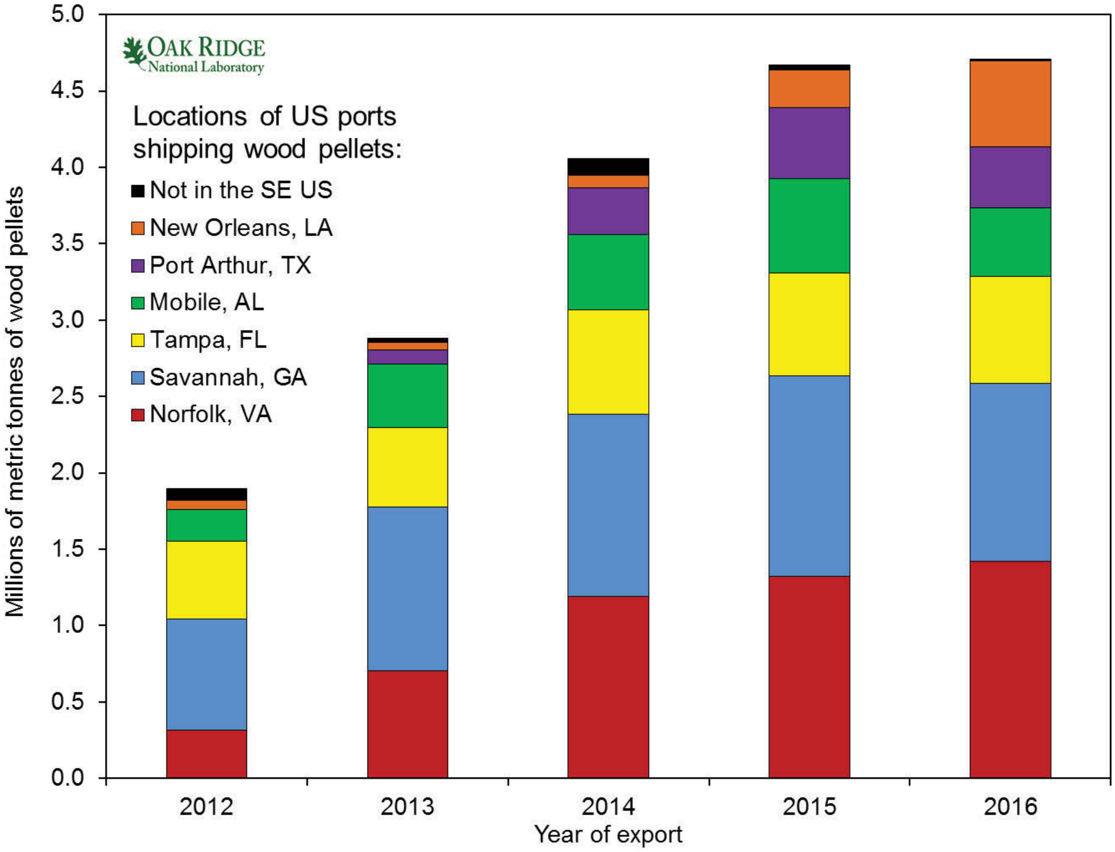

Figure 14. US International Trade Commission data show that US exports of wood pellets to Europe for bioenergy grew to 4.7 million metric tonnes in 2016

The Southeastern US region supplies nearly all of these pellets, and over half of them are shipped from the ports of Savannah, Georgia, and Norfolk, Virginia.

Forest Service Research Data Archive

Figure 15. ORNL researchers evaluated timberland characteristics in the Savannah and Chesapeake fuelsheds before and after 2009

These two regions (~12 million hectares each) supply over half of US wood pellets exported to Europe for renewable energy production. The Savannah fuelshed includes 22 South Carolina counties, 54 Georgia counties, and 7 Florida counties. The Chesapeake fuelshed area includes 33 North Carolina counties and 69 Virginia counties.

Figure 16. US Forest Service Southern Research Station staff demonstrated annual FIA data collection

The demonstration was provided to Oak Ridge National Laboratory staff and visiting researchers gathered at the University of Tennessee Arboretum's Forest Inventory and Analysis plot in May 2016. Ongoing collaboration with the US Forest Service was essential to ORNL's assessment of the effects of wood pellet production on SE US timberland.

Table 22. Results of ORNL's assessment of SE US timberland characteristics pre- and post-pellet production

The results showed that there have not been any reductions in carbon storage or volumes of naturally regenerating stands or plantations since wood pellet exports to Europe began in 2009.

Timberland Characteristic	Savannah Fuelshed	Chesapeake Fuelshed
Naturally regenerating stand volume	Increased	No change
Plantation volume	Increased	Increased
Large-diameter tree area	Increased	Increased
Medium diameter tree area	No change	No change
Small diameter tree area	No change	No change
Standing dead tree density of natural stands (#/ha)	Increased	No change
Standing dead tree density of plantations (#/ha)	Decreased	No change
Carbon content of soil and leaf litter	Increased	No change
Carbon content of live harvestable material	Increased	Increased
Carbon content of dead non-harvestable material	Increased	No change

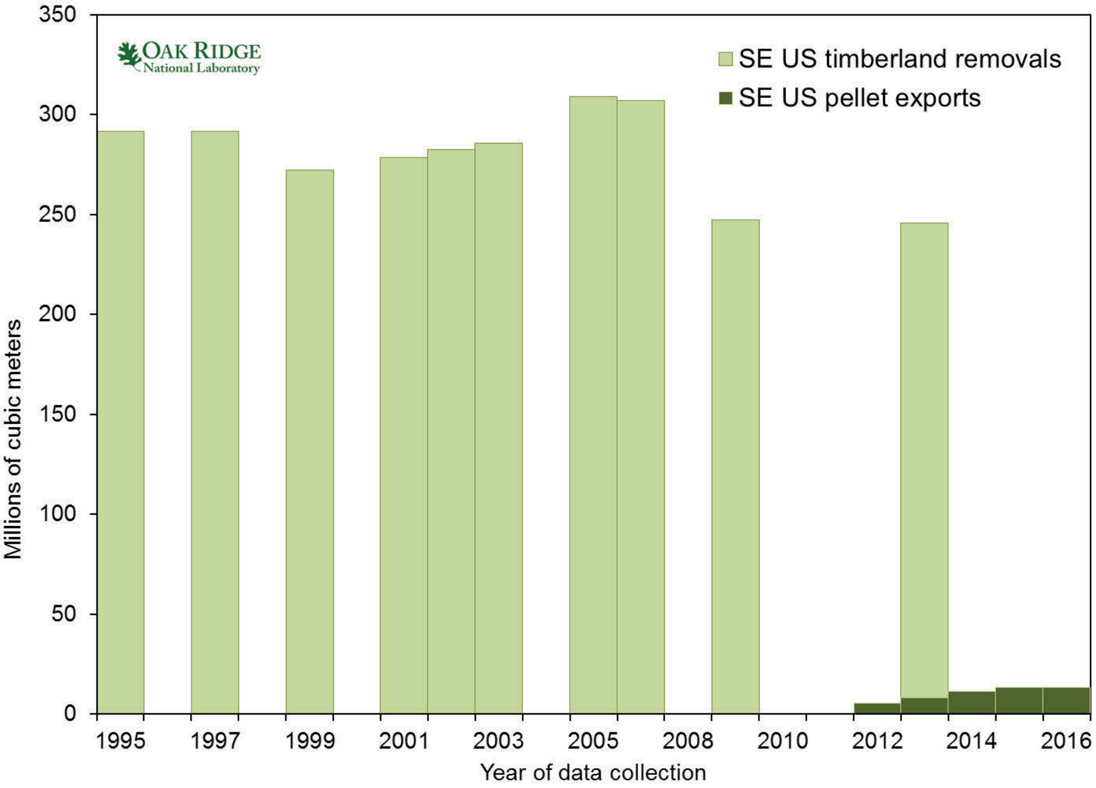

Figure 17. Wood pellet production for European markets is growing, but still comprises just a small proportion of total SE US wood production.

US Forest Service Timber Product Output data aggregated for the nine SE US states currently producing wood pellets show an overall decline in wood removal volumes since 1995. The 8 million cubic meters of woody biomass used to make pellets exported in 2013 (based on US International Trade Commission data shown in Figure 1) represented 3% of the total 2013 SE US timberland removal volume of 246 million cubic meters.

Figure 18. Continued growth in the export wood pellet industry might encourage SE US forest owners to invest in forest management

This is illustrated through a comparison of (A) unthinned and poorly managed pine forest in eastern Tennessee, which lies outside of the pellet export market, with (B) well-managed longleaf pine located in the Savannah fuelshed. Multiple studies have shown that improved forest management can lead to increased carbon sequestration and fewer impacts from wildfires and pest/disease outbreaks.

Figure 19. Urban expansion currently poses a much bigger threat to SE US forests than export wood pellet production

Market outlets for wood are needed in order to keep SE US land in forest.

CONCLUSION

This research was motivated by the US DOE national objective to better understand the potential environmental and socioeconomic tradeoffs of transitioning to renewable forms of energy. In order for the US to achieve its goal of developing a domestic and globally competitive and sustainable bioenergy industry (DOE 2016) that can stimulate rural economies while also improving the health of forested landscapes and mitigating global climate (Chazdon et al. 2016, FAO 2016), more research is needed to establish ways of consistently and effectively measuring progress toward integrated environmental, social and economic goals for forest-based bioenergy systems. The risks and opportunities for each bioenergy system will inevitably vary by feedstock and location, meaning that specific sustainability goals will need to be developed by diverse stakeholder groups within each given context (Efroymson et al. 2013). This investigation into the sustainability of the transatlantic wood pellet trade for biopower production serves as a case study to improve understanding of the environmental, social and economic benefits and tradeoffs that may occur across multiple spatial and temporal scales as a result of substituting a renewable energy resource for fossil fuel (Parish et al. 2013).

Chapter 1 of this dissertation used the telecoupling framework proposed by Liu et al. (2013) to define the bioenergy system boundaries, flows and stakeholders for the transatlantic industrial wood pellet trade. The identified primary agents (Table 4) are the key stakeholders within the bioenergy system, and the identified observed and potential effects of wood pellet production (Tables 5 & 6) can be used as a starting point for working with stakeholders to establish sustainability goals. A bioenergy system's current state and sustainability trajectory may be evaluated through a carefully selected combination of environmental and socioeconomic indicators, such as the 35 indicators in 12 categories proposed by McBride et al. (2011) and Dale et al. (2013) to evaluate bioenergy systems. Thus, once goals have been established in conjunction with the primary agents, the next step will be to identify the key indicators that should be measured to track progress toward (or away from) those goals (Dale et al. 2015). Potential key sustainability indicators for this forest-based bioenergy system include jobs, water and soil quality, biodiversity, greenhouse gas emissions, and forested land area (Dale et al. 2016). Environmental and socioeconomic datasets (preferably spatially and temporally explicit) should be gathered to help establish baselines and targets for each key sustainability indicator [see example by Parish et al. (2016)].

Chapter 2 recommended guidelines for quantitative modeling the potential effects of wood pellet production on SE US forest landscapes. Models should be fuelshed-based, meaning that potential changes to key indicators should be examined across the entire timberland area supplying a particular pellet mill (or set of pellet mills). Given the fact that it may take many years for changes in forest management to become noticeable, analyses should ideally be based on datasets collected over periods of 10 years or more. Wood pellet production should be treated as an alternative fate for low-quality timberland removals or wood removals with no other market outlet (Figure 7) rather than a primary driver of the SE US wood market. Protected forested land should be excluded from the analysis, and additional pressures on forests (such as urban encroachment, droughts and other disturbances) should be carefully considered. All assumptions made about past, current and future bioenergy system characteristics should be carefully documented.

Chapter 3 detailed a methodology for using annual US Forest Service FIA data to assess annual trends for 10 variables that characterize timberland health and productivity. This analysis method was applied to two SE US fuelshed areas to test for timberland changes that may have resulted from export pellet production beginning in 2009. As discussed in Chapter 4, very little change was detected in the fuelsheds supplying pellets to the ports of Chesapeake, Virginia and Savannah, Georgia. However, changes in forest management practices can take many years or even decades to manifest themselves in tree measurements, and so it will be necessary to continue monitoring and evaluating forest conditions across the SE US. Periodic reanalysis of annual FIA data provides a scientifically valid approach for ongoing assessment of potential changes to SE US forest conditions. And as pellet manufacturers begin providing data regarding sources of biomass for their pellet mills (e.g., Enviva 2017) more precise analyses can be performed to assess timberland conditions in the source areas for raw materials—particularly if the removal data are combined with time sequences of remotely sensed imagery.

Multiple case studies of bioenergy systems are needed to advance progress toward a stakeholder-driven adaptive management framework for local decisions developed through quantitative landscape-scale data collection and spatial modeling. Ultimately, researchers want to be able to provide decision makers with an interactive visualization tool that will help them evaluate potential tradeoffs and synergies (Raudsepp-Hearne et al. 2010) associated with multiple—and potentially conflicting—stakeholder goals, set targets and baselines for working on established priorities within a given context (Dale et al. 2015), and iteratively track progress toward (or away from) those goals as new knowledge and information becomes available, or as circumstances change.

Improved understanding of the environmental and socioeconomic costs and benefits of forest-based bioenergy systems will help policy makers to determine whether State-based best management practices are sufficient to ensure landscape-scale sustainability throughout the SE US. This knowledge will also help SE US foresters and pellet producers to assess whether or not it will be worth their time and effort to meet the EU’s proposed sustainability certification requirements for its supply of wood-based bioenergy (Olesen et al. 2016).

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VITA

Esther Sullivan Parish (born Esther Marie Sullivan) has deep roots in the southeastern United States, a love of international travel and the liberal arts, and over 20 years of work experience related to energy and the environment. Esther joined Oak Ridge National Laboratory (ORNL) in 2007 as a researcher for the Computational Sciences & Engineering Division and transitioned to the Environmental Sciences Division's Landscape Ecology and Regional Analysis Group in 2009. During her 10 years at ORNL, Esther has enjoyed working on a variety of interdisciplinary projects related to climate change impacts and renewable energy sustainability. She has been recognized several times for her work on novel computational projects and recently received a 2017 UT-Battelle individual "Science Communicator" Award for her ongoing community outreach activities. Esther lives with Brad Parish and their two children (Levi and Avery) in Brad's hometown of Kingston, Tennessee. She looks forward to using her new PhD in Energy Science and Engineering to further her scientific career at ORNL.

Esther was born in Georgia, spent four years in the Philippines as a missionary kid, and then finished elementary through high school in Chicago's Hyde Park. She graduated Valedictorian from Kenwood Academy in 1990 and went on to obtain a B.S. in Geology & Geophysics from Yale University in 1994. Immediately after college, Esther headed to the Oklahoma oilfields as an open hole logging engineer for Schlumberger Wireline and Testing. She was named one of the Best Engineers of Schlumberger Technologies for her work in Duncan and Enid.

Esther moved to the Secret City of Oak Ridge, Tennessee in 1995 to try environmental consulting. She worked on a variety of contracts for the US Department of Energy (DOE), the US Army Corps of Engineers, and the US Environmental Protection Agency. She received multiple awards for her work with the DOE Pollution Prevention Program and met her husband at the K-25 Site during that time. Esther was later employed as a Geographer for the Tennessee Valley Authority Public Power Institute and then as a Geology Instructor for Roane State Community College.

Esther earned an M.S. in Geography from The University of Tennessee in 2002 under the direction of Dr. Carol Harden. Esther's thesis combined field assessment with geographic information systems analysis to better understand urbanization-induced stream morphology within Knoxville's flood-prone Beaver Creek Watershed. Her M.S. research earned a "My Community, Our Earth" award from the United Nations Environment Programme, the National Geographic Society, the Environmental Systems Research Institute, and the Association of American Geographers.