Spatial Informatics Group

2529 Yolanda Court
Pleasanton, CA 94566
(510) 427-3571
sig-gis.com

Scope of Work:

The Carbon Impacts of UK Electricity Produced by Burning Wood Pellets from Drax's Three U.S. Mills

Project:

UK wood pellet derived electricity: Carbon emission estimates from trees, thinnings and residues sourced in non-industrial private pine plantations in the southeastern US (P Phase 2 (carbon LCA)

Report prepared for:

Southern Environmental Law Center (SELC) and National Wildlife Federation (NWF)

Points of contact:

David Carr, w: 434-977-4090, e: dcarr@selcva.org

Max Broad, w: 202-797-6643, e: broadm@nwf.org

Prepared on behalf of SIG by:

Thomas Buchholz, Ph.D., c: 802 881 5590, e: tbuchholz@sig-gis.com

John Gunn, Ph.D., c: 207 212 7723, e: jgunn@sig-nal.org

Brian Kittler (Pinchot Institute for Conservation), c: 503 473 6501, e: bkittler@pinchot.org

Date:

May 27nd 2019

Spatial Informatics Group

Contents

EXECUTIVE SUMMARY

The Southern Environmental Law Center (SELC) and the National Wildlife Federation (NWF) seek to understand the carbon life cycle assessment (C LCA) from wood pellets produced by Drax Biomass's three U.S.-based pellet mills, which are burnt for electricity production by Drax Power in the UK.

Over the past five years, the wood pellet manufacturing industry in the southeastern U.S. has expanded at a rapid pace. In 2017 alone, the U.S. exported almost 5 million metric tons of wood pellets (Forisk Consulting, 2018), tripling from 1.45 million metric tons in 2012 (EIA, 2014). The largest market for U.S. wood pellets is the UK (approximately 80%; Forisk Consulting, 2018), of which Drax Power, a UK-based utility, is the primary consumer.

Increased pellet demand in the UK (as well as the rest of the EU) is driven by policies aimed at addressing climate change and promoting renewable energy. These policies incentivize burning wood pellets for electricity production by providing subsidies to offset high costs. UK policies and the resulting subsidies, however, are premised on the mistaken belief that burning woody biomass, including wood pellets, is "carbon neutral." This policy is based on a flawed carbon accounting scheme, whereby the carbon emitted from burning the wood pellets (i.e., the stack emissions) is counted as zero no matter from where or how the pellets are sourced. Only CO_2 emissions from harvesting, processing, and transport are considered while changes to the carbon stored in the forest are ignored.

Biomass burning facilities, such as Drax, can therefore receive subsidies aimed at reducing carbon emissions without a full and accurate consideration of the facility's life cycle carbon impacts. Drax has converted four of its large coal units to burn wood pellets with the backing of significant subsidies - £789.2 million in 2018 alone[1]. As a result, Drax has become the largest consumer of wood pellets from the southeastern U.S (EIA, 2015). Although Drax still receives a majority of its U.S.-based wood pellets from third parties, such as Enviva Pellets (Drax, 2017), it has begun manufacturing its own wood pellets in the U.S.

Drax Biomass owns and operates three wood pellet mills across Mississippi and Louisiana, with these pellets destined for shipment to Drax Power in the UK. The impact of these mills on the surrounding forest carbon stocks has been little understood. This report presents carbon LCA results for the most important feedstock category used by Drax's pellet plants in the southeastern US: non-industrial private forest (NIPF) softwood plantations.

Based on previous research by SIG and the Pinchot Institute for Conservation (see Phase 1 of this project), we modeled the carbon dynamics at the point of combustion when electricity is generated, the carbon stored in wood products, as well as impacts to the NIPF carbon stock. To compare the carbon LCA balance between use of pellets versus an alternative electricity scenario, we assumed a change in forest management in NIPF softwood plantations from a no-thinning scenario (i.e., no pellet demand) to a bioenergy scenario where NIPF softwood

[1] See (Drax Group plc, 2019): Combined 2018 revenue from Renewable Obligation Certificate (ROC) sales (£467.7; p.138) and Contracts for Difference (CfD) income (£321.5; p.126).

plantations are managed on a 25-year rotation with one thinning prior to a clearcut final harvest. The main results are:

- Carbon parity, i.e. the time when accumulated carbon emissions for the bioenergy scenario equal the baseline scenario, is more than 40 years for each individual Drax pellet mill and for all three Drax pellet mills combined when compared to either the UK's 2018 electricity grid mix or the UK's targeted electricity grid mix in 2025 (UK Committee on Climate Change, 2015);
- NIPF softwood plantations produce enough biomass to satisfy 100% of wood supply needs for each plant. This implies that active management of current lands can meet demand and makes it unlikely that current demand would result in non-forest lands being converted to plantations; Carbon parity (and per MWh emissions) can be reduced when mixing NIPF softwood plantation derived feedstock with a large share (e.g., >40% of total) of a low-emission feedstock such as sawmill residues. Only the LaSalle pellet plant, which was modeled at 50% sawmill residues to reflect expected future feedstock mix from operation of a co-located sawmill, results in a parity time approaching 40 years when compared to the 2018 UK electricity grid mix;
- Compared to pellets derived from NIPF softwood plantations and burnt in stand-alone electricity generation units, other renewables (solar, wind, etc.) or combined heat and power applications have a fraction of the emissions per MWh.

These carbon parity results are *conservative* estimates, meaning that carbon parity times are likely longer than what is presented by the modeling. This is primarily the result of two conservative assumptions we made in the modeling:

First, we modeled carbon stocks and flows using a higher percentage of sawmill residues (20% for Amite and Morehouse; 50% for LaSalle) than the current feedstock mix (less than 20%) based on research from Phase I of this project. For purposes of this report, we consider "sawmill residues" to only include byproducts of the sawmill process that are of such low quality that they cannot be used for other wood products (see Section 2.3 discussion of alternative fate for sawmill residues).

Second, we did not include the potential share of hardwoods in the current feedstock mix for these three pellet plants. Our Phase I research indicated that although Drax's primary feedstock is softwood, these plants may be utilizing 5-20% hardwood feedstock as well, which tends to prolong carbon parity times.

It is important to understand that this report is limited to the carbon LCA of wood pellets produced at Drax's three U.S.-based pellet plants and burned for electricity in the UK. This report is specific to the harvesting practices and forestry practices of these three plants; it does not represent the carbon LCA for all wood pellets, nor even the carbon LCA for all of the wood pellets Drax Power burns at its UK facility as some of these pellets are the result of clear cut harvesting practices and/or the utilization of much higher percentages of hardwood feedstocks (Buchholz & Gunn, 2015).

RATIONALE

Through a subsidiary known as Drax Biomass, one of UK's largest electric stations, Drax Power, owns and operates three pellet mills across Mississippi and Louisiana. In Louisiana, plants are located in Morehouse and Urania (aka LaSalle). The Mississippi plant is located in Amite. The plants have an annual nameplate capacity of 450,000 (LaSalle) to 525,000 (Amite, Morehouse) metric tonnes (or megagrams; Mg) of wood pellets (Draxbiomass, 2019). Morehouse and Amite were greenfield plants built by Drax. LaSalle was acquired from German Pellets in 2017. Feedstock volume for all three mills is reported to be less than approximately 20% sawmill residuals and 80% tree length logs. LaSalle is expected to derive up to 50% of its feedstock from sawmill residues in the near future; partly supplied by a co-located sawmill. The Southern Environmental Law Center (SELC) and the National Wildlife Federation (NWF) seek to understand the carbon life cycle assessment (C LCA) of pellets produced by Drax's mills and burnt for electricity production by Drax in the UK. To generate a robust carbon LCA, it is important to integrate a solid understanding of the landscape carbon dynamics in the presence and absence of these pellet mills. To date, the impact of these mills on the surrounding forests has not been well understood.

1.1 Phase 1: Forest baseline development

This analysis was conducted in two phases. In Phase 1 (see separate report from October 2018), SIG, in collaboration with the Pinchot Institute for Conservation, focused on improving our understanding of business-as-usual forest management options across the relevant landscapes—i.e. what would have happened in those forests absent pellet mill demand for wood.

Based on the results of Phase 1, SIG recommended the following baseline (absence of Drax) and biomass harvest scenarios:

> *"We recommend to model as a baseline scenario (absence of Drax) a scenario where thinnings are forgone and planting densities remain the same as with pellet demand. No abandonment or land use change would occur, rotation lengths would remain the same. While ownership type does not affect growth and yield modeling, it is interesting that Drax derives most of its feedstock from non-industrial private timberlands.*
>
> *For this scenario comparison, we further recommend to reduce log sizes from 16 (absence of Drax) to 12 ft and a reduction of the top diameter limit from 3 to 1.5 inch (see e.g. Respondent P3 in Louisiana). Due to the lack of high-quality data, we would assume that cull/dead trees would also constitute a small proportion of a thinning operation and ignored in a baseline vs. current practice comparison.*
>
> *We further recommend to run a carbon LCA scenario where the Urania [LaSalle] pellet mill would derive 25%-50% of its feedstock from a newly co-located sawmill. This scenario will provide insights into the carbon implications of using industrial residues vs. forest derived feedstock."*

1.2 Phase 2: Carbon LCA for Drax pellet mills

Here we report on outcomes of Phase 2, which entailed a full carbon LCA for all three Drax pellet mills (Figure 1). Based on the outcomes from Phase 1 (see above), the modeling exercise focused on feedstock derived from non-industrial private forest (NIPF) softwood plantations – the dominant feedstock for the Drax pellet plants in the region.

Since we focus only on NIPF softwood plantations as the forest-derived feedstock plus a fraction derived from sawmill residues (conservatively modeled to be 20% for Amite and Morehouse; 50% for LaSalle based on Phase 1 research), the results translate to a mill-specific carbon footprint for a given unit of produced pellets.

We used the following assumptions derived from Phase 1 to develop the forest growth and yield simulations (see Methods section for detailed silvicultural prescriptions):

- Feedstock demand from pellet mills enables NIPF softwood plantation owners to thin plantations ("bioenergy scenario"). In the absence of the pellet mills, NIPF softwood plantations would go unthinned until the final (clearcut) harvest;
- Non-sawlog biomass from both thinnings and final harvest is shipped to pellet mills;
- All softwood plantations are regenerated at a density of 700 trees per acre;
- No conversion of natural forest to softwood plantation is considered;
- A carbon LCA was developed for each mill based on forest growth and yield models extending from 2019 to 2059 (40 years).

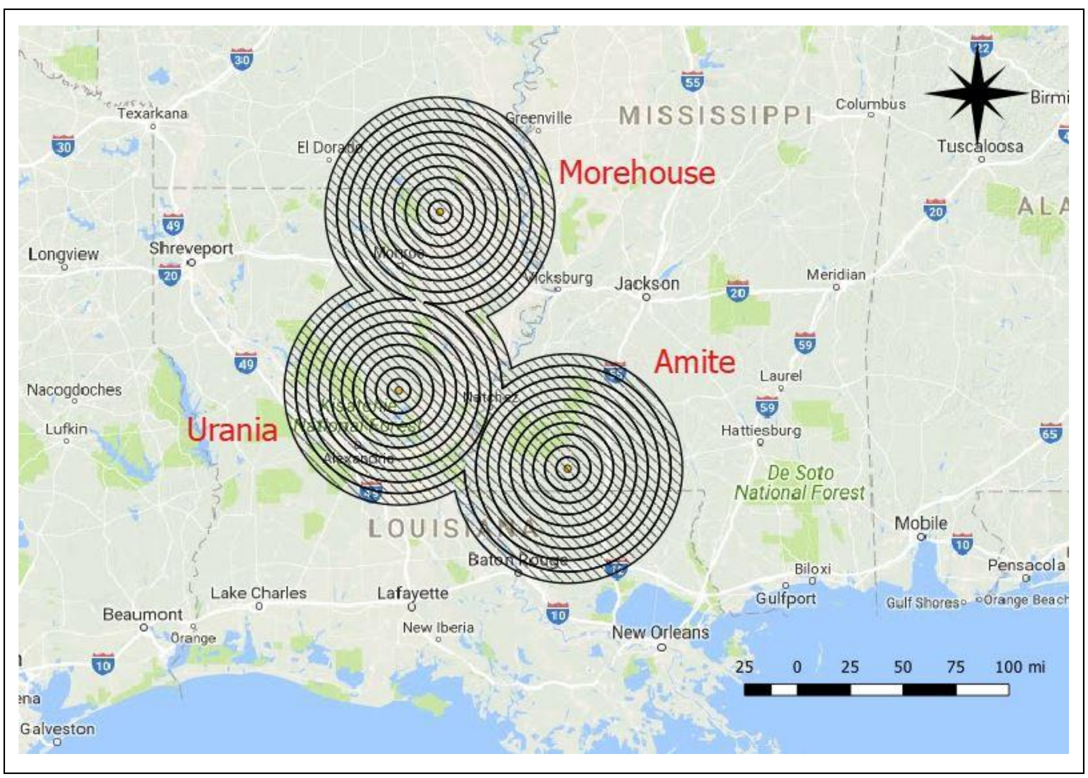

Figure 1: Drax pellet pants in Louisiana and Mississippi with a 50-mile supply radius.

2 RESULTS

2.1 Forest inventory data and biomass potential

NIPF softwood plantations totaled over seven million acres for all three wood supply areas combined and constituted around 50% of the landscape around each pellet plant (Table 1). The 50-mile radius wood supply areas only marginally overlapped.

Our modeled wood supply projections (in the bioenergy scenario, see also section 3 Methods) exceeded total pellet mill demand for each area for any given ten-year period.[2] These projections assume starting with current inventory levels on NIPF softwood plantations managed on a 25-year rotation.

Table 1: Biomass supply and FIA plot coverage for NIPF softwood plantations by wood supply area. One FIA plot represents 6,000 acres (FIA, 2005). Wood supply areas are defined by a 50-mile radius around each pellet plant (Figure 1).

WOOD SUPPLY AREA	NIPF SOFTWOOD PLANTATIONS			AVERAGE ANNUAL BIOMASS AVAILABILITY			
				2018-2027	2028-2037	2037-2047	2048-2057
	# of FIA plots	acres	% of total area	1,000 green tons	1,000 green tons	1,000 green tons	1,000 green tons
Amite	396	2,376,000	47%	1,577	1,706	1,463	1,426
LaSalle	356	2,136,000	42%	1,416	1,553	1,564	1,567
Morehouse	493	2,958,000	59%	2,131	2,419	2,474	2,600
LaSalle/Morehouse overlap	68	408,000					
LaSalle/Amite overlap	3	18,000					
Total	1,174	7,044,000	47%	4,748	5,266	5,089	5,184

[2] Assuming an annual pellet production capacity of 450k Mg for LaSalle and 525k Mg for Amite and Morehouse. The NIPF softwood plantation woodsheds alone, i.e. if this would be the sole source of feedstocks excluding sawmill residues etc., would provide sufficient feedstock covering 107%-195% of annual capacity for each ten-year period.

2.2 C LCA and carbon parity time

When evaluating the carbon footprint of electricity generation options, these options should be compared to a likely scenario of state-of-the-art or near-future generation systems. Such systems include combined heat and power options, wind and solar potentially coupled with electricity storage systems, or a dynamic electricity grid mix representing an increasing share of low-carbon electricity (Macintosh, Keith, & Lindenmayer, 2015). For this reason, we employed both the current UK grid mix (2018) and a forward looking baseline emission profile (0.146 Mg CO_2e/MWh) based on the official UK electricity grid emission target for 2025 (UK Committee on Climate Change, 2015). The 2025 target is a reduction of around 50% from the 2018 UK electricity grid emission profile of 0.283 Mg CO_2e/MWh (UK Gov, 2019).

Using Drax pellet mill specific carbon LCA data (Table 2) and both the 2018 UK grid mix and a 2025 UK grid emission profile for electricity generation[2] as baseline for electricity production (Table 3), the carbon parity time (i.e., when accumulated carbon emissions for the bioenergy scenario equal the baseline scenario) for all three wood supply areas combined and individually was not reached within the 40 year time horizon analyzed. Based on the forest carbon stock loss, the bioenergy scenario is unlikely to reach carbon parity until far beyond 2060.

Following an initial decline due to the increased harvest (thinning) activity in the bioenergy scenario, forest carbon stocks for all three supply areas combined eventually stabilized but were still below a no thinning scenario within the 40-year period analyzed. Total accumulated carbon balance[3], i.e. the changes from the baseline to the bioenergy scenario, were dominated by forest carbon stock change (Figure 2). A high initial GHG emission profile per MWh electricity produced in the first years occurs because increased harvest activities reduce forest carbon stocks below the baseline scenario (Figure 3). Only the LaSalle pellet mill, when modeled at 50% sawmill residues to reflect the expected future feedstock mix, gets close to carbon parity by year 40 when compared to the 2018 UK electricity grid mix (Figure 2a and Figure 3a). Using a higher share of renewable electricity sources such as wind or PV solar with a much lower emission profile than the targeted UK 2025 electricity grid's mix (see Table 3) would further extend the carbon parity time beyond the modeled time horizon.

From a biomass supply perspective, we consider these parity time calculations as conservative. Longer parity times are likely for two main reasons: 1) we considered a high share of sawmill residues in the current feedstock mix (data suggests that current consumption of sawmill residues is less than the 20% used in this analysis) and 2) we did not include a potential share of hardwoods in the feedstock origin which tends to prolong parity times (Buchholz & Gunn, 2015).

---

[3] Total accumulated carbon balance covers forest carbon (including forgone sequestration due to increased harvest activities), wood product stocks (carbon stored in region-specific long-lived forest products), as well as avoided electricity generation emissions from fossil fuels for electricity generation.

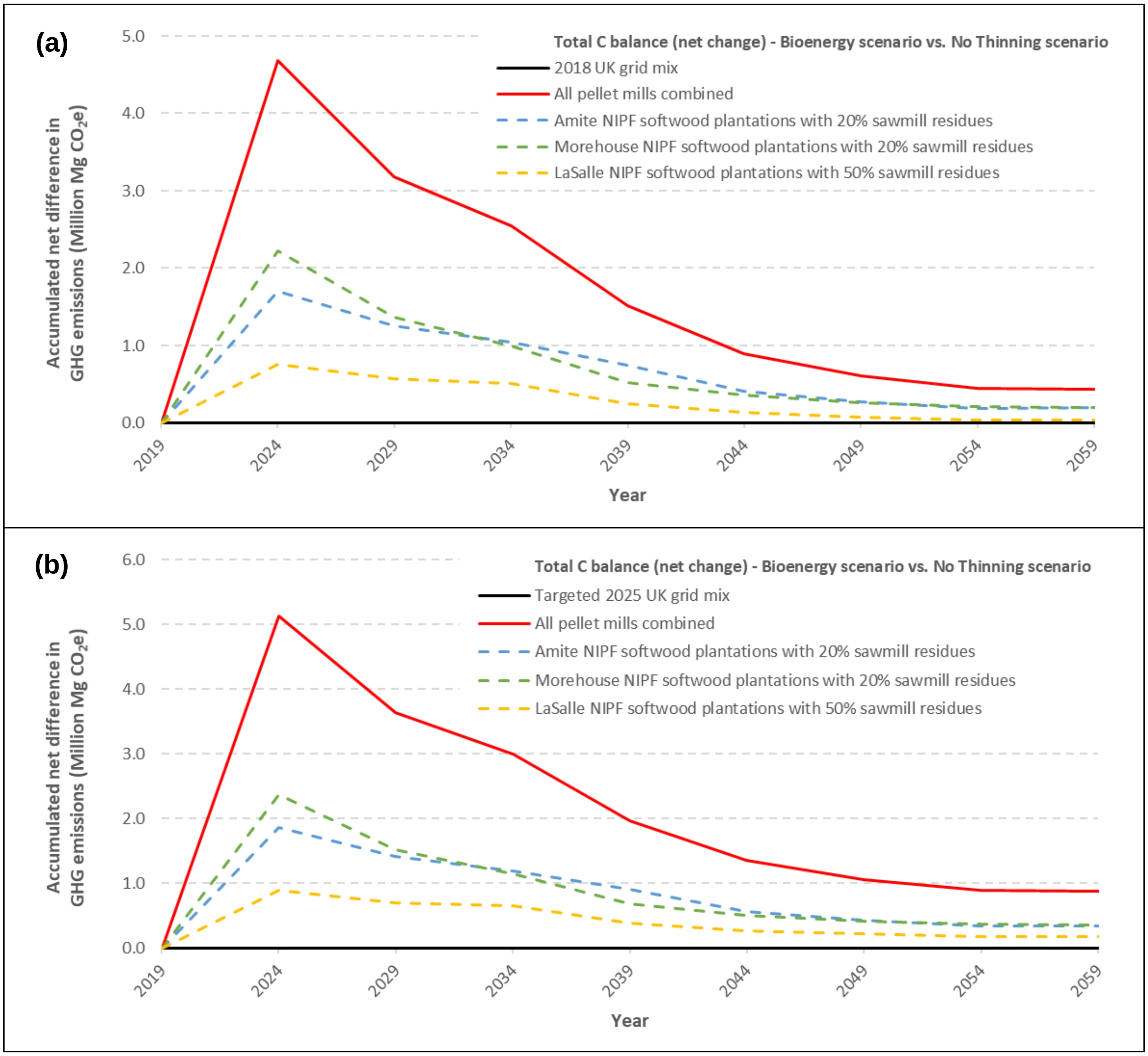

Figure 2: **Forest carbon and carbon LCA performance of bioenergy scenario compared to a baseline scenario using (a) the 2018 grid mix and (b) targeted 2025 UK grid emission profile.** This graph plots the net difference between bioenergy scenarios and the no thinning baseline scenario. While the no thinning baseline is associated with net emissions, its emissions are shown as net zero on this graph for ease of display and comparison. Trajectories of net difference in accumulated total carbon balance over time (including forest and wood products carbon stock as well as avoided fossil fuel electricity generation emissions) are shown in red for all three NIPF softwood plantation wood supply areas combined (Amite, LaSalle, Morehouse), and in the dotted lines for individual mills. These trajectories are compared to a no thinning baseline scenario (in black) that assumes (a) the 2018 UK grid emission profile, and (b) a targeted 2025 UK grid emission profile. The carbon parity time is defined by the point in time when the total accumulated carbon balance of the bioenergy scenario first equals the total accumulated carbon balance of the no-thinning scenario, i.e. the lines intersect. None of the bioenergy trajectories drop below either one of the baselines since the parity time is >40 years for each mill and all mills combined.

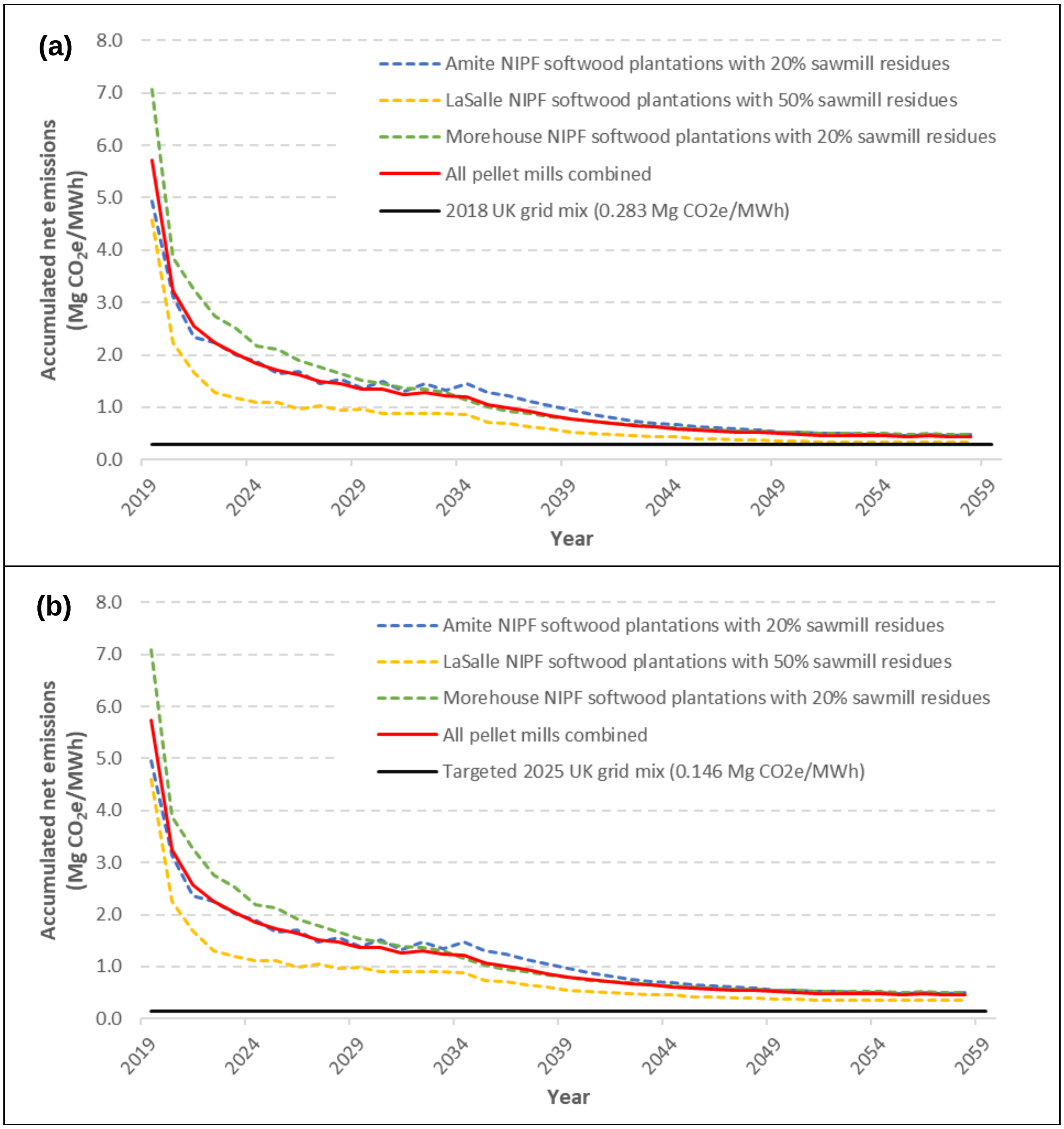

Figure 3: **Accumulated net GHG emissions per MWh of electricity produced in the UK with pellets from Drax's mills in the southeastern U.S compared to a baseline scenario using (a) the 2018 grid mix and (b) the targeted 2025 UK grid emission profile**. Biomass sources include a plant specific mix of biomass from thinnings of NIPF softwood plantations and sawmill residues vs. a no-thinning scenario. This figure shows the accumulated net GHG emissions per MWh from pellet-generated electricity in the UK for all three of Drax's mills combined and individually. Over time, GHG emissions per MWh from pellet-generated electricity decrease but do not reach GHG emissions from the (a) 2018, or (b) targeted 2025 UK grid mix over the 40-year time period analyzed — i.e., carbon parity is not reached within 40 years under either baseline scenario. An initial steep drop in accumulated net GHG emissions per MWh over the first five years occurs because the initial increase in harvest activities decreases forest carbon stocks below the baseline scenario. This steep drop is followed by a gradual recovery as forest carbon stocks stabilize at a lower level than the baseline scenario, and the recovery is accompanied by a yearly increase in the cumulative MWh of electricity produced from wood pellets. Biomass electricity emissions reach approximately 0.468 Mg CO_2e/MWh by the end of the 40-year timeline.

Table 2: Key carbon LCA parameter for pellets produced at Drax mills in the southeastern US and consumed at Drax electricity plants in the UK.

PARAMETER	UNIT	INPUT VALUE	SOURCE
C conversions			
Loblolly specific gravity	Mg/m^3	0.48	Miles, 2009
Carbon fraction softwood	% of dry weight	0.48	Aalde et al., 2006; Table 4.3
Global warming potential (GWP) inputs			
Pellet prod. & logistics (forest-derived)	Mg CO_2e/Mwh	0.122	Drax, 2015
Pellet prod. & logistics (sawmill residues)	Mg CO_2e/Mwh	0.050	DECC, 2005
Pellet Net Calorific Value (LHV)	MWh/Mg	4.9	DECC, 2005
Pellet plant efficiency (LHV)	%	38.6%	European Commission, 2016
Pellet production efficiency	Mg pellets/Mg wood	87.0%	Hanssen, Duden, Junginger, Dale, & Hilst, 2017; Table S1

Table 3: Selected electricity (grid) emission profiles with relevance to the UK.

PARAMETER	UNIT	INPUT VALUE	SOURCE
Pellet prod. & logistics (forest-derived)	Mg CO_2e/Mwh	0.122	Drax, 2015
Pellet prod. & logistics (sawmill residues)	Mg CO_2e/Mwh	0.050	DECC, 2005
UK grid mix 2025 target	Mg CO_2e/Mwh	0.146	CCC, 2015[a]
UK grid mix 2018	Mg CO_2e/Mwh	0.283	UK Gov, 2019
UK grid mix 2018 (fossil fuels only)[b]	Mg CO_2e/Mwh	0.450	Vanlint, 2018
UK coal	Mg CO_2e/Mwh	0.870	Vanlint, 2018
Natural Gas	Mg CO_2e/Mwh	0.360	Vanlint, 2018
PV	Mg CO_2e/Mwh	0.048 (0.0045)[b]	Bruckner, Bashmakov, & Mulugetta, 2014 (Pehl et al., 2017)
Wind	Mg CO_2e/Mwh	0.011 (0.0051)[c]	Bruckner, Bashmakov, & Mulugetta, 2014 (Pehl et al., 2017)

[a]) Figure 2.11; see data also at https://www.theccc.org.uk/wp-content/uploads/2015/11/Chapter-2-Power-Exhibits.xlsx

[b)] The fossil fuel only section of the 2018 UK grid mix excludes renewables and nuclear and was dominated by natural gas (>75%) followed by coal (OFGEM, 2019)

[c)] Projections for systems built in 2050

2.3 Important caveats

Besides the two limitations mentioned in section 2.2 (sawmill residue share in feedstock mix; only softwoods considered), the following additional important caveats need to be considered for this analysis:

- Forest management scenarios. We simulated one generalized forest management scenario for NIPF softwood plantations based on literature and survey results (see Phase 1 report, October 2018). However, NIPF owners would likely vary somewhat from the exact prescription used in the models. Since the median stand age of all FIA plots considered in this analysis was 25 years, this indicates that a considerable fraction of stands is not managed on a 25-year rotation.
- Methane emissions from wood chip piles. There is some concern about potential methane emissions from wood chip piles generated while the organic material begins decomposing under compost conditions. However, methane emissions from wood chip piles prior to pellet processing are not considered in this analysis due to a lack of empirical data on the issue. Of the few field-based studies on the topic, Ferrero, Malow, & Noll (2011) did not find any methane emissions during actual measurements on pine wood chip piles in Germany over 150 days. In another Finnish study using measurements from (non-wood) compost piles, Wihersaari (2005) derives a methane emission rate of 24 g/m3/day for wood chip piles. Assuming a 60-day storage period before conversion to pellets, this assumption would result in an additional 0.103 Mg CO_2e/MWh for pellet electricity[4]; adding over 20% to total bioenergy emissions of 0.468 CO_2e/MWh over a 40 year time horizon (see Figure 3). These contradicting results among a paucity of studies prevents us from considering this factor in this analysis.
- Alternative fate for sawmill residues. The alternative fate for sawmill residues in this analysis (if not used for pellet production) was considered to be immediate carbon release (i.e., within one year) following harvest. While a large fraction of sawmill residues are frequently used to satisfy on-site process-heat demand (e.g., drying of wood), the remaining fraction of sawmill residues typically has little to no market value for short-lived products such as animal bedding or landscaping products. Even when used for these products, emissions could be considered immediate. Sawmill residues used in pellet production do not fulfill quality thresholds for longer-lived products (e.g., particle boards). For some sawmills, the total output is i) too small to justify a processing line for longer lived products, or ii) is too remote to ship residues of appropriate quality to processing facilities at a competitive price.
- Forest health. Several survey respondents (see Phase 1 report, October 2018) mentioned the increased risk of insect infestations if pine plantations go unthinned. Softwood stands, particularly loblolly pine, are susceptible to the southern pine beetle. Louisiana, Mississippi and Arkansas are all considered a high-risk zone for southern pine beetle outbreaks (see Figure 4). Susceptibility is largely driven by hydrological stress caused primarily by high tree

[4] Assuming 2.3 m3 chips per solid m3 wood, a GWP of 28 for methane, 18 GJ/m3 energy content for wood, and an electric conversion efficiency of 36%

densities and weather. Thinning, prescribed burning, and reduction in planting densities are recommended strategies to reduce the risk of large-scale (carbon) loss due to southern pine beetle infestations (Birt, 2011; Nowak, Meeker, Coyle, Steiner, & Brownie, 2015; USDA FS, 2005). While these strategies will result in a near-term carbon stock reduction, potential future avoided carbon stock losses from SBP outbreaks have to be discounted by the site-specific outbreak risk. There is potential for biomass energy derived from restoration thinning activities to have a better carbon LCA profile, but that will depend on the likelihood and severity of SPB outbreaks which are difficult to predict on a site specific basis. (Liang, Hurteau, & Westerling, 2018). Deriving feedstock from newly established biomass plantations can also improve the carbon LCA profile (González-García, Mola-Yudego, & Murphy, 2013).

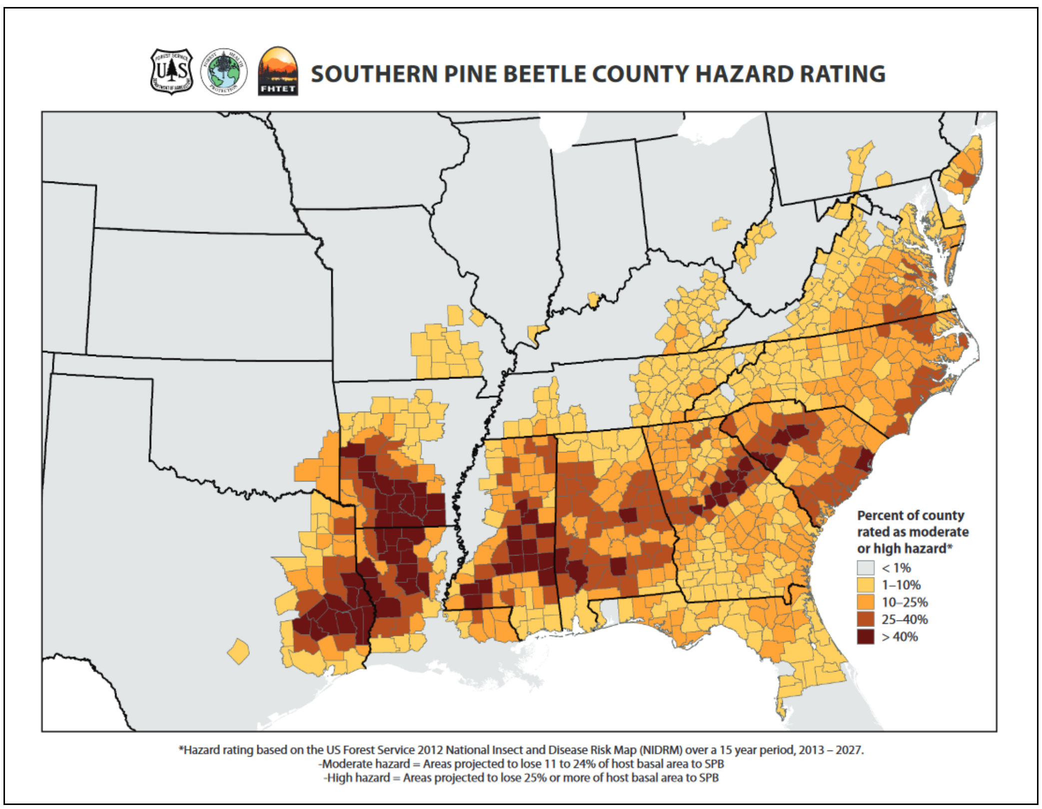

Figure 4: Southern pine beetle county hazard rating (USDA FS, 2005).

3 METHODS

3.1 Forest inventory data

We assumed a 50-mile radius supply distance for each Drax pellet mill. USDA Forest Service Forest Inventory Assessment (FIA) data for Arkansas, Louisiana and Mississippi were downloaded from FIA DataMart (FIA, 2018). The data were downloaded in the Postgresql format following the procedure described by FIA. We used BioSum (Potts, Bross, Loreno, Mozelewski, & Fried, 2018) to transform FIA data into a format readable by the USDA Forest Service Forest Vegetation Simulator Southern Variant (FVS-SN). In order for us to be able to create FVS ready files in Microsoft Access Database using BioSum, we had to carry out following intermediate steps:

- Create a Postgresql database using the procedure described in FIA's instructions;
- Create a SYSTEM DSN on a local machine after downloading an Open Database Connectivity (ODBC) driver. The DSN was created such that correct database was referenced to Postgresql server;
- Create an empty access database;
- Use import via ODBC after selecting the SYSTEM DSN created earlier and select tables from within the wizard.

FIA plots matching the following criteria were included:

- Softwood plantations;
- Owned by non-industrial private land-owners;
- Within the states of Arkansas, Louisiana and Mississippi;
- Stands inventoried between 2007 to 2017[5].

3.2 Forest growth and yield modeling

Simulation Software

We employed FVS Suppose v2.07 with the FVS-SN variant. Plots were treated as stands and all stands were adjusted to represent a basal area factor of 1 using Biosum. If one FIA plot represented more than one condition, then multiple stands were created representing single conditions based on the proportional representation of such conditions. We used BIOSUM Version 5.8.4 to create stands.

[5] FIA inventories stands on a continuous basis over a ten-year timeline in the target region. Hence, a ten-year bracket has to be employed to capture all relevant inventory plots.

Prescriptions and Simulations

The simulation was run for 40 years starting in 2019. The time interval of a cycle was set at two years. Simulation began at the year of inventory as identified from FIA data. The year of inventory ranged from 2007 to 2018 in the original plots.

100% of the unmerchantable wood (tops and limbs) were assumed to be left on the forest floor. For forest regeneration, the 'Plant' keyword was used. Automatic regeneration was disabled by using the 'NoSprout' keyword and tripling (sometimes used to stabilize random effects for small tree records) was disabled as well. Significance level for computing the confidence limits were set at 0.05.

Two forest management scenarios were modeled: The 'No thinning scenario' simulates practices in the absence of pellet mills where thinnings would be forgone due to an absence of markets for the generated biomass. The 'bioenergy scenario' assumes that the thinnings are implemented since the pellet feedstock market generates enough revenue to implement the thinnings. Planting density and rotation length were kept the same for both scenarios.

We looked at the age variable in the FIA data to determine first harvest operations. Final harvest occurred when the stand age was 25 years (or if stand age exceeded 25 years of age at the beginning of the simulation period). If the stand was already at least 25 years old in the first year of simulation, it was harvested in the same year. For final harvest, clearcutting was assumed followed by planting at a density of 700 trees per acre uniformly. Planting species was loblolly pine.[6] Thinning operations assumed thinning from below[7] across the entire diameter at breast height (DBH) range (i.e. from > 0 inch DBH). Thinnings occurred at the beginning of the cycle and planting occurs at the end of the cycle in the FVS.

We used the FFE (Fire and Fuel Extension of FVS) method for biomass prediction within the FVS. Annual root decay rate (proportion per year) was set at 0.0425 (FVS default). The DBH breakpoint between pulpwood and non-pulpwood roundwood (chip-and-saw and sawtimber) for softwood was set at 9" (FVS default for the applicable variant).

We used the inventory year as starting point for simulation, i.e. we started the simulation in 2008 if stand was inventoried in 2008 (i.e., cycle one starts at inventory year where we know the age). In our simulation, we did not grow the stands to any common start year, neither did we alter the stand inventory year. With this approach harvesting/thinning can happen in any cycle. The overall simulation length for one rotation was 25 years. The length of a cycle was kept at one year.

We used stand age as a predicate to trigger a forest harvest operation. If the age was >=25 years, we initiated a clearcut followed by planting. Once the stand was clearcut, then the same stand was replanted and would be eligible for thinning after 15 years in our simulation. If the stand age was between 15 and 20, we triggered a thinning of a stand down to a residual basal

---

[6] Over 85% of all plots in non-industrial softwood plantations for the target region were Loblolly pine stands.

[7] Thinning from below: A removal preference to small-diameter trees is given during the thinning process.

area of 70 ft^2/acre (resulting in a removal of around one third to one half of all trees) using a thin-from-below strategy if thinning was part of the scenario (i.e., bioenergy scenario).

3.3 Pellet mill specific carbon LCA

The carbon LCA accounting framework developed by SIG during the BERC 2012 study (Colnes et al., 2012) and further downscaled for the NRDC project (2015) project served as the basic accounting framework[8]. We tailored outcomes for pellet production at Drax mills in Louisiana and Mississippi, eventually generating electricity at the Drax power station in the UK (Table 2).

While FVS can provide a full carbon LCA including in-use and post-use wood product (WP) carbon pools based on regional forest product data from Smith, Heath, Skog, & Birdsey (2006), this analysis required a customized WP carbon LCA since an alternative use of pulp-grade biomass as bioenergy feedstock is not considered in Smith, Heath, Skog, & Birdsey (2006). We used the same source for forest industry products data and disposition of carbon in industrial roundwood data relevant for the southeast and substituted forest-derived pulp-grade WP pool residence times with the assumption of immediate (i.e. burned for electricity generation within one year) carbon release following harvest.

[8] While it pertains to the scenarios and growth and yield modeling rather than the carbon LCA accounting, it should be noted that the Colnes et al. 2012 assumption that the demand for more residuals would result in more sawtimber harvest was not part of the analysis presented here.

REFERENCES

Aalde, H., Gonzalez, P., Gytarsky, M., Krug, T., Kurz, W. A., Ogle, S., … Ravindranath, N. H. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Chapter 4 - Forest land* (p. 83). Retrieved from International Panel on Climate Change (IPCC) website: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_04_Ch4_Forest_Land.pdf

Birt, A. (2011). *Population Dynamics of Southern Pine Beetle in Forest Landscapes* (pp. 91–108). Retrieved from Texas A&M University website: http://www.fs.usda.gov/treesearch/pubs/39023

Bruckner, T., Bashmakov, I. A., & Mulugetta, Y. (2014). Chapter 7 - Energy Systems. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (p. 88). Cambridge ; New York: Cambridge University Press.

Buchholz, T., & Gunn, J. (2015). *Carbon Emission Estimates for Drax biomass powerplants in the UK sourcing from Enviva Pellet Mills in U.S. Southeastern Hardwoods using the BEAC model* (p. 17). Retrieved from Spatial Informatics Group LLC (SIG) website: https://www.southernenvironment.org/uploads/words_docs/Wood_Pellets_Report.pdf?cachebuster:66

Colnes, A., Doshi, K., Emick, H., Evans, A., Perschel, R. T., Robards, T. A., & et al. (2012). *Biomass Supply and Carbon Accounting for Southeastern Forests*. Biomass Energy Resource Center (BERC), Montpelier, VT, USA.

DECC. (2015). *BEAC (Biomass Emissions And Counterfactual) Model Version BEAC2015*. Retrieved from Department of Energy & Climate Change (DECC) website: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/394758/beac_2015.xlsm

Drax. (2015). *Biomass Supply* (p. 8). North Yorkshire, UK: Drax Group plc.

Drax. (2017). Keeping the options open. Retrieved from Keeping the options open website: https://www.drax.com/sustainability/keeping-options-open/

Drax Group plc. (2019). *Annual report and accounts 2018* (p. 196). North Yorkshire, UK: Drax Group plc.

Draxbiomass. (2019). Where we operate. Retrieved April 4, 2019, from Where we operate website: https://www.draxbiomass.com/#where-we-operate

EIA. (2014). U.S. wood pellet exports double in 2013 in response to growing European demand. Retrieved from U.S. wood pellet exports double in 2013 in response to growing European demand website: https://www.eia.gov/todayinenergy/detail.php?id=16391

EIA. (2015). UK's renewable energy targets drive increases in U.S. wood pellet exports. Retrieved from UK's renewable energy targets drive increases in U.S. wood pellet exports website: https://www.eia.gov/todayinenergy/detail.php?id=20912

European Commission. (2016). *State Aid SA.38760 (2016/C) (ex 2015/N) – United Kingdom Investment Contract for Biomass Conversion of the first unit of the Drax power plant* (p. 16). Retrieved from European Commission (EC) website: State Aid SA.38760 (2016/C) (ex 2015/N) – United Kingdom Investment Contract for Biomass https://publications.europa.eu/en/publication-detail/-/publication/3098ec96-cbdc-11e5-a4b5-01aa75ed71a1/language-en

Ferrero, F., Malow, M., & Noll, M. (2011). Temperature and gas evolution during large scale outside storage of wood chips. *European Journal of Wood and Wood Products*, *69*(4), 587–595. https://doi.org/10.1007/s00107-010-0512-0

FIA. (2005). *Forest Inventory and Analysis Sampling and Plot Design* (p. 3). Retrieved from USDA Forest Service website: https://www.fia.fs.fed.us/library/fact-sheets/data-collections/Sampling%20and%20Plot%20Design.pdf

FIA. (2018). FIA DataMart. Retrieved April 4, 2019, from FIA DataMart website: https://apps.fs.usda.gov/fia/datamart/datamart.html

Forisk Consulting. (2018). Wood Bioenergy Update: Q1 2018. Retrieved from Wood Bioenergy Update: Q1 2018 website: https://forisk.com/blog/2018/02/05/wood-bioenergy-update-q1-2018/

González-García, S., Mola-Yudego, B., & Murphy, R. J. (2013). Life cycle assessment of potential energy uses for short rotation willow biomass in Sweden. *The International Journal of Life Cycle Assessment*, *18*(4), 783–795. https://doi.org/10.1007/s11367-012-0536-2

Hanssen, S. V., Duden, A. S., Junginger, M., Dale, V. H., & Hilst, F. van der. (2017). Wood pellets, what else? Greenhouse gas parity times of European electricity from wood pellets produced in the south-eastern United States using different softwood feedstocks. *GCB Bioenergy*, *9*(9), 1406–1422. https://doi.org/10.1111/gcbb.12426

Liang, S., Hurteau, M. D., & Westerling, A. L. (2018). Large-scale restoration increases carbon stability under projected climate and wildfire regimes. *Frontiers in Ecology and the Environment*, *16*(4), 207–212. https://doi.org/10.1002/fee.1791

Macintosh, A., Keith, H., & Lindenmayer, D. (2015). Rethinking forest carbon assessments to account for policy institutions. *Nature Climate Change*, *5*(10), 946–949. https://doi.org/10.1038/nclimate2695

Miles, P. D. (2009). *Specific gravity and other properties of wood and bark for 156 tree species found in North America* (No. NRS-38; pp. 1–35). Retrieved from USDA Forest Service website: http://www.fs.usda.gov/treesearch/pubs/34185

Nowak, J. T., Meeker, J. R., Coyle, D. R., Steiner, C. A., & Brownie, C. (2015). Southern Pine Beetle Infestations in Relation to Forest Stand Conditions, Previous Thinning, and Prescribed Burning: Evaluation of the Southern Pine Beetle Prevention Program. *Journal of Forestry*, *113*(5), 454–462. https://doi.org/10.5849/jof.15-002

NRDC. (2015). *Think Wood Pellets are Green? Think Again.* (NRDC Issue Brief No. IB: 15-05-A; p. 5). Retrieved from Natural Resource Defence Council (NRDC) website: https://www.nrdc.org/sites/default/files/bioenergy-modelling-IB.pdf

Pehl, M., Arvesen, A., Humpenöder, F., Popp, A., Hertwich, E. G., & Luderer, G. (2017). Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nature Energy*, *2*(12), 939–945. https://doi.org/10.1038/s41560-017-0032-9

Potts, L. D., Bross, L., Loreno, S., Mozelewski, T., & Fried, J. S. (2018). *Biosum User Guide: Chapter 4 - FVS Module* (p. 31). Retrieved from USDA Forest Service website: http://biosum.info/biosum/user%20guide/BUG_Ch4_FVS_20170810.pdf

Smith, J. E., Heath, L. S., Skog, K. E., & Birdsey, R. A. (2006). *Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States*. Retrieved from http://www.treesearch.fs.fed.us/pubs/22954

Spatial Informatics Group

UK Committee on Climate Change. (2015). *The Fifth Carbon Budget - The next step towards a low-carbon economy* (p. 130). London, UK: Committee on Climate Change (CCC).

UK Gov. (2019). *Greenhouse gas reporting: conversion factors 2018*. Retrieved from UK government website: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/715425/Conversion_Factors_2018_-_Condensed_set__for_most_users__v01-01.xls

USDA FS. (2005). Southern Pine Beetle Prevention and Restoration Program. Retrieved April 4, 2019, from Southern Pine Beetle Prevention and Restoration Program website: http://southernforesthealth.net/insects/southern-pine-beetle/southern-pine-beetle-prevention-and-restoration-program

Vanlint, K. (2018). *2017 UK Greenhouse gas emissions, provisional figures* (p. 24). Retrieved from UK Department for Business, Energy & Industrial Strategy website: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/695930/2017_Provisional_Emissions_statistics_2.pdf

Wihersaari, M. (2005). Evaluation of greenhouse gas emission risks from storage of wood residue. *Biomass and Bioenergy*, *28*(5), 444–453. https://doi.org/10.1016/j.biombioe.2004.11.011