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OPINION

Status and prospects for renewable energy using wood pellets from the southeastern United States

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Abstract

The ongoing debate about costs and benefits of wood-pellet based bioenergy production in the southeastern United States (SE USA) requires an understanding of the science and context influencing market decisions associated with its sustainability. Production of pellets has garnered much attention as US exports have grown from negligible amounts in the early 2000s to 4.6 million metric tonnes in 2015. Currently, 98% of these pellet exports are shipped to Europe to displace coal in power plants. We ask, ‘How is the production of wood pellets in the SE USA affecting forest systems and the ecosystem services they provide?’ To address this question, we review current forest conditions and the status of the wood products industry, how pellet production affects ecosystem services and biodiversity, and what methods are in place to monitor changes and protect vulnerable systems. Scientific studies provide evidence that wood pellets in the SE USA are a fraction of total forestry operations and can be produced while maintaining or improving forest ecosystem services. Ecosystem services are protected by the requirement to utilize loggers trained to apply scientifically based best management practices in planning and implementing harvest for the export market. Bioenergy markets supplement incomes to private rural landholders and provide an incentive for forest management practices that simultaneously benefit water quality and wildlife and reduce risk of fire and insect outbreaks. Bioenergy also increases the value of forest

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land to landowners, thereby decreasing likelihood of conversion to nonforest uses. Monitoring and evaluation are essential to verify that regulations and good practices are achieving goals and to enable timely responses if problems arise. Conducting rigorous research to understand how conditions change in response to management choices requires baseline data, monitoring, and appropriate reference scenarios. Long-term monitoring data on forest conditions should be publicly accessible and utilized to inform adaptive management.

Keywords: best management practices, biodiversity, bioenergy, carbon, ecosystem services, forests, pellets, southeastern United States, sustainability

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Introduction

Wood-pellet production in the southeastern United States (SE USA) has garnered much attention (Olesen *et al*., 2016; Cornwall, 2017) as exports have grown from negligible amounts in the early 2000s to 4.6 million metric tonnes in 2015 (US International Trade Commission, 2016). In 2015, 98% of these pellets were shipped from the SE USA to the European Union (EU) for bioenergy (US International Trade Commission, 2016). As EU pellet demand has grown, debate has increased about potential effects on SE US forests. Environmental organizations and others have expressed concerns about potential impacts on old-growth and bottomland forests (forested wetlands that experience occasional flooding in the SE USA), net greenhouse gas (GHG) emissions, and biodiversity (Olesen *et al*., 2016; Cornwall, 2017). Yet the US Department of Agriculture (USDA) Forest Service identifies the greatest risks to SE US forests as urban expansion and land development, lack of market demand for wood products, and increases in invasive species, fires, and other disturbances related to climate change (Wear *et al*., 2013), although these risks are overlooked in some studies (e.g., Cornwall, 2017).

Evidence-based analysis is essential to address concerns and inform decision making. Evaluating effects requires an understanding of how wood-pellet demand interacts with other forest product markets and the extent to which pellet production induces synergies, tradeoffs, or other costs and benefits that can be differentiated from the effects of ongoing forestry practices in the absence of pellet markets. Our aim is to present an objective review of key issues, constraints, and opportunities associated with the wood-based pellets industry, based on documented effects of wood-pellet production on forest conditions in the SE USA.

Demand and production of wood pellets

The recent growth in global pellet demand has been driven largely by EU renewable energy targets to cut GHG emissions in 2020 by 20% from 1990 levels. European policies promoting bioenergy are partially predicated on analysis showing that increased use of bioenergy can contribute to both energy and climate objectives (Dale *et al*., 2015a; Berndes *et al*., 2016; European Union, 2016). The EU and individual member-state bioenergy policies include a mix of tax exemptions, mandatory targets, electric power feed-in tariffs, direct subsidies, and solid biomass sustainability policies that stimulate market growth of imported wood pellets (Abt *et al*., 2014; Alberici *et al*., 2014).

Wood-pellet production in the SE USA has emerged in response to several factors. The decline of pulp and paper operations has resulted in stranded wood supplies. Making pellets maintains employment in regions where the forest products industry has been a key economic driver. In addition, by-products of sawmill operations and forest management (e.g., from tree thinning to maximize timber yield, unmerchantable stems or from harvest residues such as branches and tops) provide pellet feedstock (Morrison & Golden, 2016). Furthermore, access to EU markets for pellets from SE USA is facilitated by carbon- and cost-efficient maritime shipping (Dwivedi *et al*., 2014), high-volume direct shipping lanes, and proximity of ports to productive timberlands with established forest product supply chains. Although pellet exports rose sharply after 2007, biomass for pellets comprised only 2% of total harvest removals in the SE USA in 2014 (Fig. 1), with traditional pulpwood and sawtimber representing the other 98% (Stewart, 2015). International trade data show that pellets comprised <1% of total US forestry products by weight and <0.5% of total US forest products export value during 2014 (FAOSTAT-Forestry Database, 2016, based on conversion factors in Lamers (2013) and UNECE (2009)).

Forest history sets the stage

The production of wood-based pellets should be viewed in light of the dramatic changes that the SE US landscape has undergone since large-scale settlement began in the 18th century. Two centuries of development, row crop cultivation and almost complete forest conversion resulted in high soil erosion rates. As crop production became less competitive in the eastern USA, it moved to

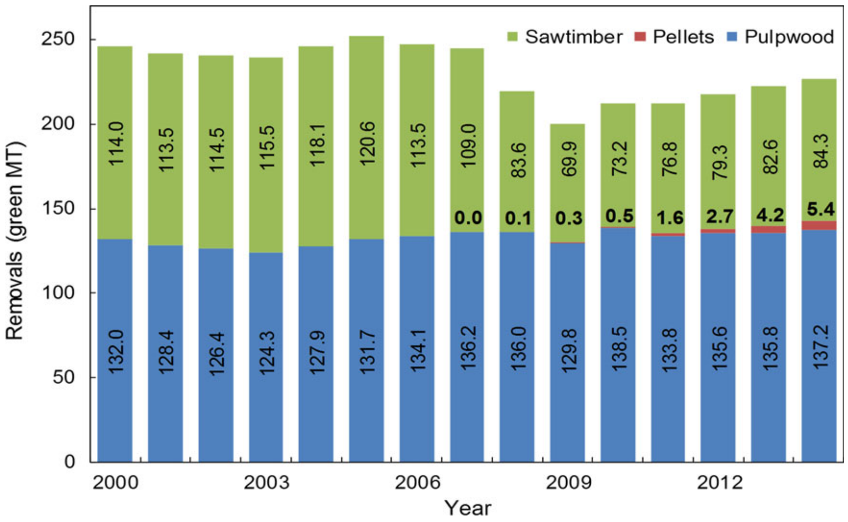

Fig. 1 Annual forest harvest removals in the SE USA shown in green million metric tonnes (MT) based on Forest2Market data reported for the Atlantic and Gulf regions (Stewart, 2015). In this figure, 2 tonnes of green wood are assumed to produce 1 tonne of dry pellets.

regions better suited to intensive agriculture and afforestation ensued (Davis, 1996). Although only 12% of global forest area is privately owned (White & Martin, 2002), 87% of SE US timberland is privately owned and about 60% is family owned (Oswalt *et al.*, 2014). Whereas institutional owners (e.g., private forest products corporations and investment firms) respond primarily to market signals, management decisions of family forest owners are motivated by diverse interests including asset preservation, profit generation, aesthetics, wildlife and recreational opportunities, and inheritance for heirs (Butler *et al.*, 2017). Harvesting decisions by family forest owners are frequently triggered by life events, such as the need to raise money for medical treatment, education, or retirement (Butler *et al.*, 2017), or by a change in ownership.

Concerns

Effects on old-growth forests

The potential for pellet-wood production to affect old-growth forests has been raised as an issue by some conservationists. However, the legacy of land clearing, logging, and agriculture has left only isolated pockets of old-growth forest in the SE USA (Davis, 1996). Remnant old-growth forests (as defined by advanced tree age, minimal human disturbance, and mature successional stage of the forest) are valued for their ecological characteristics and are almost exclusively found in protected areas where logging is prohibited (Davis, 1996). US federal policy instruments safeguarding all forests include protection of rare species under the Endangered Species Act, Safe Harbor Agreements and Habitat Conservation Plans (on private lands), and protection of ecosystem services under the Clean Water Act and Clean Air Act. State agencies, land trusts, nongovernmental organization, and citizen alliances safeguard state and private forests (Davis, 1996). Depending on the forest type and condition, that protection may involve active management. For example, fire-dependent, native longleaf pine (*Pinus palustris*) stands that once blanketed large areas of the SE USA have been reduced to 3% of their original area as a result of settlement and fire suppression (Varner *et al.*, 2005). Removing hardwood trees and management of understory vegetation via controlled burns and other practices is key for restoring the longleaf pine ecosystem across its former range and maintaining open canopy conditions in other pine forest types (Varner *et al.*, 2005; Greene *et al.*, 2016), and bioenergy can offer a market for that material.

Effects on bottomland forests

The effect of wood-pellet production on bottomland forests is also a concern. Over the past two centuries, nearly all bottomland forests were converted to other land uses (as much as 80% in some regions (De Steven *et al.*, 2015)) or have been managed for wood products. Important challenges to bottomland forest ecosystems include (i) conversion to urban uses (Wear *et al.*, 2013); (ii) anthropogenic alterations in flooding patterns (Cooper *et al.*, 2009) including those associated with dikes, dredging, oil and gas extraction, and salt water intrusion; and (iii) high populations of white-tailed deer (*Odocoileus virginianus*) that promote expansion of invasive plant species and alter tree species composition (Cogger *et al.*, 2014).

A variety of conservation programs have promoted restoration of bottomland forests previously converted to other land uses. In the 13 states that comprise the Forest Service southern forest region, nearly four thousand tracts covering more than 526 000 hectares (ha) were enrolled in the Wetlands Reserve Program from 2009–2015 to protect, restore, and enhance wetlands and bottomland forests on private farmland (King *et al.*, 2006; NRCS, 2016). Since the 1990s, over 275 000 ha of bottomland forest have been restored in the lower Mississippi River valley alone, mostly on private farmland (Berkowitz, 2013).

Conservation easements often involve management, including harvest. Forest management practices in wetlands are exempt from the Clean Water Act permitting requirements, although other regulations to protect water and biodiversity are applicable. Forest management activities cannot convert wetlands to another land use and must protect threatened and endangered species. Federal and state policies and programs such as the Endangered Species Act, state water quality laws, and forestry best management practices (BMPs) protect rare species, habitats and water quality. Zoning and taxation may further restrict allowable activities, and some pellet producers have a formal policy not to source biomass from rare forest ecosystems such as cypress and tupelo stands in wetlands (Drax Biomass Inc., 2016) and sensitive bottomland forests (Enviva Forest Conservation Funds, 2016).

While timber harvesting cycles in bottomland forests have short-term (e.g., annual to decadal) effects including declines of standing carbon stocks and alteration of habitat for forest species, managing these lands for forestry is ecologically preferable to their transformation to nonforest alternatives. As with all land-use activities, effects on biodiversity and ecosystem services of harvesting bottomland forests for bioenergy are highly variable and context specific and can have differential effects across the landscape and over time (Costanza *et al.*, 2016; Tarr *et al.*, 2016). Negative impacts of bioenergy harvests can be avoided or reduced by identifying priority areas for conservation and adopting management plans tailored to best achieve multiple goals in production forests (Joly *et al.*, 2015).

Effects on climate change

Climate change impacts are another concern in the production of wood-based pellets. The Intergovernmental Panel on Climate Change (IPCC, 2014) distinguishes between the slow domain of the carbon cycle, where turnover times exceed 10 000 years, and the fast domain (the atmosphere, ocean, vegetation, and soil), where vegetation and soil carbon have turnover times of 1–100 and 10–500 years, respectively. Fossil-fuel use transfers carbon from the slow domain to the fast domain, while bioenergy systems operate within the fast domain (Ciais *et al.*, 2013). Using wood for energy displaces fossil fuels (mostly coal) and can contribute to the phasing out of technologies and infrastructures that cause fossil carbon emissions, which is necessary for keeping fossil sources secured underground (Ter-Mikaelian *et al.*, 2015; Berndes *et al.*, 2016; Galik & Abt, 2016).

Fossil-fuel inputs to wood-pellet supply chains typically correspond to a small fraction of the energy content in the produced pellets, and fossil carbon emissions are small compared to the biogenic carbon flows associated with forest operations, transport, and pellet use (Eriksson *et al.*, 2007; Lindholm *et al.*, 2011; Gustavsson *et al.*, 2011; Lamers & Junginger, 2013; Hansson *et al.*, 2015). Thus, concerns about climate effects of wood-pellet production are mainly related to how the forest carbon cycle is affected by management changes that may result from wood-pellet production systems.

As concluded by the IPCC (2014), it is the cumulative emissions of CO_2 that largely determine global warming by the late 21st century and beyond. Woody bioenergy affects cumulative emissions through two primary mechanisms: change in biospheric carbon stocks and displacement of fossil fuel. If the goal is to stabilize global warming within a 2-degree target, for example, then critical questions are how bioenergy markets influence net changes in total biospheric carbon stocks and net changes in fossil-fuel use. The latter depends largely on how bioenergy policies influence investments in fossil-fuel-based technologies and infrastructure, which has implications for future GHG emissions. A recent analysis for Canada, in which substitution values for wood products were considered across their life cycle, found that the greatest avoided emissions occurred when bioenergy was substituted for energy obtained from high-emission fossil fuel such as coal (Smyth *et al.*, 2016).

There is no question that the use of wood from managed forests to displace fossil-based energy reduces net GHG emissions over multiple cycles of forest harvest and re-growth (Ter-Mikaelian *et al.*, 2015; Galik & Abt, 2016). It is rather the timing of net GHG savings that is currently debated, and the science literature provides different views, depending on policy objectives and context, which have a major influence on the formulation of research questions, the scale and system delineation, and other critical parameters that influence the results and conclusions (Helin *et al.*, 2013; Miner *et al.*, 2014; Dale *et al.*, 2015a; Berndes *et al.*, 2016; Cintas *et al.*, 2017).

Life cycle assessment studies concerning displacement of fossil-fuel-based EU electricity generation from SE US pellets show that GHG savings occur over varying time scales (Dwivedi *et al.*, 2014; Giuntoli *et al.*, 2015; Wang *et al.*, 2015; Fingerman *et al.*, 2016; Hanssen *et al.*, 2017). When pellets are produced from precommercial thinnings, harvest residues and mill residues, the previously sequestered carbon is returned to the atmosphere via pellet combustion in heat and power plants. This process may occur faster or slower than when the carbon is returned via decomposition or burning on site. If the pellet use returns the carbon to the atmosphere faster than decomposition or burning, short-term increases in net GHG emissions occur unless the GHG emissions savings from displacing fossil fuels outweigh the biogenic carbon emissions. The choice of spatial and temporal boundaries for analysis and the choice of reference case or counterfactual scenario affect the result and may mean that different studies come to different conclusions about the same bioenergy system (Marland *et al.*, 2013; Buchholz *et al.*, 2014; Wang *et al.*, 2015). The outcome, in addition, depends on the broader consequences of the bioenergy market itself on forest management, disturbance regimes, and forest expansion, which may or may not be considered in studies (Cowie *et al.*, 2013; Berndes *et al.*, 2016)

Overall forest stocks in the SE USA have increased for the last 50 years and are projected to continue increasing if conversion to nonforest uses is low (Wear *et al.*, 2013), while also supporting significant removals for sawtimber, pulpwood and wood-pellet production (Oswalt *et al.*, 2014; Woodall *et al.*, 2015; USDA Forest Service, 2016). On intensively managed, corporate-owned timberland, carbon stocks are essentially stable (Heath *et al.*, 2010). The presence of a bioenergy market increases the economic attractiveness of forestry, which, in turn, supports maintenance and expansion of SE forest lands and their carbon sink capacity (Miner *et al.*, 2014; Zhang *et al.*, 2015), where that capacity is defined by the ability to store more above- and below-ground carbon both now and in the future. The USDA projects declines in the SE US forest area of up to 8.5 million ha or 10% between 2010 and 2060, largely driven by population growth, income-driven urbanization and a greater projected economic attractiveness of agricultural products as compared to timber products (Wear *et al.*, 2013). Private forest landowners will need incentives, financial or otherwise, to retain forested land as forest. Loss of forested land area is one of prime causes of decline in forest carbon stocks (Körner, 2017).

In the face of uncertain future demand for lumber and other forest products (Wear *et al.*, 2013), an increase in the price of wood pellets may motivate land owners to implement shorter rotations, higher density planting, or more frequent thinning (Olesen *et al.*, 2016), which could affect carbon stocks. That being said, there is no evidence to date of a change in stocking density trends based on analysis of the US Forest Service Forest Inventory and Analysis (FIA) data for counties in the SE USA with high pellet production (Dale *et al.*, in press). Furthermore, prices for bioenergy feedstocks are unlikely to increase enough to drive wholesale shifts in forest management to favor pellet production because low-cost biomass (e.g., agricultural, logging and wood-processing residues) is plentiful across the globe.

Addressing concerns about environmental effects of bioenergy

Reliable demand for wood-based bioenergy helps address the concerns mentioned above, for it improves the business proposition to retain land in forest (Galik & Abt, 2016) and to apply practices that improve forest conditions (Anderson & Mitchell, 2016). While high-value sawtimber and pulp markets are expected to continue driving major forest management decisions, a market for low-value stems, residues and roundwood (where demand is otherwise weak) helps support better forest management, for example, by reducing the practice of slash burning to dispose of unmerchantable biomass. Furthermore, markets for products made from low-value wood provide extra income (Malmsheimer & Fernholz, 2015) that can be used for management practices such as thinning that decrease risks of insect outbreaks, disease and destructive wildfire (Coppoletta *et al.*, 2016); increase site productivity and consequent carbon uptake rates (Fox *et al.*, 2007); and address non-timber objectives such as recreation and habitat for wildlife (Evans *et al.*, 2013). Benefits of controlling disease, pests and fires on private forests extend to neighboring forests, public lands and reserves (Malmsheimer *et al.*, 2011; Dale *et al.*, 2015a).

In addition, multiple environmental benefits can be achieved via the use of wood for bioenergy. Wood pellets provide a renewable alternative to the primary anthropogenic cause of environmental effects associated with climate change: fossil-fuel use (Cowie *et al.*, 2013; Berndes *et al.*, 2016). Without bioenergy markets, woody material cut for land clearing or leftover from thinning and harvest slash is often burned on site or left to decay in piles and may, thereby, increase the potential wildfire fuel load (Fig. 2). Furthermore, mid-rotation thinning increases both forest water yield and land-owner profits (Susaeta *et al.*, 2016), and those thinnings could provide biomass for bioenergy. Hence, forest management that delivers multiple benefits for the region can be a way to support both sustained employment and diverse

Fig. 2 In east Tennessee, much wood is left on the ground after a clear-cut where it decomposes and gradually releases carbon to the atmosphere (a). After a forest clearing in northern Florida, whole trees and residues are piled (b) and then pushed into a pit to be burned (c) resulting in immediate release of carbon into the atmosphere. Both practices are common across the SE USA. Note that the person on the right in photograph b shows the size of that pile. Photograph credits: Keith Kline.

ecosystem services (Meyer *et al.*, 2015). When residues are removed for bioenergy, economic and operational limitations, as well as BMPs, ensure that adequate woody debris remains on site to protect soil and water quality (Neary & Koestner, 2012; Evans *et al.*, 2013; Fritts *et al.*, 2014; Cristan *et al.*, 2016).

Best management practices define practices to minimize soil disturbance and water quality impacts from bioenergy operations, including timber harvest and residue removal (Ice *et al.*, 2010). Neary & Koestner (2012) report that forest bioenergy production systems can be compatible with maintaining high quality water supplies in forest catchments. In their review of 30 research studies of BMPs in the SE USA, Cristan *et al.* (2016) found that forestry BMPs efficiently protect water yield and quality (e.g., decrease suspended sediment flux and concentrations of nitrate and other nutrients). Furthermore, a detailed study of Coastal Plain loblolly pine (*Pinus taeda*) plantations (where Biomass Harvesting Guidelines recommend retaining a portion of woody biomass on the forest floor following harvest) found that removal of residues from clear-cut sites for bioenergy feedstock does not impact herpetofauna, breeding bird, or winter bird populations (Fritts *et al.*, 2016; Grodsky *et al.*, 2016a,b). An integrated approach that bundles ecosystem services and financial incentives offers a means to address the diverse values of forests via proactive forest management (Deal *et al.*, 2012). BMPs, in combination with a market for wood-based pellets, provide such an approach.

Forest management can cause changes in the partitioning of precipitation between runoff, drainage, evaporation and plant transpiration (Berndes, 2002; Jackson *et al.*, 2005; Bonsch *et al.*, 2017). Measures to enhance biomass production, such as expanding forest area, shifting to shorter rotations, or increasing stocking rates (more trees per area) or forest area, can lead to increased evapotranspiration and possibly greater risk of water stress in areas of water scarcity. Measures to enhance biomass production for energy can also be beneficial and reduce water risk, for example, the probability of experiencing a deleterious water-related event. For example, in humid areas and on steep slopes, the establishment of tree cover can decrease erosion and flood risk by reducing runoff and increasing infiltration and retention of rain water in the soil. Matching bioenergy feedstocks and management practices to local conditions and constraints is essential and possible (King *et al.*, 2013). For example, Susaeta *et al.* (2016) report that privately owned forests could become an important potential source of additional water supply in SE USA under a forest-water-yield-payment system.

To ensure that wood pellets used in industrial, large-scale energy production contribute to mitigating climate change without unacceptable impacts on biodiversity and ecosystem services, the major wood-pellet-importing EU nations require that forest operations be certified to internationally accepted sustainability standards. Institutional forests commonly meet this requirement, but small SE US family forest owners often lack the resources or incentives to engage in such processes (Morris, 2014). However, most commercial timber harvests in the SE USA are performed following state-defined BMPs (Wear & Greis, 2013), with implementation rates exceeding 90% (National Association of State Foresters, 2015). Mills that export wood pellets require feedstock to originate from sites where the logging is supervised by professionals trained in wildlife habitat conservation, water quality protection, and other BMPs (National Association of State Foresters, 2015). Logger training is a component of the Sustainable Forestry Initiative’s certified Fiber Sourcing Standard, which sets expectations for responsible procurement of all fiber and is audited by an independent third party. Loggers who received training are more likely to implement BMPs during harvesting operations on nonindustrial private forests (Davis & Clatterbuck, 2003).

The value of systematic monitoring and transparency

Publicly available science-based information can bolster public trust and confidence in the effects of forest management changes (e.g., FIA, 2012; Norman *et al.*, 2013; National Association of State Foresters, 2015; Butler *et al.*, 2017) by providing evidence to determine whether bioenergy from SE US wood pellets achieves desired goals. State and federal regulations and BMPs, forest and fiber-sourcing certification programs, nonprofit conservation organizations, land trusts, and logger training programs provide a network of support and accountability for protection of both public and private SE US forest lands. The effectiveness of these safeguards is documented via ongoing collection and analysis of consistent data on actual forest conditions (FIA (Forest Inventory and Analysis), 2012), as required in the USA by the Resources Planning Act Assessment (Butler *et al.*, 2017). The application and effectiveness of BMPs undergo systematic reviews that document costs and benefits (Cristan *et al.*, 2016) as well as provide feedback to guide their continual improvement, which is a core principle of sustainable forest management (Lattimore *et al.*, 2009; Dale *et al.*, 2015b; ASTM 2016). Furthermore, when considering effects of BMPs at a watershed scale, weight-of-evidence approaches that include monitoring of multiple response parameters may be the most useful approach (Ice, 2011).

An indirect benefit of pellet demand is that EU renewable energy and climate policies are driving intensive reviews of current practices that could lead to improvements in forest management across the SE USA. To maximize this potential and mitigate risks, the costs, benefits, socioeconomic implications, and opportunities of wood-based bioenergy should be scientifically quantified on a regional basis to inform decisions regarding tradeoffs among energy options, forest use, and multiple environmental objectives. Continued monitoring of the effects of forest harvest and management and implementation of sustainable management practices are necessary to instill confidence that priority forest ecosystems are conserved, water quality is protected, and BMPs are followed. Furthermore, the net effects of bioenergy systems need to be monitored to verify that they are helping to achieve both near-term emission reduction targets and long-term temperature targets.

Conclusion

Forests produce a range of products: sawlogs, pulp logs, low-value logs, and poles as well as residues. How the forest is managed affects the proportion of each product available, revenues, and environmental effects. Renewable bioenergy should ideally improve the delivery of social, economic and environmental benefits from forestry. Bioenergy markets can assist landowners and society to achieve desired economic, social, and environmental outcomes by supplementing incomes to private landholders and thereby enabling management required to improve forest conditions and protect ecosystem services.

The balance of evidence, some of which is reviewed here, suggests that current levels of wood-pellet production in the SE USA have had a benign effect on forest ecosystem services. Future production has the potential for positive effects when it builds landowner commitment to retain land in forest cover and when wood-pellet production becomes more efficiently integrated into proactive forest management plans. Regulatory and voluntary provisions exist to protect forests. Nonetheless, systematic monitoring and evaluation of managed forests are essential to ensure that intended outcomes are achieved. Knowledge gained from monitoring and rigorous scientific research should be used to inform continual improvement of forest management and should be reflected in decision making in both the USA and the EU.

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References

Abt KL, Abt RC, Galik CS, Skog KE (2014) *Effect of policies on pellet production and forests in the U.S. South: a technical document supporting the Forest Service update of the 2010 RPA Assessment*. Gen. Tech. Rep. SRS-202. U.S. Department of Agriculture Forest Service, Southern Research Station, Asheville, NC 33 p.

Alberici S, Boeve S, van Breevoort P, *et al.* (2014) Subsidies and costs of EU energy. European Commission. Available at: https://ec.europa.eu/energy/en/content/final-report-ecofys (accessed 28 January 2017).

Anderson N, Mitchell D (2016) Forest operations and woody biomass logistics to improve efficiency, value, and sustainability. *Bioenergy Research*, **9**, 518–533.

ASTM (2016) E3066: Standard Practice for assessing the relative sustainability involving energy or chemicals from biomass. ASTM International Committee E-48. Available at: https://www.astm.org/Standards/E3066.htm (accessed 19 January 2017).

Berkowitz JF (2013) Development of restoration trajectory metrics in reforested bottomland hardwood forests applying a rapid assessment approach. *Ecological Indicators*, **34**, 600–606.

Berndes G (2002) Bioenergy and water: the implications of large-scale bioenergy production for water use and supply. *Global Environmental Change*, **12**, 253–271.

Berndes G, Abt B, Asikainen A *et al.* (2016) Forest biomass, carbon neutrality and climate change mitigation. From Science to Policy 3. European Forest Institute, Finland. Available at: http://www.alphagalileo.org/AssetViewer.aspx?AssetId=116589&CultureCode=en (accessed 19 January 2017).

Bonsch M, Humpenöder F, Popp A *et al.* (2017) Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, **8**, 11–24.

Buchholz T, Prisley S, Marland G *et al.* (2014) Uncertainty in projecting GHG emissions from bioenergy. *Nature Climate Change*, **4**, 1045–1047.

Butler SM, Butler BJ, Markowski-Lindsay M (2017) Family forest owner characteristics shaped by life cycle, cohort, and period effects. *Small-Scale Forestry*, **16**, 1–18.

Ciais P, Sabine C, Bala G *et al.* (2013) Carbon and other biogeochemical cycles. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM), pp. 465–570. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Cintas O, Berndes G, Cowie AL, Egnell G, Holmström H, Marland G, Ågren GI (2017) Carbon balances of bioenergy systems using biomass from forests managed with long rotations: bridging the gap between stand and landscape assessments. *Global Change Biology Bioenergy*, doi:10.1111/gcbb.12425.

Cogger BJ, De Jager NR, Thomsen M, Adams CR (2014) Winter browse selection by white-tailed deer and implications for bottomland forest restoration in the Upper Mississippi River Valley, USA. *Natural Areas Journal*, **34**, 44–153.

Cooper RJ, Wood LA, Gannon JJ, Wilson RR (2009) Effects of timber harvest and other factors on a floodplain forest indicator species, the prothonotary warbler. *Wetlands*, **29**, 574–585.

Coppoletta M, Merriam KE, Collins BM (2016) Post-fire vegetation and fuel development influences fire severity patterns in reburns. *Ecological Applications*, **26**, 686–699.

Cornwall W (2017) Is wood a green source of energy? Scientists are divided *Science*, **355**, 18–21.

Costanza J, Abt R, McKerrow AJ, Collazo JA (2016) Bioenergy production and forest landscape change in the southeastern United States. *Global Change Biology Bioenergy*, doi:10.1111/gcbb.12386.

Cowie A, Berndes G, Smith T (2013) On the timing of greenhouse gas mitigation benefits of forest based bioenergy. IEA Bioenergy ExCo: 2013:04. Available at: www.ieabioenergy.com/publications/on-the-timing-of-greenhouse-gas-mitigation-benefits-of-forest-based-bioenergy (accessed 19 January 2017).

Cristan R, Aust WM, Bolding MC, Barrett SM, Munsell JF, Schilling E (2016) Effectiveness of forestry best management practices in the United States: literature review. *Forest Ecology and Management*, **360**, 133–151.

Dale VH, Kline KL, Marland G, Miner RA (2015a) Ecological objectives can be achieved with wood-derived bioenergy. *Frontiers in Ecology and the Environment*, **13**, 297–299.

Dale VH, Efroymson RA, Kline KL, Davitt M (2015b) A framework for selecting indicators of bioenergy sustainability. *Biofuels, Bioproducts & Biorefining*, **9**, 435–446.

Dale VH, Parish ES, Kline KL, Tobin E (In press) How is wood-based pellet production affecting forest conditions in the southeastern United States? *Forest Ecology and Management*.

Davis MB (ed.) (1996) *Eastern Old Growth Forests: Prospects for Discovery and Recovery*. Island Press, Washington, DC.

Davis CT, Clatterbuck WK (2003) Role of the Tennessee Master Logger Program in implementation of best management practices on non-industrial private forests. *Southern Journal of Applied Forestry*, **27**, 36–40.

De Steven D, Faulkner SP, Keeland BD, Baldwin MJ, McCoy JW, Hughes SC (2015) Understory vegetation as an indicator for floodplain forest restoration in the Mississippi River Alluvial Valley, USA. *Restoration Ecology*, **23**, 402–412.

Deal RL, Cochran B, LaRocco G (2012) Bundling of ecosystem services to increase forestland value and enhance sustainable forest management. *Forest Policy and Economics*, **17**, 69–76.

Drax Biomass Inc. (2016) Drax Biomass collaborates to protect Louisiana wetlands. Biomass Magazine. Available at: http://biomassmagazine.com/articles/13825/drax-biomass-collaborates-to-protect-louisiana-wetlands (accessed 19 January 2017).

Dwivedi P, Khanna M, Bailis R, Ghilardi A (2014) Potential greenhouse gas benefits of transatlantic wood pellet trade. *Environmental Research Letters*, **9**, 024007.

Enviva Forest Conservation Funds (2016) Protecting sensitive bottomland forests in North Carolina and Virginia. Available at: http://envivaforestfund.org/ (accessed 16 February 2017).

Eriksson E, Gillespie AR, Gustavsson L, *et al.* (2007) Integrated carbon analysis of forest management practices and wood substitution. *Canadian Journal of Forest Research*, **37**, 671–681.

European Union (2016) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (Text with EEA relevance). Available at: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0028 (accessed 19 January 2017).

Evans AM, Perschel RT, Kittler BA (2013) Overview of forest biomass harvesting guidelines. *Journal of Sustainable Forestry*, **32**, 89–107.

FAOSTAT-Forestry Database (2016) Food and Agriculture Organization of the United Nations Forest Products Statistics, Rome, Italy. Available at: http://www.fao.org/forestry/statistics/84922/en/ (accessed 19 January 2017).

FIA (Forest Inventory and Analysis) (2012) Forest resources of the United States, 2012. A technical document supporting the 2015 update of the RPA assessment. Available at: http://www.srs.fs.usda.gov/pubs/47322 (accessed 19 January 2017).

Fingerman K, Iriarte L, Fritsche UR *et al.* (2016) Biomass Use and Potential for export to the European Union from 2015 to 2030: United States Southeast – Case Study. Intelligent Energy Europe. Available at: http://www.biotrade2020plus.eu/images/IINAS_et_al_2016_WP_3_case_study_report_US_Southeast_FINAL.PDF (accessed 18 January 2017).

Fox TR, Jokela EJ, Allen HL (2007) The development of pine plantation silviculture in the southern United States. *Journal of Forestry*, **105**, 337–347.

Fritts SR, Moorman CE, Hazel DW, Jackson BD (2014) Biomass harvesting guidelines affect downed woody debris retention. *Biomass and Bioenergy*, **70**, 382–391.

Fritts SR, Moorman CE, Grodsky S, Hazel D, Homyack J, Farrell C, Castleberry S (2016) Do biomass harvesting guidelines influence herpetofauna following harvests of logging residues for renewable energy? *Ecological Applications*, **26**, 926–939.

Galik CS, Abt RC (2016) Sustainability guidelines and forest market response: an assessment of European Union pellet demand in the southeastern United States. *Global Change Biology Bioenergy*, **8**, 658–669.

Giuntoli J, Agostini A, Edwards R, Marelli L (2015) *Solid and gaseous bioenergy pathways: input values and GHG emissions*. JRC Report EUR 26696. Luxembourg.

Greene RE, Iglay RB, Evans KO, Miller DA, Wigley TB, Riffell SK (2016) A meta-analysis of biodiversity responses to management of southeastern pine forests -

opportunities for open pine conservation. *Forest Ecology and Management*, **360**, 30–39.

Grodsky SM, Moorman CE, Fritts SR, Castleberry SB, Wigley TB (2016a) Breeding, early-successional bird response to forest harvests for bioenergy. *PLoS One*, **11**, e0165070.

Grodsky SM, Moorman CE, Fritts SR, Hazel DW, Homyack JA, Castleberry SB, Wigley TB (2016b) Winter bird use of harvest residues in clearcuts and the implications of forest bioenergy harvest in the southeastern United States. *Forest Ecology and Management*, **379**, 91–101.

Gustavsson L, Eriksson L, Sathre R (2011) Costs and CO_2 benefits of recovering, refining and transporting logging residues for fossil fuel replacement. *Applied Energy*, **88**, 192–197.

Hanssen SV, Duden AS, Junginger HM *et al.* (2017) Wood pellets, what else? Greenhouse gas parity times of European electricity from wood pellets that are produced in the south-eastern United States using different softwood feedstocks. *Global Change Biology Bioenergy*, (Published online). doi: 10.1111/gcbb.12426.

Hansson J, Martinsson F, Gustavsson M (2015) Greenhouse gas performance of heat and electricity from wood pellet value chains – based on pellets for the Swedish market. *Biofuels, Bioproducts and Biorefining*, **9**, 378–396.

Heath L, Maltby V, Miner R *et al.* (2010) Greenhouse gas and carbon profile of the US forest products industry value chain. *Environmental Science and Technology*, **44**, 3999–4005.

Helin T, Sokka L, Soimakallio S *et al.* (2013) Approaches for inclusion of forest carbon in life cycle assessment – a review. *Global Change Biology Bioenergy*, **5**, 475–486.

Ice GG (2011) Assessing best management practices effectiveness at the watershed scale. *Applied Engineering in Agriculture*, **27**, 925–931.

Ice GG, Schilling EB, Vowell JL (2010) Trends for forestry best management practices implementation. *Journal of Forestry*, **108**, 267–271.

IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Core Writing Team, Pachauri RK, Meyer LA). IPCC, Geneva, Switzerland, 151 pp.

Jackson RB, Jobbagy EG, Avissar R *et al.* (2005) Trading water for carbon with biological carbon sequestration. *Science*, **310**, 1944–1947.

Joly CA, Huntley BJ, Verdade LM, Dale VH, Mace G, Muok B, Ravindranath NH (2015) Chapter 16. In: *Biofuel Impacts on Biodiversity and Ecosystem Services* (eds Souza GM, Joly CA), pp. 555–580. Scientific Committee on Problems of the Environment (SCOPE) Rapid Assessment Process on Bioenergy and Sustainability, Paris, France.

King SL, Twedt DL, Wilson RR (2006) The role of the Wetland Reserve Program in conservation efforts in the Mississippi River Alluvial Valley. *Wildlife Society Bulletin*, **34**, 914–920.

King JS, Ceulemans R, Albaugh JM *et al.* (2013) The challenge of lignocellulosic bioenergy in a water-limited world. *BioScience*, **63**, 102–117.

Körner C (2017) A matter of longevity: tree longevity rather than growth rate controls the carbon capital of forests. *Science*, **355**, 130–131.

Lamers P (2013) Sustainable international bioenergy trade: evaluating the impact of sustainability criteria and policy on past and future bioenergy supply and trade. PhD Dissertation, Utrecht University, ISBN 978-90-8672-058-3.

Lamers P, Junginger M (2013) The 'debt' is in the detail: a synthesis of recent temporal forest carbon analyses on woody biomass for energy. *Biofuels, Bioproducts & Biorefining*, **7**, 373–385.

Lattimore B, Smith CT, Titus BD, Stupak I, Egnell G (2009) Environmental factors in woodfuel production: opportunities, risks, and criteria and indicators for sustainable practices. *Biomass and Bioenergy*, **33**, 1321–1342.

Lindholm EL, Stendahl J, Berg S, Hansson PA (2011) Greenhouse gas balance of harvesting stumps and logging residues for energy in Sweden. *Scandinavian Journal of Forest Research*, **26**, 586–594.

Malmsheimer RW, Fernholz K (2015) How laws, practices, and markets ensure sustainable forest biomass feedstocks from the southeast US. *World Biomass*, **2015**, 8–12.

Malmsheimer RW, Bowyer JL, Fried JS *et al.* (2011) Managing forests because carbon matters: integrating energy, products, and land management policy. *Journal of Forestry*, **109**, S7–S48.

Marland G, Buchholz T, Kowalczyk T (2013) Accounting for carbon dioxide emissions. *Journal of Industrial Ecology*, **17**, 340–342.

Meyer MA, Chand T, Priess JA (2015) Comparing bioenergy production sites in the Southeastern US regarding ecosystem service supply and demand. *PLoS One*, **10**, e0116336.

Miner RA, Abt RC, Bowyer JL *et al.* (2014) Forest carbon accounting considerations in US bioenergy policy. *Journal of Forestry*, **112**, 591–606.

Morris PR (2014) *Non-Industrial Private Forest Landowners' and Agriculture Landowners' Perceptions and Knowledge of Biomass and the Bioenergy Industry in North Carolina and Tennessee*. Master of Science. University of North Carolina, Raleigh, NC. Available at: https://repository.lib.ncsu.edu/bitstream/handle/1840.16/9679/etd.pdf?sequence=2 (accessed 2 April 2017).

Morrison B, Golden JS (2016) Southeastern United States wood pellets as a global energy resource: a cradle-to-gate life cycle assessment derived from empirical data. *International Journal of Sustainable Energy*, (Published online). doi:10.1080/14786451.2016.1188816.

National Association of State Foresters (2015) Protecting water quality through state forestry best management practices. National Association of State Foresters, Washington, DC. Available at: http://www.stateforesters.org/sites/default/files/issues-and-policies-document-attachments/Protecting_Water_Quality_through_State_Forestry_BMPs_FINAL.pdf (accessed 19 January 2017).

Neary DG, Koestner KA (2012) Forest bioenergy feedstock harvesting effects on water supply. *WIREs Energy and Environment*, **1**, 270–284.

Norman SP, Hargrove WW, Spruce JP, Christie WM, Schroeder SW (2013) Highlights of satellite-based forest change recognition and tracking using the ForWarn System. Gen. Tech. Rep. SRS-GTR-180. 30 p. USDA-Forest Service, Southern Research Station, Asheville, NC. Available at: http://www.srs.fs.usda.gov/pubs/44239 (accessed 19 January 2017).

NRCS (National Resources Conservation Service) (2016) NRCS Conservation Programs. US Department of Agriculture, Washington, DC. Available at: https://www.nrcs.usda.gov/Internet/NRCS_RCA/reports/fb08_cp_wrp.html (accessed 19 January 2017).

Olesen AS, Bager SL, Kittler B, Price W, Aguilar F (2016) Environmental Implications of Increased Reliance of the EU on Biomass from the South East US. European Commission Report ENV.B.1/ETU/2014/0043, Luxembourg. 357 p. doi: 10.2779/30897. Available at: http://www.aebiom.org/wp-content/uploads/2016/08/DG-ENVI-study-imports-from-US-Final-report-July-2016.pdf (accessed 19 January 2017).

Oswalt SN, Smith WB, Miles PD, Pugh SA (2014) *Forest Resources of the United States, 2012: a technical document supporting the Forest Service 2015 update of the RPA Assessment*. Gen. Tech. Rep. WO-91. 218 p. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC.

Smyth C, Rampley G, Lemprière TC, Schwab O, Kurz WA (2016) Estimating product and energy substitution benefits in national-scale mitigation analyses for Canada. *Global Change Biology Bioenergy*, (Published online). doi:10.1111/gcbb.12389.

Stewart P (2015) Wood Supply Market Trends in the US South. Forest2Market, Inc. Available at: http://www.theusipa.org/Documents/USSouthWoodSupplyTrends.pdf (accessed 19 January 2017).

Susaeta A, Soto JR, Adams DC, Allen DL (2016) Economic sustainability of payments for water yield in slash pine plantations in Florida. *Water*, **8**, 382–398.

Tarr NM, Rubino MJ, Costanza JK, McKerrow AJ, Collazo JA, Abt RC (2016) Projected gains and losses of wildlife habitat from bioenergy-induced landscape change. *Global Change Biology Bioenergy*, (Published online). doi: 10.1111/gcbb.12383.

Ter-Mikaelian MT, Colombo SJ, Chen JX (2015) The burning question: does forest bioenergy reduce carbon emissions? A review of common misconceptions about forest carbon accounting. *Journal of Forestry*, **113**, 57–68.

UNECE. 2009. Forest product conversion factors: Project overview and status. March 2009 report by the United Nations Economic Commission for Europe (UNECE). Available at: http://www.unece.org/fileadmin/DAM/timber/meetings/forest-products-conversion-factors.pdf (accessed 22 February 2017).

US International Trade Commission (2016) Interactive Tariff and Trade DataWeb. Washington, DC. Available at: https://dataweb.usitc.gov/ (accessed 19 January 2017).

USDA Forest Service (2016) Future of America's Forests and Rangelands: Update to the 2010 Resources Planning Act Assessment. US Forest Service General Technical Report WO-94. Available at: https://www.treesearch.fs.fed.us/pubs/53212 (accessed 31 March 2017).

Varner JM, Gordon DR, Putz E, Hiers JK (2005) Restoring fire to long-unburned *Pinus palustris* ecosystems: Novel fire effects and consequences for long-unburned ecosystems. *Restoration Ecology*, **13**, 536–544.

Wang W, Dwivedi P, Abt R, Khanna M (2015) Carbon savings with transatlantic trade in pellets: accounting for market-driven effects. *Environmental Research Letters*, **10**, 114019.

Wear DN, Greis JG (2013) *The Southern Forest Futures Project: Technical Report*. Gen. Tech. Pre. SRS-178, 533 p. United States Department of Agriculture, Forest Service, Research and Development, Southern Research Station, Asheville, NC.

Wear DN, Huggett R, Ruhong R, Perryman B, Shan S (2013) Forecasts of forest conditions in regions of the United States under future scenarios: a technical document supporting the Forest Service 2012 Resources Planning Act Assessment. Gen. Tech. Rep. SRS-GTR-170. USDA-Forest Service, Southern Research Station, Asheville, NC. 101 p. Available at: http://www.srs.fs.usda.gov/pubs/43055#sthash.IIXY3o4O.dpuf (accessed 19 January 2017).

White A, Martin A (2002) Who owns the world's forests? Forest tenure and public forests in transition Forest Trends, Washington, DC. 30 p.Available at: http://www.cifor.org/publications/pdf_files/reports/tenurereport_whoowns.pdf (accessed 19 January 2017).

Woodall CW, Coulston JW, Domke GM *et al*. (2015) *The U.S. forest carbon accounting framework: stocks and stock change, 1990–2016*. Gen. Tech. Rep. NRS-154. 49 p. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA.

Zhang FM, Chen JM, Pan YD *et al*. (2015) Impacts of inadequate historical disturbance data in the early twentieth century on modeling recent carbon dynamics (1951–2010) in conterminous US forests. *Journal of Geophysical Research-Biogeosciences*, **120**, 549–569.