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# DOES BIOENERGY DEMAND IMPROVE FOREST MANAGEMENT?

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# EXECUTIVE SUMMARY

Policies in the European Union, the United States, and Canada support the use of forest biomass in heating, power generation, and transportation as a climate mitigation strategy. This support continues despite evidence from several scientific studies that forest bioenergy does not generally reduce lifecycle greenhouse gas (GHG) emissions when compared with fossil fuels. Forest bioenergy has even sometimes been erroneously considered carbon neutral. This flawed perception results from a misunderstanding of life-cycle assessment studies that ignored biogenic $CO_2$ emissions and did not consider the counterfactual use of land or biomass in a no-bioenergy scenario. Analyses comparing biomass harvest against a no-bioenergy scenario show that a decrease in forest carbon stock from increased removal of wood for energy is balanced over time by the GHG savings that derive from replacing fossil fuels. Until that point is reached, however, the bioenergy system will release more $CO_2$ than the fossil system. This is known as the carbon payback time. The length of the payback time depends on many factors, including the type of woody feedstock and assumptions on alternative land use.

The bulk of the scientific literature indicates that using wood for bioenergy increases GHG emissions compared with fossil fuels over a period of decades (Agostini, Giuntoli, & Boulamanti, 2014; European Commission, 2016). A smaller number of studies find the opposite, that forest bioenergy delivers substantial GHG savings over a reasonable timeframe of 20–30 years. In a literature review, though, we found that the latter studies generated this result by assuming that bioenergy demand would spur substantial changes in the forest sector. Such changes would include increased wood growth and productivity through intensive management and planting of forests that would reduce the carbon debt, an umbrella concept we use to indicate time necessary to offset the initial emissions from forest clearance.

In this study, we investigate whether there is evidence that bioenergy demand is likely to cause these improvements. We use statistical analysis to test for linkages between the recent ramp-up in bioenergy production and prices, and changes in forest management, residues harvest, and forest area. We focus our analysis on Canada, Sweden, and the United States. These three countries have large forestry sectors and have substantially increased their forest bioenergy production. The bioenergy literature shows they have also been extensively studied.

We examine available evidence of changes in the removal of logging residues, such as small branches and treetops; stand management, including site preparation, thinning, and fertilization; forest species composition; and total forest area in the three countries. In addition, we study the use of salvage logs from an extensive mountain pine beetle infestation in Canada, which is not applicable in the two other countries. Our findings are summarized in Table ES 1. Note that the strength of the evidence varies. For example, there is weak evidence that bioenergy demand has resulted in the increased harvest of logging residues in Sweden and Canada, but there is no such evidence in the United States. In some cases, our analysis was limited by data availability.

**Table ES1.** Strength of historical evidence that bioenergy demand has driven forest management changes that can reduce bioenergy carbon debt by region.

| Forest management change | | Canada | Sweden | U.S. |
|---|---|---|---|---|
| **Increased residue removal** | Logging residues | Weak | Weak | None |
| | Salvage logs from infestation | Strong | Not applicable | Not applicable |
| **More intensive stand management** | Site preparation | None | Moderate | Strong |
| | Thinning | None | Strong | Strong |
| | Fertilization | None | Weak | Strong |
| **Change to higher yielding species** | | None | Weak | Moderate |
| **Afforestation / avoided deforestation** | | None | None | None |

From this analysis, we draw the following conclusions:

- **Available evidence doesn't support assumptions that bioenergy demand will improve forest management and encourage new planting.** We find no evidence that the rise in bioenergy demand over the past one to two decades has increased forest area in any of the three countries studied. For other improvements to forest management, we find some evidence of a link to bioenergy demand but not in all three countries.
- **Where there is evidence of a forest management response to bioenergy demand, it is weaker than assumed in the literature.** In the United States, for example, there is strong evidence that bioenergy demand has led to a 12% increase in pine plantation productivity, most likely through more intensive stand management (Table ES 1). However, that is far less than the doubling of yields assumed in some studies.
- **Policymakers should not assume that forest bioenergy will significantly mitigate climate change.** Historical evidence does not support estimates of short carbon payback times for forest bioenergy. Our results suggest that long carbon payback times and poor climate performance are more realistic. Policies promoting energy from existing forests are unlikely to achieve climate mitigation in the near or medium term. Ancillary policy tools to promote improved forest productivity and sustainable forest management are needed to achieve any mitigation in the medium and long term.
- **Forest bioenergy policy should support only additional biomass.** There are two circumstances under which forest bioenergy would deliver meaningful climate benefits: (1) when tops, branches, small wood from thinning, and salvage wood are harvested sustainably, and (2) when biomass is grown on land with low-carbon stocks that would otherwise remain unused. These pathways should be explicit requirements for forest bioenergy policies to ensure climate benefits. We find that bioenergy using only trunks and limbs from existing forests is not likely to be an effective climate mitigation strategy.

It is possible for forest bioenergy to be part of effective climate policy, but only with very strong sustainability guardrails to ensure that climate and other environmental benefits are achieved. Policy support for sustainable bioenergy should be provided in the context of a broader climate strategy, including incentives for a broad range of low-carbon energy solutions such as wind and solar power, electric vehicles, advanced alternative fuels produced from wastes, and expanding and safeguarding natural carbon sinks.

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# INTRODUCTION

Policies in the European Union and the United States promote the use of forest biomass for energy production as a climate change mitigation strategy.

The EU Renewable Energy Directive sets a target of 20% renewable energy use in 2020 as well as a 10% renewable energy target in transport (European Parliament & Council of the European Union, 2009). This directive has recently been extended to 2030, with an updated target of 32% renewable energy use and a 14% sub-target for renewable energy in transport in 2030 (European Parliament & Council of the European Union, 2018). In addition, there is a 3.6% sub-target for advanced biofuels in transport in 2030. Biomass supplied 65% of all renewable energy consumed in the EU in 2016 (EUROSTAT, n.d.). Very little forest biomass has been used to produce transport fuels, but the advanced biofuel target could provide an incentive for this pathway.

In the United States, many states have renewable energy mandates that include encouraging the use of biomass (National Conference of State Legislatures, 2019), and national law directs federal agencies to count forest bioenergy as carbon neutral in policies (United States Congress, 2018). Canada is designing a Clean Fuels Standard that would encourage the use of forest biomass in stationary sources as well as transport (Environment and Climate Change Canada, 2018).

Policy support for forest bioenergy continues despite concerns that the use of forest resources for energy may not reduce lifecycle GHG emissions compared with fossil fuels. Forest bioenergy has sometimes been erroneously considered to be carbon neutral. This flawed concept derives from a misinterpretation of past life-cycle assessment studies that ignored biogenic $CO_2$ emissions and did not consider the use of land or biomass in a no-bioenergy scenario (Agostini et al., 2014; Giuntoli & Marelli, 2018). Analyses that do compare biomass harvest against a no-bioenergy scenario instead show that a decrease in forest carbon stock from expanded removal of wood for energy is balanced over time by the GHG savings deriving from substitution for fossil fuels. Until that point, though, the bioenergy system will have released more $CO_2$ than the fossil-fuel system. This is known as the carbon payback time. We use the term carbon debt as an umbrella concept to indicate bioenergy systems that are worse than fossil fuels for a period of time. The length of the payback time depends on many factors, including the type of woody feedstock and assumptions on alternative land use. The bulk of the scientific literature indicates that using wood for bioenergy increases GHG emissions compared with fossil fuels over decades or centuries (Agostini et al., 2014; European Commission, 2016).

However, a smaller number of studies conclude the opposite: That forest bioenergy, including the use of wood, can deliver substantial GHG savings over the 20–30 year timeframe typically used for carbon accounting in biofuel policy under specific assumptions (European Parliament & Council of the European Union, 2009; U.S. Environmental Protection Agency [U.S. EPA], 2010; Matthews, Hogan, & Mackie, 2018).

This divergence in the literature on the climate performance of forest bioenergy largely reflects different modeling methodologies and assumptions on the response of forest management to bioenergy demand (Agostini et al., 2014). Studies finding a positive carbon balance for forest bioenergy assert that growing bioenergy demand could stimulate forest management changes aimed at improving forest productivity and growth. Raising the demand for forest biomass would increase the price of wood, which would create an incentive for forest owners to invest in measures to increase output. Forest owners could then improve the productivity and carbon stocks of their stands through more-intensive management, such as more-frequent fertilization, or by planting faster-growing tree species. They could also raise biomass output by increasing the harvest of logging residues that otherwise would have been left to decompose on the forest floor, generating $CO_2$, or by carrying out thinning operations. These kinds of removals can achieve carbon benefits within policy-relevant time horizons because they do not affect the growing stock of the forest (Agostini et al., 2014). Some studies on carbon debt also assume that increased bioenergy demand will drive afforestation, or the planting of additional forest, resulting in greater overall forest area and increasing carbon stocks and wood production. The demand responses aim to produce biomass that is 'additional,', that is, it would not be produced in the absence of bioenergy demand (Searchinger, 2008). However, such demand might also simply divert resources from other markets and affect the consumption of different types of wood products. Because long-lived wood products continue to store carbon for many years and may displace $CO_2$-intensive products used in the construction sector such as concrete, any changes to wood-product consumption can affect the carbon balance of bioenergy. The GHG balance of forest bioenergy varies widely depending on the assumptions chosen for responses to bioenergy demand (Matthews et al., 2018). Even though these assumptions are critical to our understanding of the climate performance of bioenergy, there is very little information available about the empirical bases for such assumptions.

This study assesses the evidence on the response of various forest management changes to bioenergy demand. We use historical evidence on forest management intensity, species changes, total forest area, and harvest of residues to track whether these variables have responded to biomass price changes. We focus on Canada, Sweden, and the United States. These countries have large forestry sectors and have experienced booming production of wood for bioenergy in recent years. Several modeling studies have assessed the GHG balance of using forest biomass for energy in each of these countries. We examine each country separately, reviewing the literature modeling carbon accounting of forest bioenergy and analyzing available historical data on forest management practices. We reach conclusions on how well the modeling assumptions are supported by the evidence.

It is critical for policymakers to understand whether forest bioenergy is capable of delivering meaningful climate benefits, and if so, under what conditions and on what time scale. This study aims to fill a key knowledge gap for parsing the divergent literature on forest bioenergy carbon accounting. If the literature finding a positive contribution of bioenergy to climate change mitigation does so under unrealistic or arbitrary assumptions, this should be brought to light so that decision makers can focus support on lower-risk renewable pathways such as wind and solar power and advanced alternative fuels from wastes.

## CANADA

Canada's forests account for 9% of the world forest cover (Statistics Canada, 2018) and includes large areas of boreal forest (Ecological Framework of Canada, n.d.). The main forest-rich provinces are British Columbia, Ontario, and Quebec. Canada's forest sector is managed differently from the other countries reviewed in this study because the majority of forest land is public. Provincial governments award different types of contracts for logging and management rights on public land. Commonly they award long-term contracts to private forest companies, which conduct logging and are responsible for forestry operations and management. These private companies earn revenue from selling harvested forest products and in return pay annual rents and stumpage prices to provincial governments (British Columbia Ministry of Forests and Range, 2006).

Forest companies in Canada thus have less power to influence forestry decisions than in countries with predominantly private forests. The Chief Forester, an independent civil servant, defines the Annual Allowable Cut (AAC) based on scientific analysis to guarantee long-term, sustainable timber yield. Forestry companies under long-term contracts have certain legal responsibilities, including requirements to regenerate harvested stands, either by planting or seeding, and to remove or dispose of harvest residues to limit wildfire risk and the spread of pests (Legislative Assembly of British Columbia, 2002). Forestry companies still have discretion in many management decisions, for example harvesting a lower amount than the AAC, determining on-site preparation methods, fertilization rates, and thinning frequency, and choosing whether to burn on-site or remove forest logging residues.

The Canadian forestry industry has experienced large changes in the past two decades. There has been a massive infestation of mountain pine beetle, mostly in British Columbia, that has resulted in widespread tree death. The amount of wood killed by mountain pine beetle in British Columbia over time is depicted in Figure 1. Tree death from the infestation rose rapidly in the early 2000s, peaking in 2005, and has slowly declined since. The provincial government increased the AAC in the early 2000s to allow companies to retrieve as many affected logs as possible before they decayed and became unsuitable for sawmills (Industrial Forestry Service Ltd., 2015). As a result, total wood harvests in Canada peaked in 2004. Total harvests declined sharply from 2005–2009, most likely as a result of several factors including the decline in wood volume affected by mountain pine beetle, the economic recession of 2008–2009, and the continuing decline in demand for pulp, which is mainly used for paper and cardboard production, also shown in Figure 1. The total AAC for Canada has also declined, but to a much smaller degree than the decline in harvests (National Forestry Database, n.d.a).

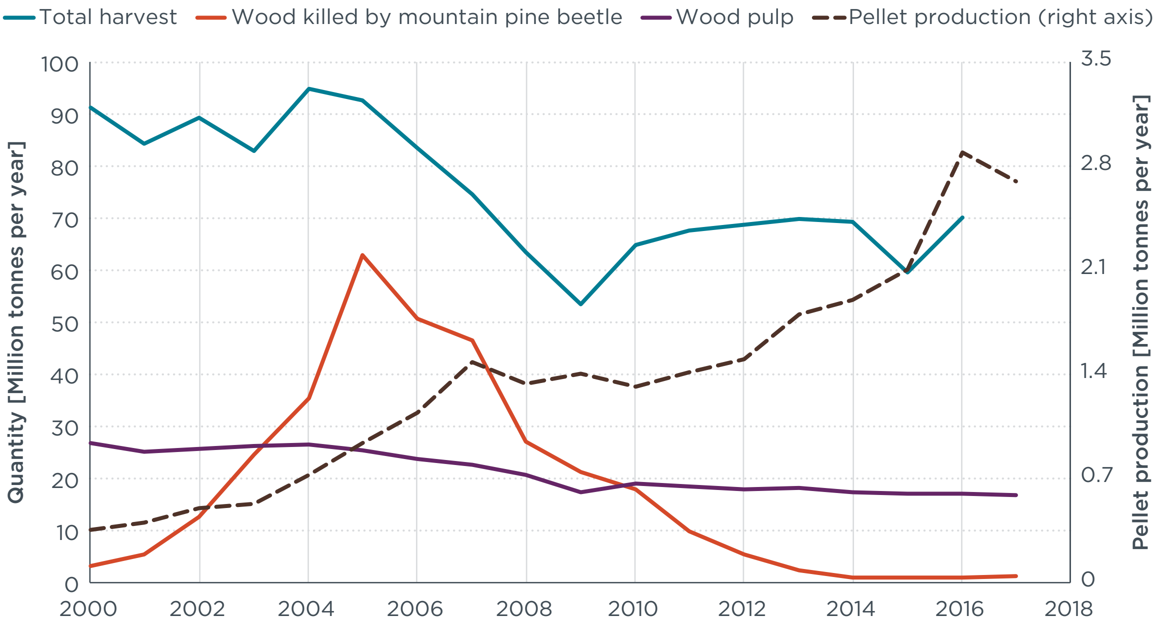

**Figure 1.** Total timber harvest, wood pulp production, and forest killed by mountain pine beetle (left axis) and pellet production (right axis) in Canada. Sources: Pellet production data from Wood Pellet Association of Canada (n.d.) and FAOSTAT (n.d.); Wood pulp data from FAOSTAT (n.d.); Total harvest and pine beetle data from National Forestry Database (n.d.b).

Canadian production of wood pellet fuel continued increasing throughout this period (Figure 1, right axis), ramping up from 1.5 million to 3.0 million tonnes per year over the past 10 years. More than 80% of Canadian wood pellets were exported in 2017, mainly to the United Kingdom and Japan (Murray, 2018). We focus our attention on British Columbia as it accounts for more than 65% of Canada's pellet production and has the largest number of pellet mills in the country (Murray, 2018).

Recent tree mortality from mountain pine beetle (*Dendroctonus ponderosae*) and decreasing demand for wood pulp may have contributed to the increase in wood pellet production. Pellets may have been an outlet for salvage logs in the 2000s as well as for sawmill byproducts that would historically have been used by the declining pulp and paper industry. On average, 47% of harvested saw logs ends up as lumber or veneer, with wood chips, sawdust and shavings, and bark and other residues known as hog fuels accounting for the remainder. In 2013, two-thirds of Canadian wood pellets were produced from these mill byproducts (Figure 2). Almost one-quarter of Canadian pellets in 2013 were made from logs, most likely salvage logs killed by mountain pine beetle. There may be a time lag between tree deaths from mountain pine beetle (Figure 1) and when salvage logs are used in pellets. British Columbia is the only Canadian province to use harvest residues in pellets (Bradburn, 2014).

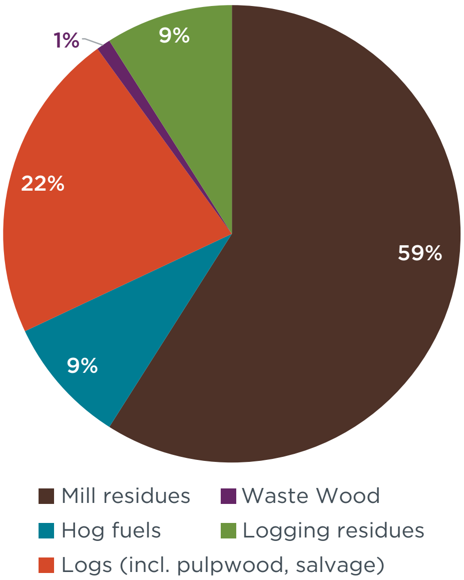

**Figure 2.** Feedstock base for wood pellets in British Columbia in 2013. Source: Bradburn, 2014.

Rising demand for Canadian pellets could result in changes to the mix of feedstocks used in pellet production. If total wood harvests continue to decline in Canada, the production of sawmill residues will also decrease. Salvage logging from mountain pine beetle damage has probably already dropped. Any significant future expansion of Canada's pellet industry is thus likely to come from increased use of logging residues or nonsalvage stemwood, or limbs and trunks, such as pulpwood (Industrial Forestry Service Ltd., 2015).

## LITERATURE REVIEW

Several studies have assessed the GHG balance of using Canadian forest biomass for energy production, with varying results depending on the assumptions on changes in forest management. According to economic theory, we should expect bioenergy demand to affect forest management through price signals. Bioenergy policy raises the demand for pellets, which should lead to price increases for pellet feedstocks. Higher demand for these feedstocks should expand the supply of wood through greater production. Increased output could come from several changes, including collection of additional logging residues, expanded wood harvest from broadened areas, or more-efficient production on existing harvested area by fertilization or thinning, for example. Other responses could take place through indirect feedbacks: Jonsson and Rinaldi (2017) report that increased demand for wood pellets could translate into higher demand for sawmill byproducts, which in turn could lead to greater profitability for sawmills and potentially an increase in harvesting of saw logs.

In this section, we review modeling studies on the GHG balance of Canadian forest bioenergy, focusing on assumptions concerning changes in forest management.

Forest management strategies that can increase productivity and output as well as those that improve the GHG balance of bioenergy vary somewhat by region. Lemprière et al. (2013) present an extensive review of these potential strategies in the context of Canada's boreal forests. One set of strategies focuses on accelerating the regeneration of harvested stands through planting, seeding, site preparation, and control of competing vegetation. Tree growth in boreal forests is usually limited by availability of the nutrients nitrogen and phosphorus, so fertilization in the first 10 years of stand growth could accelerate growth and increase yields. The GHG balance of forest bioenergy could also be improved through afforestation or avoided deforestation. Although gross deforestation rates in Canada have been small compared with the overall forest area with 0.02% lost annually, this still translates into high GHG emissions.

Studies on Canadian forest bioenergy generally find GHG benefits only when logging residues are used, but not for whole-tree harvesting, even when assuming that forest management practices will improve. A large portion of logging residues in Canada are burned at roadside rather than left to decay in the forest. Smyth et al. (2014) found that any dedicated harvest of stemwood for bioenergy would not achieve any climate mitigation. Some scenarios included forest management improvements such as additional pre-commercial thinning; faster regeneration from the previous harvest; fertilization, leading to a 20% increase in volume increment; and improved seeds. However, all scenarios with additional harvest of standing wood for bioenergy cause net additional carbon emissions compared with fossil fuels. Only scenarios that concurrently increase the use of logging residues, expand the recovery of small logs for bioenergy, and avoid residue burning at roadside provide the highest climate mitigation potential by 2050, even after an initial carbon debt of 11 years.

Smyth et al. (2017) made similar findings. This study found that bioenergy from a reduction in slash burning and an increased recovery of harvest residues, without any additional stemwood harvest, would provide climate mitigation across Canada with average payback times of six to nine years. In line with previous results, Smyth et al. (2018) found that for a region in Ontario, climate change mitigation could be obtained simply by reducing residue burning and leaving the residues to decay instead. Xu, Smyth, Lemprière, Rampley, and Kurz (2018) also found that reducing residue burning and using part of the logging residues for energy in British Columbia could produce climate change mitigation starting the first year.

Laganière, Paré, Thiffault, and Bernier (2017) found that even using logging residues or salvage logs for bioenergy might entail long payback times. This study showed that the use of logging residues, excluding stumps, can indeed provide immediate climate mitigation when the alternative is burning them at roadside. However, the researchers found that bioenergy from logging residues provides carbon benefits compared with being left to decay in the forest only after a period of 10–60 years, depending on the decay rate, the energy source substituted, and the final energy commodity produced. Interestingly, this study also found that the use of salvaged trees for bioenergy has payback times ranging from 25 to more than 100 years. Trees killed by infestations, in fact, remain standing for years after death, decomposing very slowly at around 2% per year, and once fallen continue to decompose slowly at around 4% per year due to their large size. Finally, in agreement with the previous studies, Laganière et al. (2017) found that standing trees harvested specifically for energy provide no climate mitigation within 100 years. Only if forest management changes achieve a doubling of growth after bioenergy harvest would the payback time for fast-growing standing wood be reduced to 40 years. Furthermore, the researchers found that payback time for salvage logs can be shortened to 30 years when actions are taken to double the regeneration growth rate.

Overall, these studies find that climate mitigation for Canadian bioenergy can be achieved only through recovering additional logging residues while at the same time reducing the amount of residue burning. Below, we explore the historical evidence to verify whether increased harvest residue usage has indeed been linked to pellet production. We also investigate whether rising pellet production is linked to improved forest management during regeneration and site tending and with changes in the rate of deforestation.

## HISTORICAL TRENDS

In this section we analyze the available statistical data from the Canadian forest inventory and for British Columbia's forest sector specifically to investigate whether harvesting-residue collection and other forest management changes may have responded to increasing bioenergy demand in Canada.

### Pulp log prices and pellet production

To investigate whether bioenergy demand has influenced forest management practices in Canada, we would ideally compare data on these practices with the prices of pellets or of pellet feedstocks. This comparison would elucidate whether price increases driven by bioenergy demand have incentivized forest managers to increase biomass output. Unfortunately, data over time is not available for the prices of Canadian pellets sold under long-term supply contracts, nor for the main pellet feedstocks of sawmill residues and hog fuels. We use pulp log prices as a proxy for pellet prices even though this is not ideal as pulp logs have not been used in pellet production, at least before 2013 (Figure 2), but the markets for these resources are likely to be linked because pulp logs and sawmill residues are both used in pulp making and other wood products. Figure 3 shows pulp log prices for British Columbia on the left axis and pellet production for Canada on the right axis. Both parameters increase over the same time period, and we find that they are significantly positively correlated, suggesting that changes in demand for pellets may translate to changes in pulp log prices and supporting our use of pulp log prices as a proxy for pellet prices.[1]

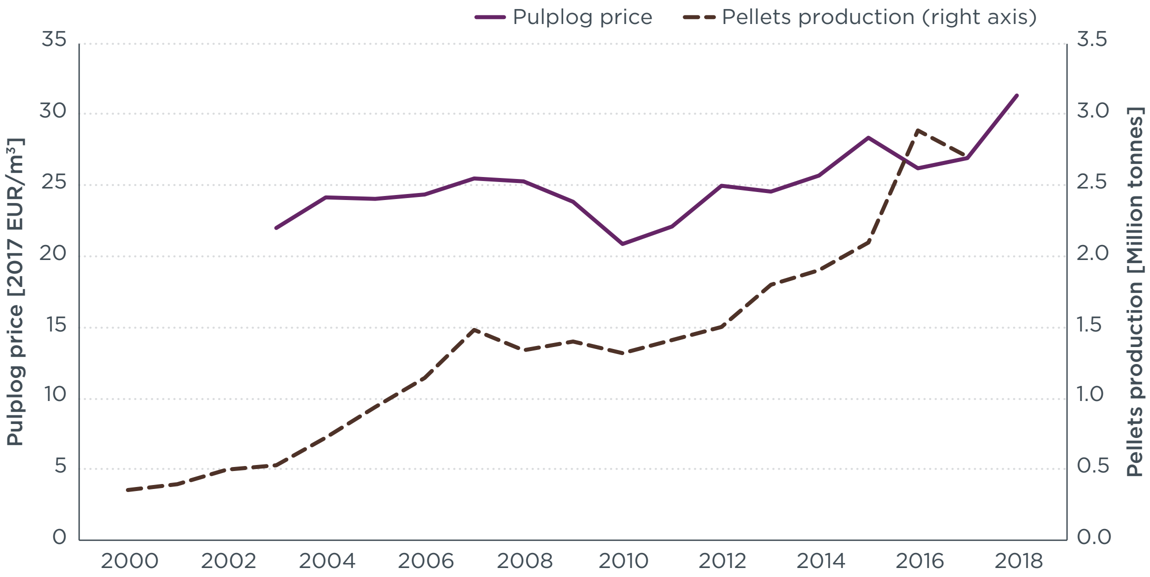

**Figure 3.** Pulp log prices in British Columbia (left axis) and Canadian pellet production (right axis). Source: (BC Ministry of Forestry, as cited in UNECE, 2018).

## Logging residue utilization

Increasing the use of certain logging residues in pellet production, such as tops and branches, could improve the GHG performance of bioenergy from Canada (Agostini et al., 2014; Giuntoli, Caserini, Marelli, Baxter, & Agostini, 2015; Matthews at al., 2018). The use of harvest residues, including tree tops and small branches but excluding stumps and coarse deadwood, for bioenergy is typically found to deliver climate benefits over shorter timescales than stemwood (Giuntoli et al., 2015; European Commission, 2016). However, this practice is limited by the quality of the biomass itself: Slash and stumps cannot be debarked and thus contain higher levels of impurities—ash-forming matter such as minerals and salts (Zevenhoven, Yrjas, & Huppa, 2010)—compared with white, debarked pulpwood. Since industrial wood pellets must comply with quality standards that limit the level of impurities, the quantity of logging residues used in pellet production must be limited (Ter-Mikaelian et al., 2015).

We have data on pellet composition only for the year 2013, so it is not possible to determine directly whether pellet composition is changing over time. To our knowledge, there is no data on total logging residue collection over time. Instead, since residues in Canada are commonly either removed or burned at roadside, we use the ratio between GHG emissions from slash burning and annual harvested area in British Columbia (Government of British Columbia, n.d.a) as an inverse proxy for logging residue collection (Figure 4). If logging residue collection is increasing, we would expect to see this index decline. This is indeed what we see in the data in Figure 4; furthermore we find that the decline in slash burning is significantly correlated to the trend of pellet

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[1] We consider linear regressions to be statistically significant if $p<0.05$ throughout this study. Correlation is not causation, and it is not possible to know from a simple linear regression whether pellet production influences pulp log prices or vice versa, nor how both variables may be influenced by extraneous factors. Here, and throughout this study, we interpret simple linear correlations cautiously, as indicative of possible links but not determinative of causal relationships.

supply. Based on the information available (Figure 2), we conclude that it is possible that bioenergy demand may be driving increased removal of logging residues and consequently a decrease in emissions from slash burning, although the trend was ongoing before the growth in pellet production, and other drivers may be at play. The use for bioenergy of logging residues that would have been burned in the forest guarantees immediate carbon benefits and could be treated as one of the few carbon-neutral biomass sources, provided emissions from forest operations are accounted for (Giuntoli et al., 2015).

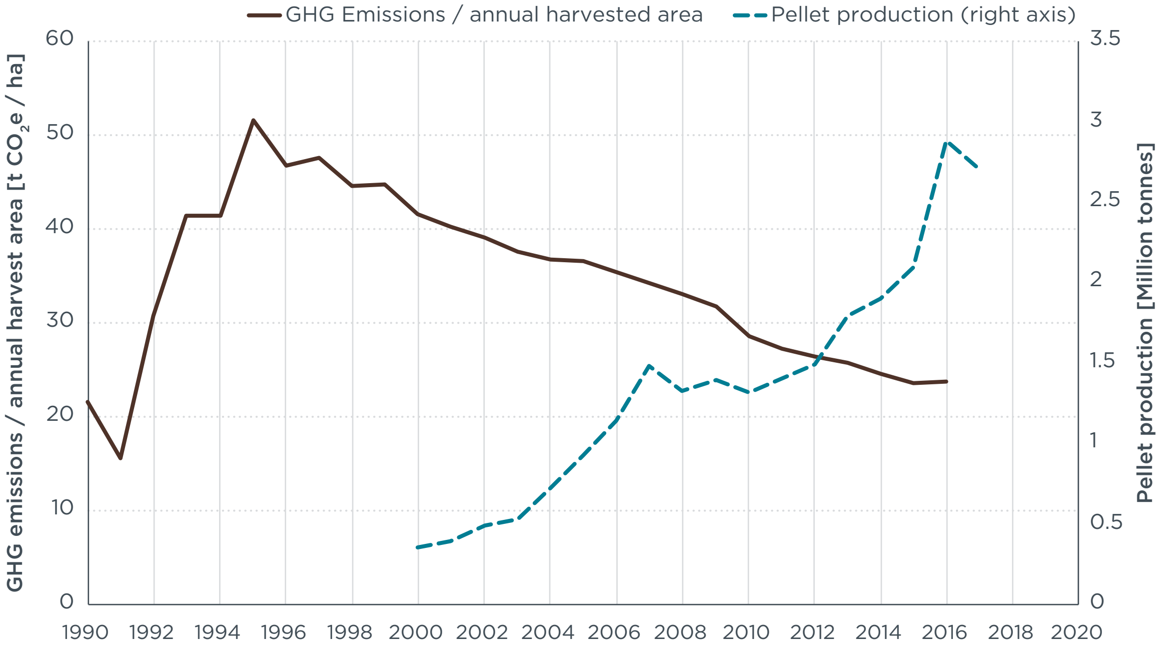

**Figure 4.** Ratio between GHG emissions from slash burning and annual harvested area in British Columbia and pellet production over time. Source: Government of British Columbia, (n.d.a.).

### Site preparation

Site preparation can influence forest growth rates. Methods typically used in Canada include mechanical treatment such as harrowing, ploughing, and windrowing; herbicides for weed control; and prescribed burning (National Forestry Database, n.d.c).

Figure 5 shows the trend in area treated with these various operations as well as the share of total logged area over which site preparation treatments were carried out in British Columbia. Since the '90s, the area subjected to treatments has decreased significantly, to the point were only 20% of logged stands were treated in 2016. Prescribed burning has decreased except for a spike during the peak years of tree death from mountain pine beetle, when a larger area was treated to contain the spread of the pest. A possible explanation for this is that long-term field studies have shown that site preparation in Canada is not effective. While it has an effect in increasing growth of stands at younger ages, the final yield of merchantable wood at harvest age is not significantly different from that of untreated plots (Cortini, Comeau, Boateng, & Bedford, 2010).

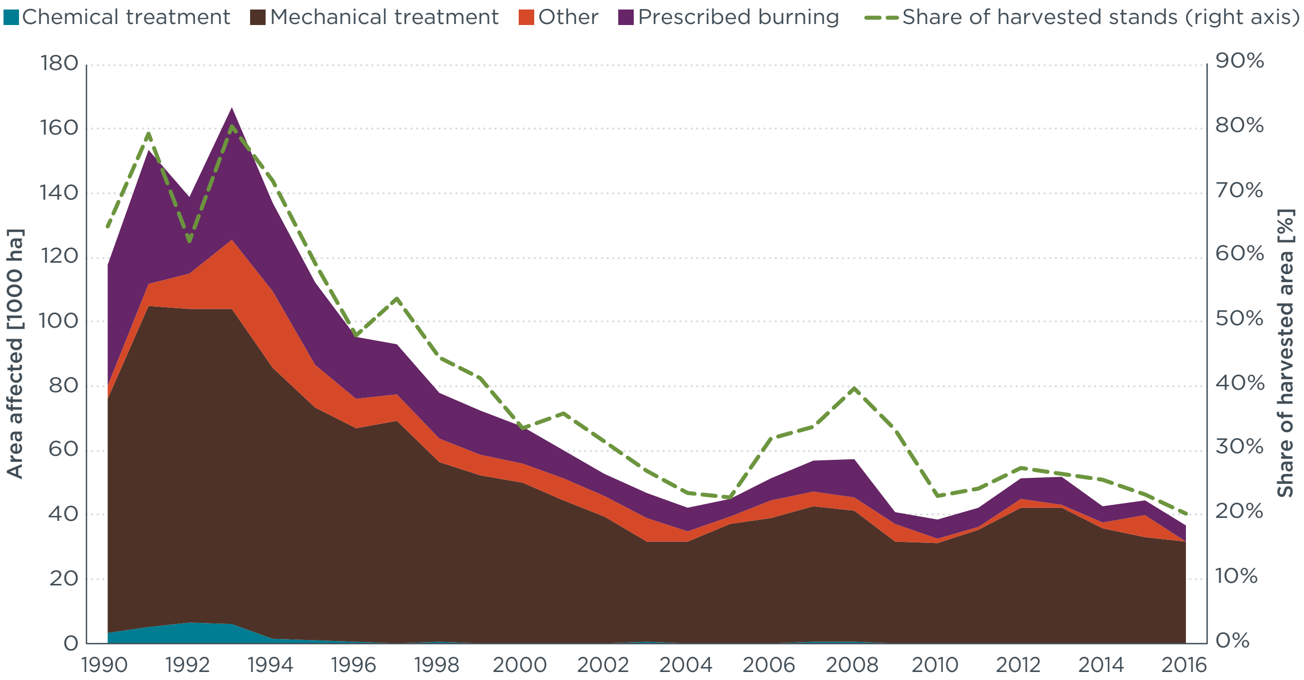

**Figure 5.** Site preparation treatments over time in British Columbia (left axis) and share of annual harvested area over which the treatments are applied (right axis). Source: National Forestry Database, 2018c.

We conclude that the extent of site preparation has little relation to bioenergy demand. The reduction in site preparation practices may have negative consequences for the GHG balance of Canadian forestry, as Laganière et al. (2017) have shown that increasing stand growth rate in the early years after harvest of the previous stand can reduce carbon payback times for bioenergy, as long as these changes result from bioenergy demand.

## Site regeneration and site tending

Once a stand is prepared and regenerated through seeding or planting, other silvicultural operations can be carried out to improve stand health and eventually productivity. Since 1987, the British Columbia government has promoted and invested in "incremental silvicultural" practices, including fertilizing, pruning, and planting of selected seedlings from orchards with higher productivity. Figure 6 shows the trend in annual area where certain treatments have taken place in British Columbia. In recent years, pruning and pre-commercial thinning have almost disappeared, despite the government initiative. Fertilized area, on the other hand, has increased slightly since the 1990s. Over the period 2011 – 2016 an average of 10% of the area harvested annually was fertilized. The use of selected seedlings has increased linearly since 1990. Over the past five years, an average of 70% of annually harvested area was regenerated with improved seedlings. Removal of competing vegetation has decreased since the 1990s.

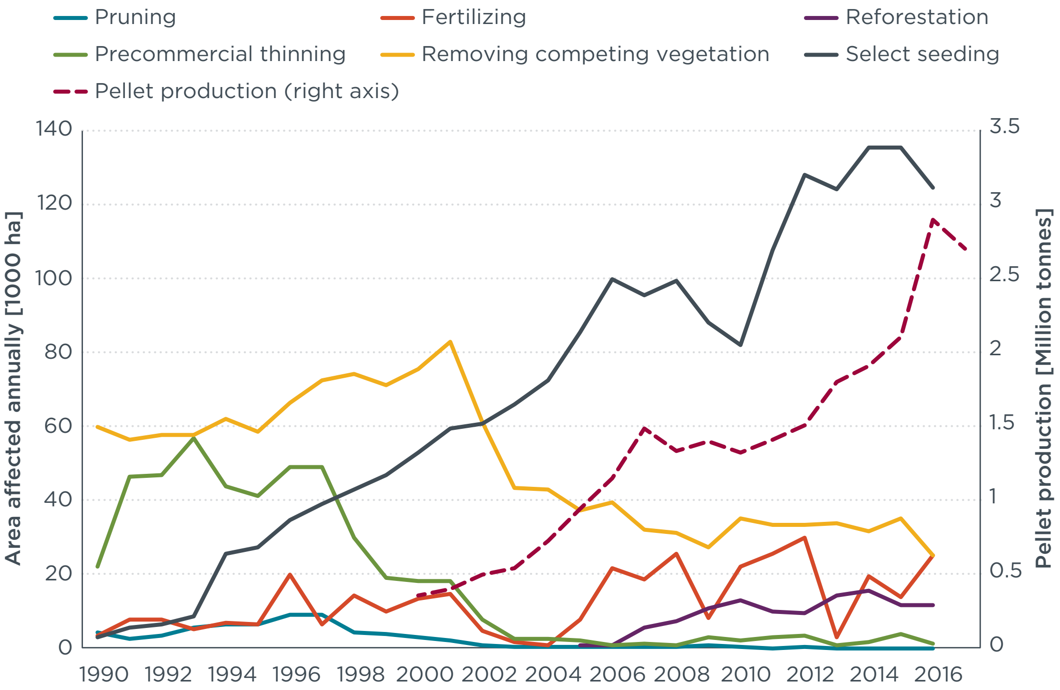

**Figure 6.** Site tending treatments (left axis) and pellet production (right axis) in British Columbia. Source: National Forestry Database, 2018c, Government of British Columbia, n.d.c.

These changes do not appear to be related to bioenergy demand. We could not find any significant correlation between the trends in these operations and pulp log prices. Changes in forest management practices are likely to be the result of government programs. For instance, the increase in planting of select seedlings has been roughly linear since 1990, long before the growth in pellet production, and is most likely a result of a provincial government initiative to promote incremental silvicultural practices that began in 1987. It seems more probable that changes in these silvicultural operations are a result of public investments rather than market mechanisms and that bioenergy demand has not played a role in influencing site-tending practices.

## Afforestation

Changes in forest area can have a major impact on the carbon balance of woody bioenergy. If timberland area declined as a result of bioenergy demand reducing forest stocks, this would negatively affect the climate performance of bioenergy. On the other hand, if an increase in demand for bioenergy were to lead to either increased forest area or to a reduction in deforestation, this would increase forest carbon stocks, generate additional biomass, and lead to a positive carbon balance for bioenergy.

Canada has lost around 1.2 million hectares (Mha) of forest land from 1990–2015 on a fairly linear trend. This was partially mitigated by the Forest for Tomorrow program, which started in 2005 and has promoted the reforestation of areas outside of those that the industry is obligated to regenerate (Government of British Columbia, n.d.b). This program successfully reforested more than 9 thousand hectares (kha) a year since 2005 for a total of almost 110 kha in British Columbia. This program has also facilitated the uptake of select seedlings. The rate of afforestation is not correlated with pulp log prices. Although afforestation has increased over some of the same period as the rise in Canadian pellet production, it is more likely that afforestation is a result of the Forest for Tomorrow program than a response to bioenergy demand.

## Canada summary

The forest sector in Canada is heavily regulated by provincial governments, which may shield management decisions from market signals. There is evidence that some management improvements may be contributing to faster forest growth and thus carbon sequestration and to production of additional biomass in British Columbia. However, these changes appear more likely to be driven by specific government policies than by bioenergy demand. Despite the limited data availability, we find that GHG emissions from slash burning are decreasing in British Columbia and that bioenergy demand may be one of the drivers for this decline by providing a market value for residues to be used in pellet mills.

**Table 1.** Summary of evidence that bioenergy demand may have led to forest management improvements in Canada.

| Literature assumption | Historical trend | Evidence trend driven by bioenergy demand | consequences for carbon accounting of bioenergy |
|---|---|---|---|
| **Increased removal of logging residues.** | Ratio of GHG emissions over annual harvested area in British Columbia (inverse proxy for residue collection) has decreased since 1995. | **Plausible.** Trend is in line with increased utilization of residues for pellet production, although the trend was ongoing before pellet production picked up. | Use of logging residues for bioenergy instead of slash burning provides immediate carbon benefits. |
| **Increased removal of salvage logs from infestation.** | Tree mortality from mountain pine beetle infestation peaked in 2005 and has declined to near zero. | **Likely.** Bioenergy demand may have increased utilization of salvage logs, but this trend is not likely to continue in the future as supply of salvage logs is not elastic. | Unclear. Use of salvage logs improves GHG performance only if coupled with intensive re-establishment of forest stands. |
| **More intensive site preparation.** | Extent of site preparation operations has decreased since 1990. | **None.** Trend is opposite of what economics would predict. | Unclear. Recent evidence suggests site preparation may have no effect on long-term stand productivity and thus on GHG performance. |
| **More intensive site tending practices.** | Some practices have increased since 1990, including the use of selected seedlings and fertilization. Others have declined, including pre-commercial thinning and pruning. | **None.** Some practices have increased alongside pellet production, but these increases began years earlier at the same time as the start of government programs. | Unclear. Increase in some site tending practices could improve GHG balance, but decline in other practices may worsen GHG balance. |
| **Afforestation** | Afforestation has taken place along with a government program introduced in 2005, however the overall rate of deforestation has not changed in the last 30 years. | **None.** The timing of afforestation matches the government program, and there is no correlation with pellet production. | Afforestation would improve GHG balance. |

## SWEDEN

Sweden's productive forests span two ecoregions, boreal forests in the north of the country and temperate broadleaf and mixed forests in the south. Sweden has a long history of forest management aimed at sustained production of timber products, based on clear-cut harvests and even-aged stands (Egnell & Björheden, 2016). The Swedish forestry sector is largely characterized by non-industrial private forests and by large forest companies.

In 2016, solid biomass produced 6.8% of Sweden's electricity consumption and around 61% of heat (Eurostat, n.d.). Future policies continue to rely on woody biomass to increase Sweden's share of renewable sources (Government Offices of Sweden, 2019). Production of forest fuels from slash (tops and branches), stumps, and stemwood grew from around 1 million dry tonnes in 1995 to 5 million dry tonnes in 2016. Data from 2017 show that fuelwood accounted for 38% of total forest fuels, followed by slash, 33%; roundwood, 24%; whole tree chips, 3%; and a small fraction of stump chips, 0.3%.

Similarly to the previous chapter, we first survey the literature to identify potential changes in forest management practices and how these changes could be fostered by bioenergy demand, we then analyze the historical evidence looking for signals that any of these changes may be taking place. Finally, we analyze whether literature assumptions are realistic and the eventual consequences for carbon accounting of forest bioenergy.

### LITERATURE REVIEW

We group the relevant studies on Swedish forestry into three categories. First we describe studies assessing general strategies to increase the productivity of Swedish forests. Second, we review studies that have quantified the effects of intensified management on forest growth. Third, we introduce studies that calculate the carbon balance of bioenergy produced from Swedish forests.

Literature on the Swedish forestry sector has identified potential forest management improvements that could increase growth that are similar to those in Canada. Egnell & Björheden (2016) list options to increase forest productivity, including improved site preparation such as vegetation control, soil scarification, and the use of faster-growing tree species and genotypes; increased fertilization and irrigation; and afforestation. Soil scarification refers to tilling of soil to improve seedling establishment and to reduce the risk of damage from insects. The authors highlight that because of the nature of long-rotation forestry, increasing forest growth will reap rewards for forest owners only in the very long term, and the profitability of these management strategies is thus often low. More complete utilization of the forest is a shorter-term option to increase bioenergy production. According to Egnell & Björheden (2016) there is large scope to increase the removal of logging residues as well as to increase the practice of thinning in Sweden.

The following studies assessed the effectiveness of these strategies in increasing forest productivity. Nilsson, Fahlvik, Johansson, Lundström, and Rosvall (2011) simulated the potential growth increase achievable from fertilization, high-yielding species, seedling selection, and afforestation, based on historical data on yields and management practices across Sweden. They found that the annual increment could almost double over 100 years when applying a combination of these intensive forestry management practices compared with a business-as-usual scenario. Planting lodgepole pine (*Pinus contorta* subsp. *latifolia*), a high-yielding species, combined with intensive fertilization of young stands was the most effective strategy.

Sathre, Gustavsson, and Bergh (2010) carried out a life-cycle analysis of forest bioenergy in Sweden assuming an intensive fertilization regimen. This study modeled a treatment of 100–150 kg/ha of nitrogen as well as other nutrients biannually in young stands followed by aerial applications of 100–125 kg/ha of nitrogen every 7–10 years in mature stands. They found that this treatment could more than double forest productivity, increasing stemwood volume from the current 5.3 $m^3$/ha/year to 10.8 $m^3$/ha/year.

Poudel et al. (2012) simulated Swedish forest growth response to increased pre-commercial thinning, fertilization, planting of lodgepole pine, and soil scarification. They found that even in the reference scenario, biomass harvest could increase by 50% in the next 100 years while simultaneously expanding standing biomass by 30%, reflecting the expected impacts of climate change on forest growth. This study estimated that a combination of higher $CO_2$ concentrations, higher temperatures, and longer growing seasons in boreal regions could increase forest productivity in Sweden by 33% without any management change.

The following studies have investigated the impact of intensive forestry management in Sweden on the overall carbon balance of bioenergy. It is important to understand that these studies generally do not draw a causal link between bioenergy demand and forest management, but rather exogenously make assumptions on forest management changes and the predicted growth responses. Lundmark et al. (2014) modeled a scenario both increasing the harvest of logging residues and stumps and assuming that wood harvest could climb by 50% as a result of increased fertilization and forest regeneration. The researchers found that the overall carbon benefit of Swedish forests—including the use of bioenergy to substitute for fossil fuels and changes in carbon stocks in forests and harvested wood products—could potentially increase by 66% by 2100 compared with a baseline scenario.

Cintas et al. (2017) obtained similar results. The researchers also modeled the overall carbon balance for several forest management scenarios over time, including increasing logging residues and stump extraction and actions to increase forest growth. They found that, while each of these treatments would achieve carbon mitigation compared with a baseline in the long term, the timing and magnitude of GHG savings change with the scenario considered. Increasing forest growth together with bioenergy production generates carbon benefits from the start of the analysis. However, scenarios focusing solely on increased extraction of logging residues and stumps are found to achieve GHG benefits only after 20 and 40 years, respectively.

In contrast with these studies, Cintas et al. (2016) present the only analysis for Sweden that models the effect of bioenergy demand on forest management changes in addition to the impact of forest management on bioenergy carbon balance. They used a model that calculates the optimal forest management plan to maximize the economic output of the forest. While traditional management is optimized to produce saw timber and pulpwood, the authors changed the management objective to place an equal weight on the production of saw timber, pulpwood, and forest fuels, implicitly assuming that bioenergy demand will increase revenue from forest fuels to match those of saw timber and pulpwood. Their model finds that the economically optimal forest management strategy would be to reduce saw timber output and increase extraction of pulpwood and forest fuels, much of which would result from increased thinning intensity and recovery of logging residues. This is a surprising finding. Increased use of saw timber in long-lived materials results in carbon substitution credits, as well as temporary carbon storage benefits. Other studies discussed in the U.S. section have found increased saw timber production to improve the overall GHG balance of forest systems. Furthermore, for lack of a forest-sector model, the complex interlinkages between material and energy uses of wood were not accounted for in the study.

These studies differ in their conclusions on whether increased use of logging residues provides GHG benefits over a reasonable time period. Generally, they find that improved management through increased thinning, fertilization, and switching to higher-yielding species is necessary to increase forest biomass output. It is important to keep in mind that climate change is likely to be increasing growth in Swedish forests in a baseline scenario without bioenergy demand.

## HISTORICAL TRENDS

In this section we analyze statistical data from the Sweden National Forestry Inventory and from the Swedish Forest Agency (Skogsstyrelsen, n.d.a; Swedish University of Agricultural Sciences, n.d.a) to investigate whether forest management practices have historically responded to changes in biomass prices, and whether the magnitude of changes assumed in the modeling studies is consistent with what has been observed historically.

### Forest fuels extraction and forest product prices

Increasing demand for biomass for bioenergy is expected to translate into an increase in biomass prices and effect changes in forest management practices.

The production of forest fuels in Sweden has grown steadily since 2000. This category includes any forest biomass used for energy purposes. Figure 7 shows the production of primary forest fuels over time. For the period 2000–2006, only data on total forest fuels production is available, while starting from 2007 we can differentiate by type of feedstock. Tops, branches, and stumps have accounted for a large fraction of total forest fuels production in years for which data is available. In the past eight years, however, it appears that the use of residues for energy has decreased while the use of standing trees, including whole tree harvest and roundwood, and firewood have increased. The production of firewood appears to have increased rapidly from 2011 to 2013, but this may reflect a change in classification. The definition of firewood is not clear; this category could include roundwood that is not of high enough quality to be used as saw timber, as well as possibly thinnings and small logs. Because data is not available for 2012, an interpolation of data between 2011 and 2013 is shown in the figure.

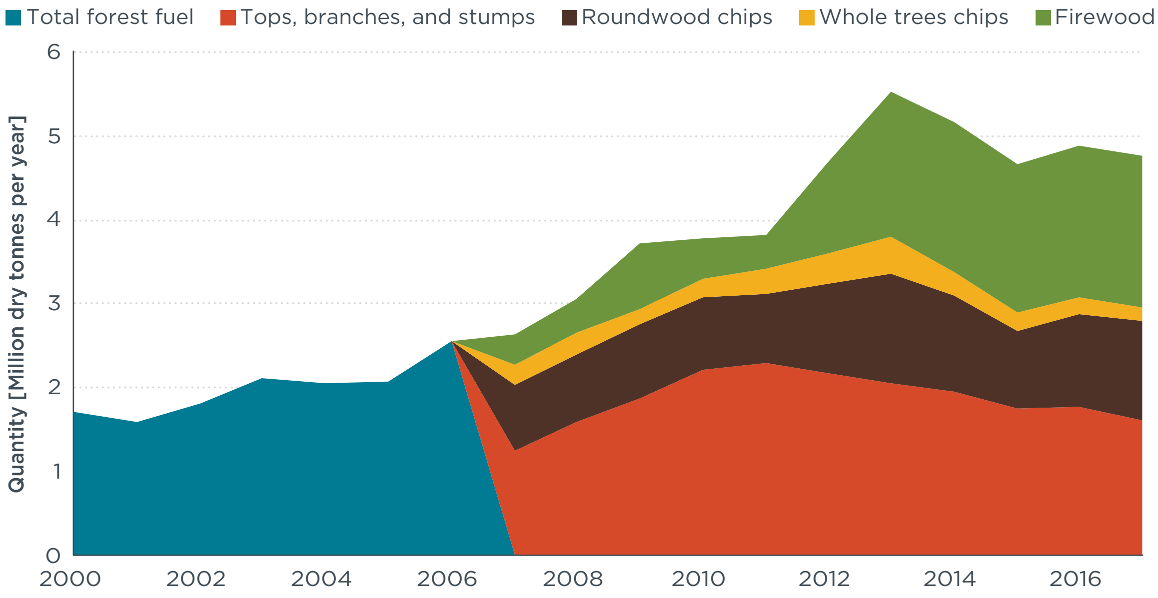

**Figure 7.** Primary forest fuels production in Sweden. Source: Skogsstyrelsen (Swedish Forest Agency) (2014) and Energimyndigheten (n.d.).

Over roughly the same period that total forest fuels production increased, prices of forest fuels and similar products rose as well. Figure 8 shows the prices of forest fuels and a few other bioenergy products, including wood pellets, wood chips, and wood residues sold to power stations. All of these prices increased steadily until various points between 2010 and 2013 and then declined slightly. For comparison, Figure 8 also shows prices of pulp logs and saw logs, which are non-energy forest products. These prices in constant 2017 euros have remained stable since the data series began in 1995. It is thus clear that the demand for bioenergy specifically, and not for wood products overall, has been driving the increase in prices for energy products. The prices of wood chips and wood residues sold to power stations are both significantly correlated with total forest fuels production and with removals of tops, branches, and stumps.

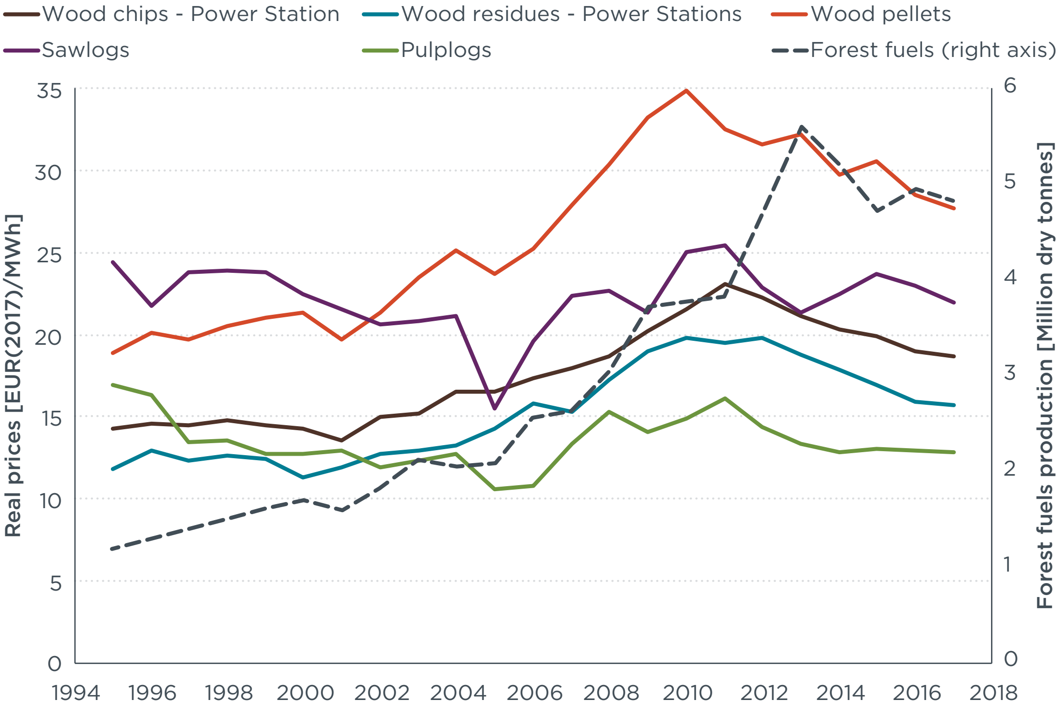

**Figure 8.** Price of various forest fuels supplied to power stations and total forest fuel production in Sweden. Prices of forest fuels, chipped or whole, supplied to power stations, and saw logs and pulp logs in 2017 euros per MWh (left axis). The green line shows total production of domestic forest fuels in Sweden (right axis). Source: Statistikdatabas, (n.d.).

## Forest productivity

Overall forest productivity in Sweden has increased steadily over the past 10 years in parallel with rising harvest levels, but it is unclear whether deliberate forest management practices as a result of bioenergy demand have been driving this trend. Figure 9 shows a five-year running average of the mean annual increment of Sweden's forest growth, reflecting the average growth of Sweden's forests in million cubic meters per year (left axis). This metric has been steadily rising since the 1970s. Environmental factors have most likely had a role in this rising growth rate. The change in annual temperatures in Sweden from pre-industrial levels, shown on the right axis in Figure 9, have also been increasing over this period with global climate change. Because of its northern latitudes and relatively cold temperatures, a rise in Sweden's temperatures can be expected to increase forest growth. In addition, atmospheric deposition of nitrogen from air pollution, which can fertilize forest growth, tripled from the 1950s to the 1980s–1990s before declining starting in the early 1990s (Bertills & Nasholm, 2000). Figure 9 shows atmospheric deposition of ammonium ($NH_4$) over the period for which data is available.

Another factor that may have contributed to forest growth in Sweden is a change in age structure with a greater relative proportion of younger trees in Sweden's forests over time. Younger trees have higher growth rates than older trees. We calculate an age-class index based on the distribution of Sweden's forest area by age class, shown in Figure 9; this shows the average tree age in Sweden's forests declining from the 1950s to the 1990s and remaining stable thereafter. This shift may be due to the past transition to clearcutting and artificial regeneration (Lundmark, Josefsson, & Ostlund, 2013), together with afforestation efforts between 1955 and 1970 and a shift toward harvesting the oldest stands (Lindahl et al., 2017).

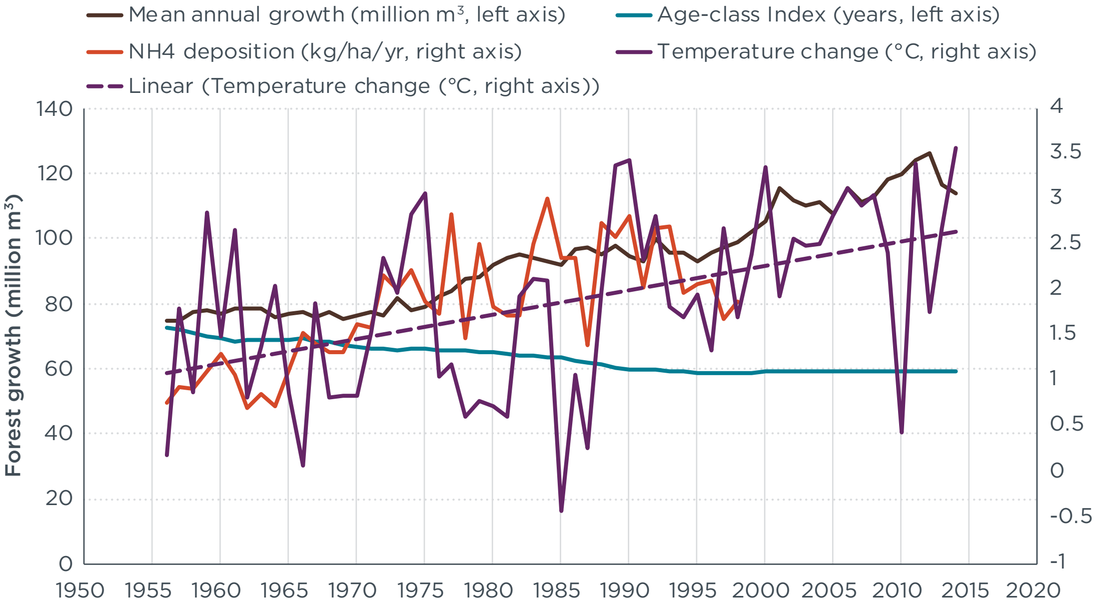

**Figure 9.** Mean annual increment of Swedish forest growth and nonmanagement explanatory factors. Source: Swedish University of Agricultural Sciences (n.d.b,c), Bertilis and Nasholm (2000), and World Bank Climate Change Knowledge Portal, (n.d.).

Each of these factors has statistically significant correlations with mean annual increment—positive correlations for temperature and atmospheric ammonium deposition, and a negative correlation for age-class index. This suggests these factors have contributed to increased forest growth. This finding does not preclude the possibility that changes in forest management other than changes to age structure have also contributed to increased forest growth. For instance, a peak in artificial fertilization in the mid-1970s might be responsible for the increase in increment shown in those years. In the following sections, we investigate possible links between other management activities and bioenergy demand.

## Forest management activities

In this section we investigate the trends in annual application of several forest management activities in Sweden, including pre-commercial and commercial thinning, soil scarification, removal of competing vegetation, fertilization, and ash-recycling. These operations are used in intensively managed plantations and are aimed at increasing stand productivity as well as the quality of the timber stock.

Figure 10 shows the historical trend of forest area annually affected by several silvicultural practices. The use of each of these practices has either been increasing or has remained steady since the mid-1990s. The largest relative change over this period has been in pre-commercial thinning, the rate of which has quadrupled since the 1990s. Pre-commercial thinning is the removal of selected young trees before they have reached a sufficient size to produce merchantable wood in order to improve the quality of the remaining trees. The rates of other practices, regular thinning and the removal of competing vegetation, have also increased over the past two decades. Thinning refers to the removal of select trees at a later stage, when trees have generally reached a sufficient size to be sold at least as pulpwood. The removal of competing vegetation, referred to as "cleaning" in the official Swedish statistics, is essentially pre-commercial thinning at an earlier stage, when trees are saplings, and it removes other types of undesired vegetation as well as very small trees. This practice focuses on removal of nonpreferred tree species.

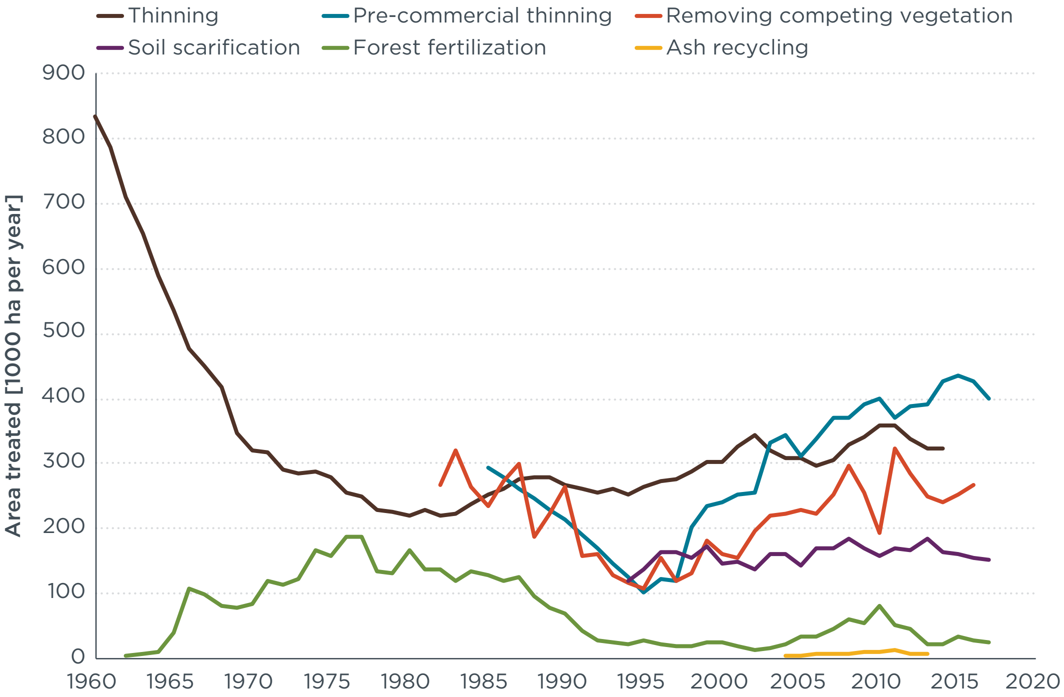

**Figure 10.** Annual areal extent of forest management activities in Sweden over time. Source: Swedish University of Agricultural Sciences (n.d.d)

Traditionally, each of these thinning practices has been used to improve the growth rate of stands and to increase the diameter of remaining trees to improve saw log quality, even at the expense of total production volume, and thus might be expected to respond to saw log price expectations. However, we find significant correlations between the annual area under thinning, pre-commercial thinning, and removal of competing vegetation and the prices of wood chips sold to power stations, while we find no correlation between these practices and pulp log or saw log prices. This finding strongly suggests that all of these thinning practices are responding to bioenergy demand. This especially makes sense for pre-commercial thinning and removal of competing vegetation, which typically do not produce any merchantable wood unless the saplings and young trees are chipped and sold for energy. It is thus logical that forest managers may increase the short-term output of these products in response to higher wood chip prices.

Application of mineral fertilizer has largely declined since a peak in the 1970s. In 2017 it was practiced on only an eighth of the area as in 1976 (Figure 10). Fertilization rates rose again slightly in the 2000s but dropped after 2010. The long-term decline in fertilization rates could be due to changing societal perceptions of forest fertilization as well as changes in saw log prices. Starting in the 1980s, a growing environmental movement began opposing fertilization in forestry, and this pressure persists (Hedwall, Gong, Ingerslev, & Bergh, 2014). At the time of the highest rates in fertilization, saw log prices peaked in the 1970s at more than €90/m$^3$ in 2017 euros, most likely linked to the oil crisis and the subsequent increased use of wood for energy (Brunberg, 2010). Prices of saw logs have since decreased to an average of €52/m$^3$ in 2017 euros over the past 30 years. The long-term trend in fertilization rates correlates significantly with saw log prices. The responsiveness of fertilization to saw log prices suggests that a significant increase in the price of wood for bioenergy could also induce a return to higher fertilization rates. However, the absolute frequency of forest fertilization is unlikely to approach the levels assumed in some of the studies on the carbon balance of bioenergy. Nilsson et al. (2011), for instance, assume that fertilization is applied to mature stands every 10 years over an area of 1.7 Mha, and more intensive fertilization is applied every two years to young stands over an additional area of about 1 Mha to achieve their result of doubling forest growth by 2100. At peak forest fertilization rates in 1976, fertilization was applied on only 0.8% of total productive forest area. This is equivalent to fertilizing 1.9 Mha of forest every 10 years. In 2017, fertilized area was equivalent to fertilizing 0.3 Mha of forest every 10 years. Fertilization rates would thus have to return to high levels not seen since the 1970s to partially replicate Nilsson et al.'s scenario, and they would have to expand much more to achieve the full growth increase modeled. This does not seem likely given the changes in silvicultural practices and views on environmental protection since the 1970s. It would also be likely to require the price of biomass used for bioenergy to reach a similar level as saw log prices at their historical peak.

Trends in the other forest management practices—soil scarification and ash recycling—have remained flat over time. Scarification, or the tilling of soil, improves establishment of seedlings while reducing the risk of damage from the large pine weevil (*Hylobius abietic*). Ash recycling refers to the application of ash from wood combustion, which contains nutrients from the wood, excluding nitrogen (Emilsson, 2006). Soil scarification already takes place on 88% of the area felled each year, so there is little scope to further increase its rate of adoption in response to bioenergy demand.

Thus, there are indications that bioenergy demand is increasing the prevalence of thinning and related operations. However, the main driver of increased forest productivity is drastically increased fertilization, and there is no evidence that this has responded to bioenergy demand in the past 20 years or that it could do so with the same magnitude as assumed in studies.

### Site regeneration and tree species

Whether a harvested stand is regenerated naturally or artificially through planting or seeding can play an important role in overall forest management. Artificially regenerated stands can achieve higher productivity of industrial-quality roundwood than natural ones (Hallsby et al., 2015) because regeneration enables the application of site establishment measures such as limiting competition from other vegetation, planting improved genotypes or higher-yielding species, and facilitating fertilization in young stands. Further, artificially regenerated stands allow for intensive levels of disturbance of the stands, as required for collection of logging residues. Artificial regeneration has been increasing since 2000, and in 2015, more than 80% of logged stands were replanted. The rate of artificial regeneration is significantly correlated with the price of both wood chips and saw logs. This could be tied to bioenergy or timber demand, or could be a result of unrelated changing forestry practices and legislation.

As the rate of artificial regeneration has increased, we might expect to observe increased penetration of more-productive species. Lodgepole pine, a species native to the U.S. Pacific Northwest and Canada, has been reported to have around 30% higher yields compared with Sweden's native Scots pine (Elfving, Ericsson, & Rosvall, 2001). Artificially regenerated stands planted with lodgepole pine could thus increase the productivity of the forest landscape. For this reason, Nilsson et al. (2011) assumed that 1.12 Mha would be planted with lodgepole pine by 2050 in their intensified forestry scenario. It should be noted that Swedish regulations allow the use of so-called exotic, or nonindigenous, tree species as exceptions only (9 § skogsvårdsförordningen [1993:1096]), and that the Swedish Forest Agency interprets this regulation to the effect that regeneration with lodgepole pine should be at most 14 kha per year.

Figure 11 also shows the change in forest area of various species and stand assemblies in Sweden since 1985. The total area under lodgepole pine, which makes up only around 2% of total forest area, increased by around 200 kha from 1985 to 1993 and has increased very slowly since then. There have also been increases in mixed and broadleaf forests to 15% of total forest area and, to a lesser extent, other pine forests to 39% of total forest area, which is likely to include Scots pine. The prevalence of spruce at 27% of total forest area and mixed conifer forest at 14% of total forest area has declined markedly since 1985. While the composition of Sweden's forests is changing, it is doing so relatively slowly; only around 5% of Sweden's total forest area has changed species composition since 1985.

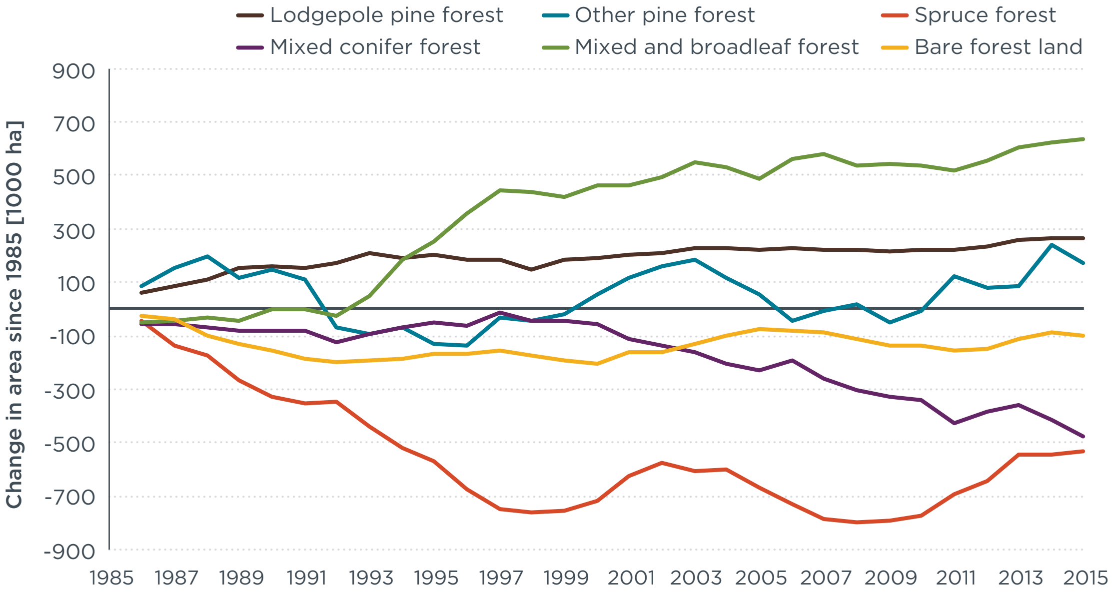

**Figure 11.** Change in area of major forest species in Sweden since 1985 Source: Swedish University of Agricultural Sciences (n.d.e), Skogsstyrelsen (n.d.b).

The increase in lodgepole pine is significantly correlated with the prices of wood chips sold to power stations and negatively correlated with saw log and pulp log prices. This could mean that lodgepole pine is increasingly planted to supply bioenergy or that lodgepole pine produces poor wood for saw logs and pulp logs, which seems unlikely. In any case, it is important to note that the magnitude in these changes is very slight. At the current rate of lodgepole pine area increase since 1990, we project an additional 100 kha of this species in 2050 compared with 2015. This is far lower than the 1,120 kha of additional lodgepole pine that is assumed to be planted by 2050 to achieve the increased growth modeled by Nilsson et al. (2011).

## Afforestation

Total forest area in Sweden has fluctuated since the 1950s, but overall there is no statistically significant correlation between increases or decreases in area or bioenergy prices over this period. As forest fuel and woodchip prices increased from around

2000–2012 (Figure 12), total forest area expanded and contracted without any overall trend. It thus seems unlikely that total forest area has changed or that net afforestation has occurred in response to bioenergy demand in Sweden. This finding is in contrast with the assumption in Nilsson et al. (2011) that the output of Swedish forests could be increased by 2050 by expanding forest area by 0.4 Mha.

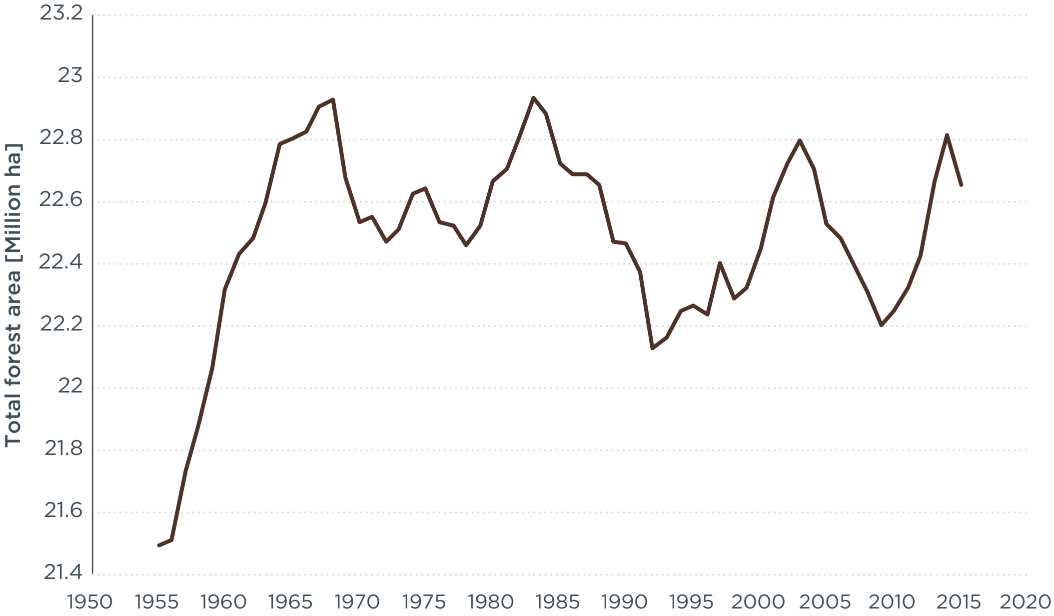

**Figure 12.** Total area of productive forest land in Sweden. Source: Swedish University of Agricultural Sciences (n.d.f).

### Sweden summary

There is evidence that bioenergy demand may have had a modest impact on increasing total forest biomass removals in Sweden. The practice of thinning at several stages of forest growth appears to have grown in response to prices of wood sold for energy purposes. Similarly, the removal of forest fuels has increased with rising bioenergy prices, albeit the share of tops, branches, and stumps has actually decreased at the expense of expanded removals of standing wood. However, it is likely that other changes in Sweden's forests have occurred independently of bioenergy demand. Increasing forest productivity is most likely primarily a result of climate change, atmospheric nitrogen deposition, legacy management, and changes in fertilization in the 1960s–1990s. No net afforestation has taken place in Sweden since the mid-1900s, and while the prevalence of higher-yielding tree species is increasing, this trend is very slow, and high-yielding lodgepole pine still accounts for a very small fraction of total forest area. There is little evidence that the magnitude of changes assumed in studies that forecast a positive carbon balance for Swedish bioenergy is likely or even possible.

**Table 2.** Summary of evidence that bioenergy demand may have led to forest management improvements in Sweden.

| Literature assumption | Historical trend | Evidence trend driven by bioenergy demand | consequences for carbon accounting of bioenergy |
|---|---|---|---|
| **Increased removal of forest fuels** | Overall growth in forest fuels supply, mainly in firewood, whole tree harvest and roundwood chips. | **Likely.** Forest fuels removal correlates with bioenergy prices. | Unclear, depending on the wood products included in the statistical data. |
| **Increased removal of tops, branches, and stumps.** | Increasing removal until 2011, then decreasing. | **Unlikely.** Logging residue and stump removals correlate with bioenergy prices, but overall collection declined while total forest fuel collection increased. | The use of tops and branches is linked to short payback times, while use of stumps may have negative carbon balance. |
| **Increased thinning intensity.** | Thinning, pre-commercial thinning, and removal of competing vegetation have all increased. | **Likely**. Thinning intensity correlates with bioenergy prices. | Improved carbon balance of bioenergy from increasing biomass output from a forest area without negatively affecting the growth of the remaining stock. |
| **Increased forest growth rates through improved silvicultural practices.** | Forest growth has increased continuously for the past 45 years | **Unlikely.** Fertilizer use has increased recently, but only slightly. Rates of other forest management activities have not changed significantly. Forest growth more likely the result of environmental factors and legacy management. | Increasing forest growth would produce additional biomass, allowing increased removals with low carbon debt. |
| **Afforestation.** | No change. | **None.** | Would improve carbon balance of bioenergy by increasing land carbon stocks and biomass resources additional to a no-bioenergy scenario. |
| **Change to higher-yielding tree species.** | The prevalence of lodgepole pine, a high-yielding species, has increased slightly. | **Plausible.** This effect could be a result of bioenergy demand, but it is very small in magnitude. | Improves carbon balance of bioenergy by increasing forest landscape productivity. |

## UNITED STATES

Finally we assess the southeastern region of the United States,[2] which spans several ecozones, mainly temperate conifer and broadleaf forests. Ecosystems in the southeastern United States are rich in endemic species, and the region has been recognized as an important biodiversity hotspot (Hammel, 2015; Noss et al., 2015). Forest ownership is 87% private, and of this, two-thirds is nonindustrial private, with the remainder owned by forest companies. There are both naturally regenerated forests and more intensively managed pine plantations. In the past decade, wood pellet production has increased rapidly in this region, powered by growing demand from Europe, which is projected to increase further (Dale et al., 2017; Copley, 2018).

We first review studies modeling the carbon balance of bioenergy produced from wood pellets in the southeastern United States, focusing on assumptions related to forest management. We then examine the historical evidence for signals that bioenergy price changes have altered forest management practices. We conclude with an assessment of how well the evidence supports these literature assumptions, and what the resulting impact is on the GHG balance of bioenergy in the United States.

### LITERATURE REVIEW

Since the United States started exporting large quantities of wood pellets, a number of studies have assessed the potential GHG impacts of bioenergy from wood from this region. Some studies have focused on the impact improved forest management practices could have on forest productivity and consequently on the overall GHG performance of bioenergy. Others have assessed how bioenergy demand could change overall forest area and thus carbon stocks in the region.

Jonker, Junginger, and Faaij (2014) and Jonker, van der Hilst, Markewitz, Faaij, and Junginger (2018) both assess how improving forest productivity could affect carbon payback times of bioenergy from conifer plantations in the southeastern United States. Jonker et al. (2014) assumes plantation yields of 4, 5.6, and 9.7 dry tonnes per hectare per year (t/ha/yr). The lowest yield is meant to represent limited forest management operations, while the highest would reflect intensive site preparation, two rounds of fertilization during stand rotation, herbicide application, and one thinning operation. This study calculates payback times of 39–57 years for pellets in the low-yield scenario, 21–37 years in the medium scenario, and 8–17 years in the high scenario, compared with coal.[3] In a similar study, Jonker et al. (2018) assessed scenarios with combined roundwood and logging residue yields of 8.7–14.1 dry t/ha/yr, depending on forest management intensity. They conclude that the total yield of wood is not the only parameter determining the final carbon balance: The quality of the roundwood produced—saw timber, pulpwood or slash—is crucial. The main reason for these findings is that saw timber is suitable for the production of longer-lasting harvested wood products, which contribute to climate change mitigation by storing carbon as well as substituting for high-carbon intensity structural products such as concrete and steel. Additional thinnings can produce pulpwood and small roundwood without affecting the overall yield of saw timber produced and may thus result in a better carbon balance compared with management strategies that maximize total yield, which would increase the production of smaller-sized pulpwood at the expense of saw log production. However, if bioenergy demand were to stimulate changes in management aimed at maximizing total yields, producing

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[2] We use the composition of the southeastern United States as given in U.S. forest statistics, including the following 13 states: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia.

[3] For the landscape-level analysis compared with a baseline of no harvest of existing plantations.

greater quantities of smaller roundwood, this would worsen the carbon performance of the forest compared with conventional management strategies.

Other studies have tried to integrate market dynamics in their analyses. K.L. Abt, R.C. Abt, Galik, and Skog, (2014) and Galik and R.C. Abt (2016) use an economic model to evaluate the potential impacts of additional bioenergy demand on forest carbon stocks. K.L. Abt et al. (2014) find that even in a baseline projection without additional bioenergy demand, the timberland area would decrease between 2010 and 2040 both for natural forests and for pine plantations. This study models a loss of around 2.2 million hectares of natural forest and around 1.6 Mha of pine plantations. They find that additional bioenergy demand would cause a slight increase of 0.4 Mha in pine plantation area by 2040 compared with 2010, while not affecting the decline in natural forest area. This study thus projects that bioenergy demand would limit forest land loss compared with the baseline scenario. Galik and R.C. Abt (2016), using the same economic model but different assumptions and constraints, similarly modeled 2.3 Mha of avoided deforestation, mainly from an increase in pine plantations compared with the baseline scenario. Similar conclusions were reached by Duden et al. (2017): Using the same economic model they found an increase in pine plantation area of 0.8 Mha and an avoided loss of 0.2 Mha of natural forests compared with the baseline scenario. Supporting these assumptions, Dale, Parish, Kline, and Tobin (2017) and Dale et al. (2017) find that forest area and timber volume in the southeastern United States did not decrease at the same time that U.S. pellet exports increased from 2009–2015. The authors expected that in a baseline scenario, southeastern U.S. forest area should have declined over this period and therefore argue that bioenergy demand prevented net deforestation. These researchers conclude that demand for wood pellets had a positive effect on forest ecosystems by giving forest landowners an economic incentive to retain land in forest cover. The additional market for these products created demand for pulpwood resources that might have been stranded by a decline in demand for pulp and paper while providing economic value for various residual harvest products such as thinnings, logging residues, and small roundwood.

The U.S. literature thus finds that a favorable GHG balance of bioenergy depends on either dramatically improved forest productivity resulting from more intensive management, or reduced deforestation compared with expected trends.

## HISTORICAL TRENDS

In this section we analyze statistical data from the U.S. Forest Service to examine historical evidence for the trends assumed in the literature and whether those trends appear to be correlated with bioenergy demand.

### Pulpwood prices and pellet production

Wood pellet production in the U.S. has tripled over the past decade. Figure 13 shows U.S. wood pellet production on the left axis. Pellet production expanded from around 2 million tonnes produced mainly for domestic consumption in 2008 to 7 million tonnes a year in 2017, with an installed capacity of almost 12 million tonnes in that year (U.S. Energy Information Administration (EIA), 2018). The southeastern region of the United States accounted for around 75% of the installed capacity in 2018 and 100% of the production of wood pellets of industrial quality. Exports of U.S. industrial wood pellets to the European Union increased from 2.3 million tonnes in 2012 to 5 million tonnes in 2017 and are forecast to increase further (Dale et al., 2017; Lang, 2016; Copley, 2018). K.L. Abt et al. (2014) reported that the feedstock mix used for pellet production in the U.S. South had shifted from 100% sawmill residues in 2010 to more than 60% pulpwood in 2013, with less than 40% sawmill residues. More recent data shows that the share of residues used in pellet mills rebounded to reach 47% in 2017 (Ekstrom, 2017). While Ekstrom

(2017) reports that both sawmill and logging residues are responsible for this increase, evidence that actual logging residues are used as pellet feedstock is rare (discussed further in section: Removal of forest residues).

Pellets can be traded on spot markets, but mainly they are sold through long-term contracts between suppliers and buyers, and data on pellet prices defined in contracts over this period is not available. Since pulpwood is currently the main feedstock for pellet production, we show pine pulpwood stumpage prices in Figure 13 (right axis) as an indicator of bioenergy prices. The trend in pulpwood prices has closely followed that of pellet production since 2011. It is likely that pulpwood prices did not follow the increasing trend in pellet production before then because pellet production exclusively used sawmill residues before that point (K.L. Abt et al., 2014). Nonetheless, pulpwood prices and pellet production are significantly correlated over the entire time series shown in Figure 13. This relationship suggests that bioenergy demand (as evidenced by pellet production) influences pulpwood price, although it is likely that other factors drive changes in pulpwood price as well. For the remainder of this section, we investigate possible links between pulpwood price and forest management changes to test whether these changes might be a market-mediated effect linked to bioenergy demand.

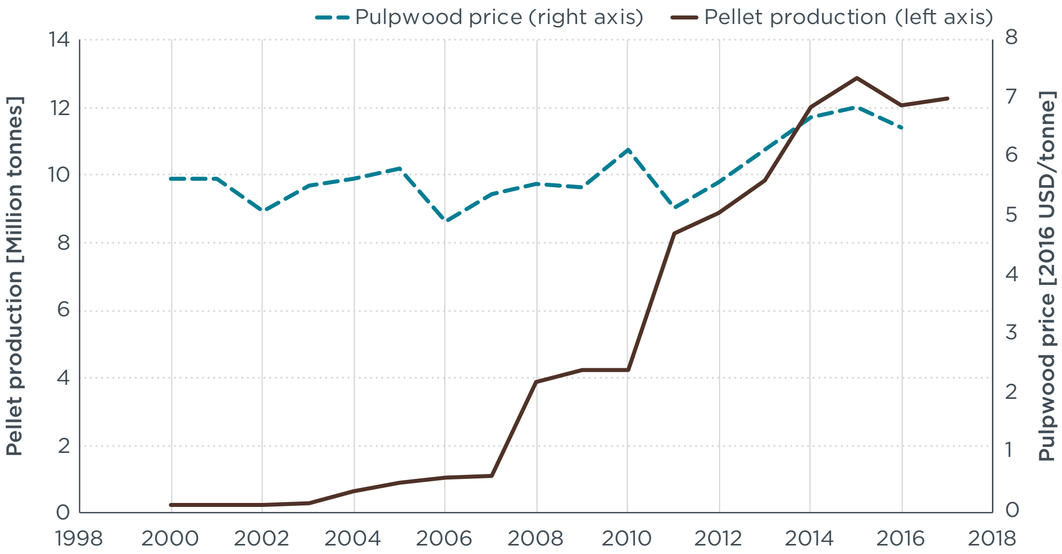

**Figure 13.** U.S. pellet production (left axis) and pine pulpwood prices (right axis). Source: U.S. Industrial Pellet Association (2015), Jeffries & Leslie (2017), U.S. EIA (2016).

## Removal of forest residues

The use of logging residues for energy is generally believed to provide climate change mitigation in the short term (Agostini et al., 2014; Giuntoli et al., 2015; Matthews, Hogan, & Mackie, 2018). Perhaps as a result of these findings, several pellet producers and buyers have claimed most of the feedstocks going to pellet mills to be “logging residues” (Hammel, 2015). However, the devil is in the details: While the authors above refer to logging residues strictly as tops and branches that would decay if left in the forest, other authors include in the “residues” category every wood product that is not economically profitable, including crooked and small stemwood produced during clear-cut operations, thinning stems of pulp log quality, and even stumps. Indeed, data reported by K.L. Abt et al. (2014), Stange Olesen, Bager, Kittler, Price, and Aguilar (2015), and Booth (2018) show that no logging residues were used in U.S. pellet mills until 2014 and only 1% by late 2016.

Data on the quantity and type of residues removed from forest stands is scarce. We use the quantity of wood products deriving from nongrowing stock[4] as a proxy for logging residues. Figure 14 shows the quantity of wood products from nongrowing stock as a ratio of total products output from 1995–2015 (left axis). This measure, which we interpret as indicating the proportion of logging operations that harvested residues, remained fairly stable between 1999 and 2015, while in the same period pellet production in the southeastern United States rapidly increased. We find no correlation between this measure of the frequency of residue removal and pellet production or pine pulpwood prices. While the data available are uncertain, we do not detect any evidence that bioenergy demand has increased the harvest of logging residues or their incorporation into pellets used for bioenergy.

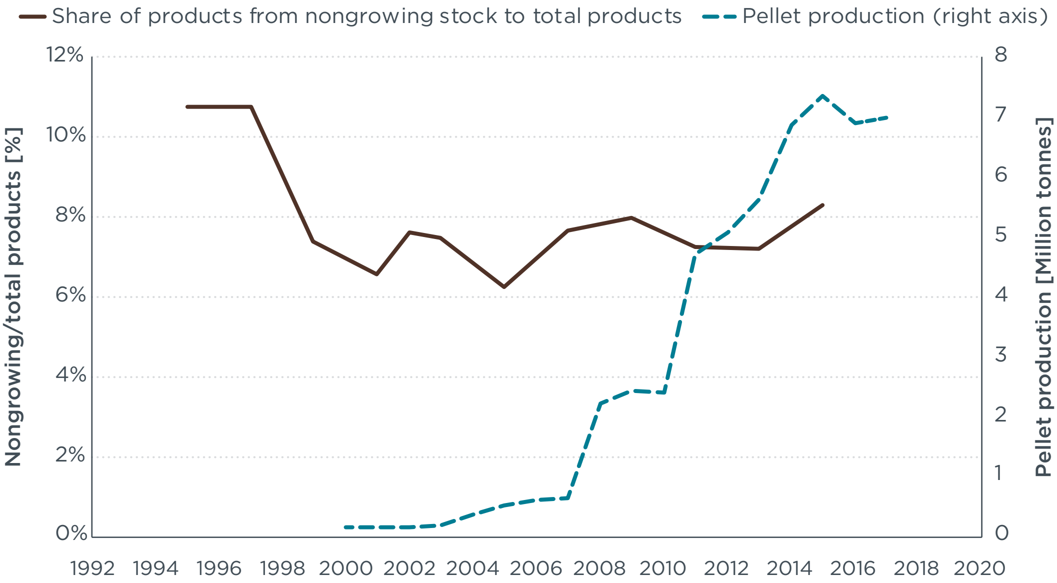

**Figure 14.** Logging residue removal as a ratio of total roundwood removals [left axis] and wood pellet production [right axis] in the southeastern United States. Source: U.S. Department of Agriculture, Forest Service (2012).

## Stand productivity

Increasing the productivity or yield of forest stands can raise biomass output without reducing carbon stocks and thus lower carbon payback times. Here, we examine changes in productivity in private forests of two major forest types in the southeastern United States, loblolly-shortleaf pine and oak-hickory. The U.S. Forest Service conducts a survey every five years and reports statistics on the area of each forest type that is in various productivity classes, ranging from 1.4 to more than 8.4 cubic meters per hectare per year in stand growth (U.S. Department of Agriculture, Forest Service, n.d.a). This is shown on the left axis in Figure 15 for the period 1992–2017, showing the median year for each five-year survey period.

For each forest type, there is a distribution across productivity classes, with most forest area generally in the middle productivity classes. Over time, the area distribution for loblolly-shortleaf pine forests has shifted rightward toward more productive classes; in the 2017 survey, the highest productivity class of more than 8.4 $m^3$/ha/yr growth represented the greatest area of any class for this forest type. The area distribution for oak-hickory forests has remained fairly constant over time. To help interpret changes in

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[4] According to the U.S. Department of Agriculture, Forest Service. (n.d.a.) (2012, page 20): "Removals can come from two sources: (1) the growing-stock portion of live trees [...]; and (2) other nongrowing stock sources such as tops and stumps." Total removals are thus classified as: Products from growing stocks, products from nongrowing stock, logging residues, other removals.

area distribution, we calculate a productivity index, which represents an area-weighted average productivity for each forest type, assuming the median productivity of each class of 11.2 $m^3$/ha/yr for the less than 8.4 $m^3$/ha/yr class, shown on the right axis in Figure 15. We provide more detail on the calculation of the productivity index in the Appendix. The productivity index increases 16% from 6.6 to 7.7 $m^3$/ha/yr for loblolly-shortleaf pine and remains stable at around 5.5 $m^3$/ha/yr for oak-hickory forests over this period. It is thus clear that the average productivity of loblolly-shortleaf pine forests in the southeastern United States has increased over the past 25 years, while that of oak-hickory forests has not. Unfortunately, to the best of our knowledge, there is no data available on the prevalence of silvicultural practices such as site preparation, thinning, and fertilization in the United States, so we are unable to assess in detail the possible underlying drivers of this trend.

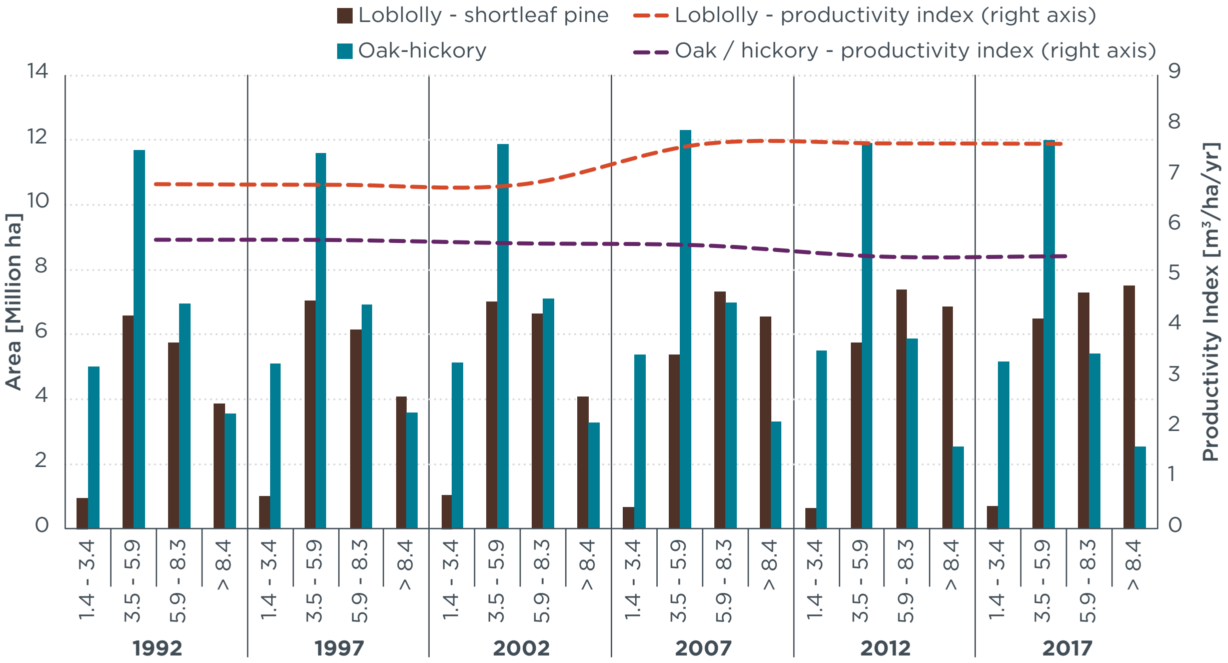

**Figure 15.** Area in each stand productivity class (provided in the X-axis in cubic meters per hectare per year) for the two main stand compositions in private forests in the southeastern United States. (left axis) and productivity index (right axis). Source: U.S. Department of Agriculture, Forest Service (n.d.a,b).

We find that the productivity index is significantly positively correlated with pellet production as well as pine pulpwood prices. This suggests that bioenergy demand may have been a positive driver of productivity improvements in pine plantations, generally supporting the assumption in Jonker et al. (2014) and Jonker et al. (2018) that bioenergy demand could result in higher forest productivity. However, it is important to place the specific assumptions on productivity found in the literature in the context of the range of observed historical productivity improvements. Jonker et al. (2014) included a high-productivity scenario with an average yield of 9.7 dry tonnes/ha/yr, roughly equivalent to 21 $m^3$/ha/yr.[5] However, the historical data show that until 2017, only a negligible 0.2% portion of the stand area was reported to have a productivity of more than 7.2 dry t/ha/yr, roughly equivalent to 15.7 $m^3$/ha/yr.[6] The median yield of 5.6 dry t/ha/yr, or 12 $m^3$/ha/yr, assumed by Jonker et al. (2014) appears instead more reasonable,

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[5] Assuming a density of 450 kg/$m^3$.

[6] Resource Planning Act Assessment reports report productivity up to 8.4 $m^3$/ha/yrHowever, this productivity level is too low for current loblolly pine plantations. The U.S. Forest Service reports data with productivity classes up to 15.7 $m^3$/ha/yr. Based on the latest available data for loblolly pine yields, our productivity index considers a value for the highest productivity class, which is equal to 11.2 $m^3$/ha/yr.

although still very much at the high end of the range of reported values. Jonker et al. (2018) assume average yields of roundwood of almost 9 dry t/ha/yr, or around 20 $m^3$/ha/yr, for conventional pine cultivation, which is more than double current average pine yields. Thus, while there is evidence that a recent increase in productivity of U.S. loblolly-shortleaf forests may be due to bioenergy demand, the scale of productivity increases assumed in studies on U.S. bioenergy cannot be supported by observed data.

### Tree species

Data assessed in the previous section make clear that not only is the productivity of the U.S. softwood species loblolly-shortleaf pine increasing while that of hardwood oak-hickory is not, but also the softwood species deliver consistently higher productivity than the hardwood mix. In addition, most pine stands are intensively managed plantations, while hardwood stands are mainly naturally regenerated forests (U.S. Department of Agriculture, Forest Service, n.d.a). A shift from the lower-yielding hardwoods to more productive pines is in fact something that modeling studies (Galik and R.C. Abt, 2016; Duden et al., 2017) suggest might happen in response to bioenergy demand, contributing to the overall forest productivity increase they assume in their studies.

Indeed, the area with planted pine has grown from 17% to 23% of all timberland area in the past 20 years. Figure 16 shows the total area of softwood and hardwood timberlands in U.S. South since the 1950s (left axis). From the 1950s until the 1980s, hardwood area increased, most likely following natural regeneration of abandoned cropland, while softwood area declined. Area began to shift back to softwoods starting in the late 1990s. The increase in softwood area occurs over a similar period as the increase in pine pulpwood prices (Figure 16, right axis). We find a significant positive correlation between these two variables, and it is logical that an increase in pine pulpwood price could drive an increase in pine area. However, the increase in both pine pulpwood prices and pellet production (Figure 13) began in 2008–2012, while the expansion of softwood area began in the late 1990s. It thus seems likely that factors other than bioenergy demand spurred the reversal from area loss to gain for U.S. softwood timber. While it is possible that bioenergy demand caused the increase in softwood area since around 2010, it is not clear that it is likely to be the sole or main driver of this trend.

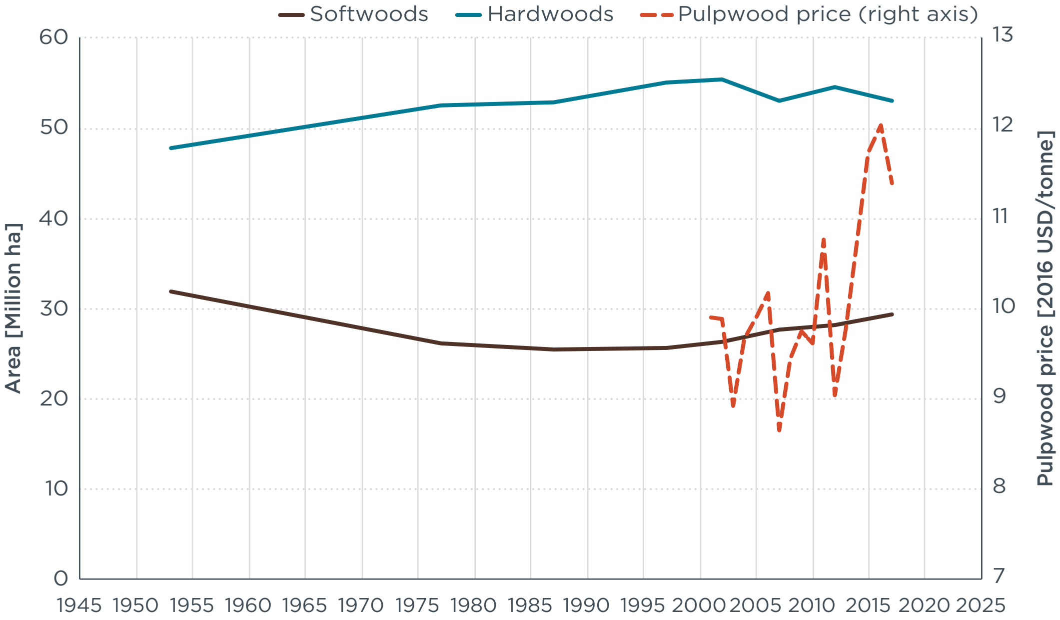

**Figure 16.** Area of softwood and hardwood timber species (left axis) in the U.S. South in relation to pine pulpwood prices (right axis). Source: U.S. Department of Agriculture Forest Service (n.d.a)

### Afforestation

Several studies (K.L. Abt et al., 2014; Galik and R.C. Abt, 2016; Duden et al., 2017) predict that bioenergy demand will increase total forest area by preventing baseline deforestation. These studies follow Wear and Greis (2013), which projects a large loss of forest land to urban development in the southeastern United States over the coming 30 years.

Historical evidence supports the point that urban development contributes to deforestation, but this appears to be balanced out by afforestation from other land uses. Jeffries and Leslie (2017) report that urban development in the U.S. was indeed the main cause of deforestation from 1982 to 2012, accounting for 49% of total deforestation. Statistics from the U.S. Department of Agriculture (n.d.a) indicate that around 6 Mha, or 8%, of total forest land in the U.S. South was lost from 1964–1987, while at the same time developed land expanded by around 4 Mha. However, in recent years the U.S. South has actually seen an increase in forest area of around 3 Mha (Figure 17). This pattern contrasts sharply with the assumption in K.L. Abt et al. (2014) that 3.8 Mha of timberland will be lost from 2010 to 2040. Furthermore, timberland area has increased since the late 1980s despite an increase in urban land of 2.3 Mha from 1982–2012 (Jeffries & Leslie, 2017).

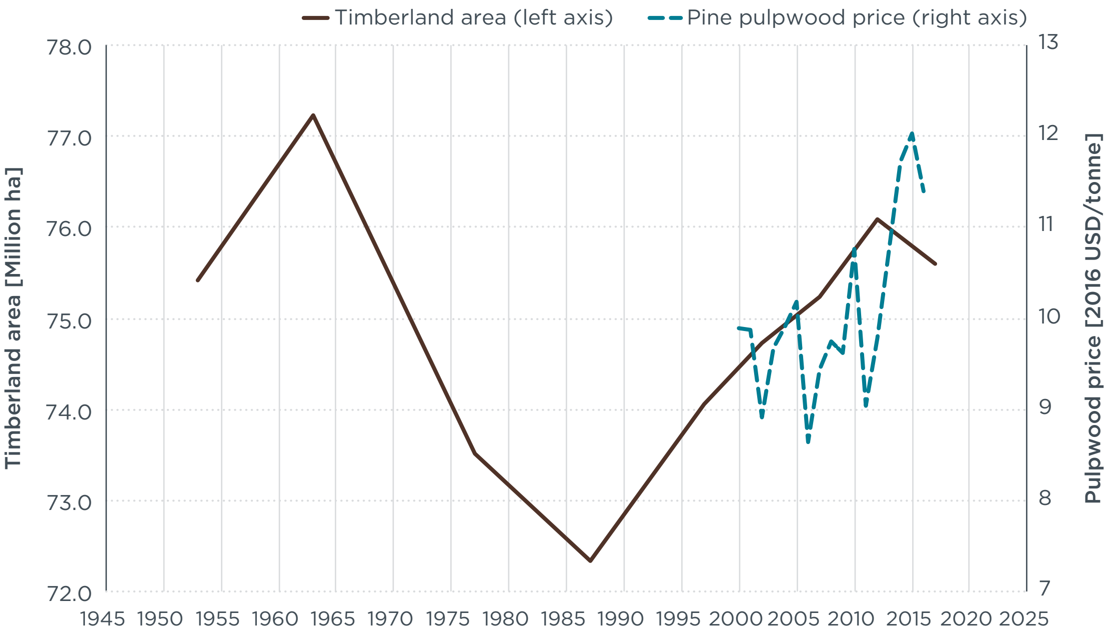

**Figure 17.** Timberland area in the southeastern United States for all ownership categories (left axis) and prices for pine pulpwood (right axis). Source: U.S. Department of Agriculture Forest Service (n.d.a)

Pulpwood prices, shown on the right axis in Figure 17, increased over some of the same time period as the increase in timberland area. However, the afforestation trend began far earlier than the recent increase in pulpwood prices, which started around 2012, and we find no correlation between the two variables. It thus seems likely that afforestation from the late 1980s has been driven by other factors such as cropland abandonment, rather than having any specific link to bioenergy. Cropland area declined by 8.6 Mha from 1982–2012, and over this period 86% of afforestation took place on declining cropland and pastureland (Jeffries & Leslie, 2017).

### Timber products composition

We may expect to see a shift in the production of large saw logs toward increased small-diameter pulpwood if bioenergy demand increases the relative value of pulpwood. This is relevant because, as shown by Jonker et al. (2018), the management of plantations with the goal of optimizing total wood yield for bioenergy reduces carbon benefits compared with traditional management. This is because total yields may be increased through shorter rotations and greater production of small-diameter pulpwood with less production of saw timber-quality roundwood. A plantation with less saw timber would in turn be expected to produce fewer long-lived harvested wood products and thus to limit the benefits of the associated carbon storage in the products and the substitution benefits of high carbon-intensity structural and nonstructural construction elements such as steel and concrete.

However, the relationship between bioenergy demand and long-lived wood products may not be what Jonker et al. (2018) modeled. Composite wood products such as oriented strand board, fiberboard, and particleboard can be made from small-diameter pulpwood and still provide storage and substitution benefits as building and furniture materials. Figure 18 shows that the use of composite products has been increasing since the 1960s, while the total amount of traditional lumber including plywood and other veneer products remained constant from the mid-1980s through the mid-2000s. The production of all wood products took a steep dive around the time of the Financial Crisis in the late 2000s and has yet to fully recover.

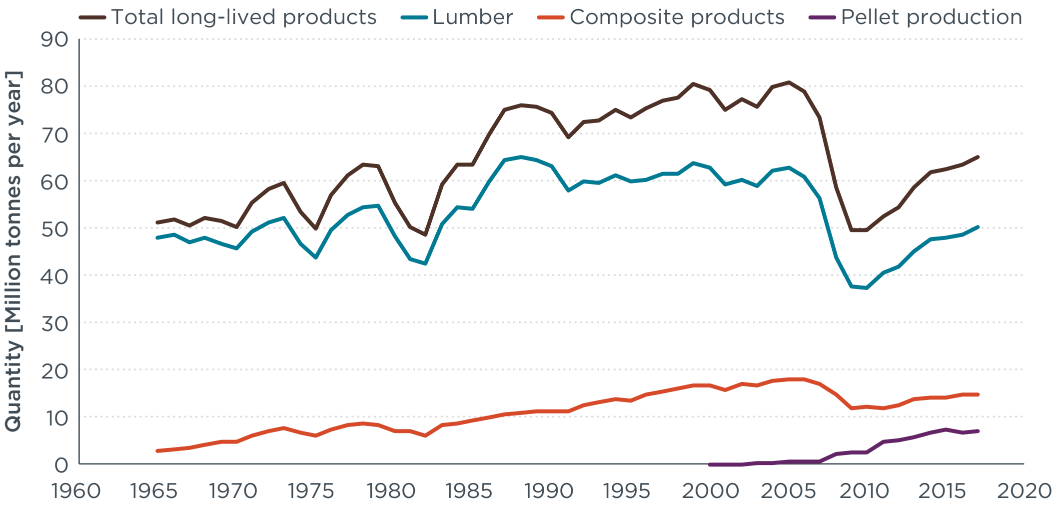

**Figure 18.** U.S. national production of long-lived wood products and pellet production in the southeastern United States. Source: Howard & Jones (2016).

We therefore would not expect a shift in forest management toward smaller-diameter pulpwood to necessarily affect the use of long-lived wood products. In fact, it is possible that technological advances in the production and use of composite products could be shifting forest management toward smaller-diameter trees anyway, regardless of any influence of bioenergy demand, and without negatively affecting the overall carbon balance. Even though the carbon effects of plantations managed with shorter rotations and younger stands may be positive, trade-offs with other ecosystem services, especially habitat quality, should be investigated carefully (Williams, 2018).

If anything, the rise in composite products is likely to tighten competition between pellets and long-lived wood products as they use the same raw materials (Jonsson & Rinaldi, 2017). This could theoretically increase the use of nonbiological building materials such as concrete. However, it is not clear from the trends shown in Figure 18 that pellet production has directly influenced the output of composite products over the past decade.

### Pulp and paper demand

Some studies argue that bioenergy demand has provided a market for stranded pulpwood plantations originally established to meet pulp and paper demand, and that U.S. pulpwood is therefore available for bioenergy with no indirect climate consequences (Dale, Parish, Kline, & Tobin, 2017; Jonker et al., 2014).

Demand for graphic paper, newsprint, and printing and writing paper has been declining since the late 1990s, consistent with the rise in the use of computers. This trend is shown in Figure 19, along with output of other paper products and paper recycling rates. Total production of pulp for paper mirrors the decline in printing and writing paper. On the other hand, packaging and wrapping paper, reflecting expanding trade and e-commerce, as well as household and sanitary paper show steady or even slightly rising production levels. Part of the decline in pulp production can also be explained by improvements in resource efficiency and use of recovered paper from recycling.

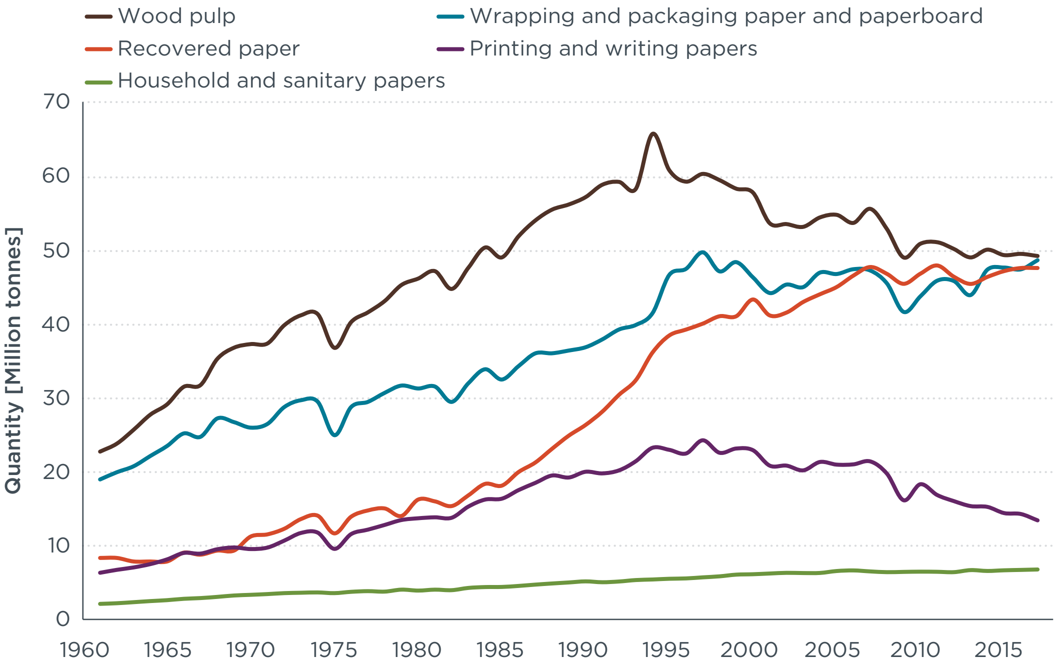

**Figure 19.** Production of pulp and paper products in the United States. Source: FAOSTAT (n.d.).

The evidence supports the conclusion that bioenergy may be replacing the use of pulpwood and sawmill by-products for paper products. However, that does not mean that this resource is available for bioenergy without climate impacts, as argued by Dale, Parish, Kline, & Tobin (2017) and Jonker et al. (2014). If stranded pulpwood plantations were not harvested for bioenergy, the forest carbon stock would remain standing, providing carbon storage benefits (Ter-Mikaelian, Colombo, & Chen, 2015). The reduction in forest carbon stock when harvesting these trees for bioenergy should be accounted for in estimating the GHG balance of bioenergy.

### U.S. summary

There is evidence that bioenergy demand may have been one of the drivers for modest gains in the productivity of pine plantations and expansion of softwood plantations, but not to any other changes in U.S. forests that could improve the GHG balance of bioenergy. The average productivity of loblolly-shortleaf pine plantations in the southeastern United States has increased by around 15% at the same time that U.S. pellet production has ramped up, far less than the doubling assumed in some bioenergy studies. There is little or no evidence that bioenergy has led to an increase in the harvest of logging residues, an increase in total forest area compared with the baseline trend, changes in tree species, or any changes in wood products composition. Although it is possible that bioenergy may use stranded pulpwood plantations no longer needed for paper production, the harvesting of this resource reduces forest carbon stocks, negatively affecting the GHG balance of bioenergy. Overall, there is little evidence for U.S. forest management changes mitigating the carbon debt of bioenergy in recent years.

**Table 3.** Summary of evidence that bioenergy demand may have led to forest management improvements in the United States.

| Literature assumption | Historical trend | Evidence trend driven by bioenergy demand | Consequences for carbon accounting of bioenergy |
|---|---|---|---|
| **Increased removal of logging residues.** | Logging residue removal has remained stable while pellet production has increased. | None. There seems to be no connection between residues removal and pellet production. | Increased residue removal would have improved GHG performance of bioenergy. Evidence suggests this has not occurred. |
| **More intensive site preparation and tending practices that dramatically improve stand productivity.** | Average productivity of pine plantations has increased in the last 20 years. | Likely. Productivity significantly positively correlated with pellet production and pulpwood prices. | Increased productivity improves the GHG balance of bioenergy. This effect is likely to be smaller than assumed in the literature. |
| **Shift from natural hardwood forests to more productive softwood plantations.** | Softwood area has increased, but this trend started before the ramp-up in pellet production. | Plausible. Softwood area significantly positively correlated with pulpwood prices, but the softwood area increase began much earlier than bioenergy ramp-up. | Increased softwood area would improve the GHG balance of bioenergy. |
| **Afforestation compared with a baseline of declining forest area.** | Timberland area has been increasing steadily since the late 1980s, well before the ramp-up in pellet production. | Likely none. Timberland area trend appears to be caused by other factors. | Afforestation or avoided deforestation would improve GHG balance. Evidence suggests this has not occurred. |
| **Reduction in long-lived harvested wood products.** | Increased use of composite wood products, which can be from pulpwood. | Unlikely. Production of both pellets and composite wood products has increased together, although it is possible wood pellet production has slowed growth in composite wood product consumption. | A reduction in long-lived wood products would worsen GHG balance |
| **Pulpwood free of indirect effects due to declining paper industry.** | Declining pulp demand due to reduced graphic paper production and increased recycling. | None. | None. Use of stranded pulpwood plantations for bioenergy reduces forest carbon stock, which must be accounted for. |

# CONCLUSIONS AND POLICY RECOMMENDATIONS

Given the large spread of estimated carbon payback times and carbon accounting models published across the literature, it can be difficult for policymakers to understand the net carbon impacts of forest bioenergy. In this study, we reviewed several prominent, well-cited studies that reported relatively low carbon payback times for forest bioenergy and concluded that bioenergy can provide climate change mitigation within a reasonable timeframe. We find that these studies rely on assumptions that bioenergy demand will spur substantially more-efficient forest management or increases in forest area to reach their findings of low carbon payback times.

This study presents the most extensive comparison of bioenergy literature assumptions and historical evidence of forest management changes published to date. We assess the available historical record looking for indicators of the types of forest management improvements assumed by studies estimating a favorable GHG balance for bioenergy in Canada, Sweden, and the United States. In particular, we assess whether there is evidence that the recent increase in bioenergy demand over the past decade has resulted in any of these assumed responses that might improve the carbon balance of that bioenergy. We find:

- **Weak evidence that bioenergy demand increases collection of tree tops and branches in Canada and Sweden, although data availability is poor.** Bioenergy demand does not appear to have increased the collection of logging residues—treetops and small branches—in the United States. In Sweden, logging residues have been used for energy for many years, but the latest statistics indicate that forest fuels may be mainly composed of roundwood and fuelwood, rather than slash. In Canada, bioenergy demand may have decreased the amount of residues burned in the forest and increased usage of wood from trees killed by an extensive mountain pine beetle infestation. Availability of statistical data on quantities and types of residues collected is a limiting factor to the analysis. The use of tops and branches for bioenergy could achieve positive carbon balance in the short term, so the lack of evidence of increased use of these feedstocks indicates that current forest bioenergy is most likely not mitigating climate change as effectively as thought or at all. Nonetheless, the use of forest residues that would have been burned in the forest guarantees immediate carbon benefits, and there is evidence that this is taking place in British Columbia.
- **Moderate evidence that bioenergy demand drives more-intensive forest stand management, which may have a weak positive effect on growth.** Productivity of forests in Sweden and pine forests in the United States has increased alongside bioenergy demand. In Sweden, this is mainly a result of legacy management and a more favorable growing climate, but we find that bioenergy may have played a role in increasing thinning operations. In the United States, loblolly pine plantations have seen increasing productivity, but this effect is far smaller than the magnitude assumed in the bioenergy literature. There is little evidence that bioenergy has contributed to either improved forest management or growth in Canada, where public policy incentives are the main drivers for change in forest management. The bioenergy literature relies on improved silvicultural practices for positive carbon balances for forest bioenergy, but we find that either bioenergy demand is not driving these changes, or it does so to a much smaller degree than assumed in the literature. One possible reason for this finding is that forest owners may be hesitant to invest in management changes that will not produce higher revenue for several decades in response to short-term changes in wood prices.

- **Weak evidence that bioenergy demand drives a shift toward higher-yielding tree species during replanting.** There is evidence that area planted with high-yielding pine species is expanding in the United States and Sweden, while improved genotypes are being planted in Canada. Bioenergy demand may have contributed to the increases in Sweden and the United States but not in Canada, and these changes may be driven by other factors. Higher-yielding species increase forest landscape productivity and deliver additional biomass which can be used for bioenergy with positive carbon benefits. Nonetheless, broader considerations on forest ecosystem health should be also taken into account.
- **No evidence that bioenergy demand results in increased forest area compared with a baseline scenario.** There are fluctuating historical trends in total forest area across the three countries studied, but in none of them has the trend clearly changed with the ramp-up in bioenergy demand. There is stronger evidence that changes in forest area are driven by other factors, for example cropland abandonment in the United States. This is critical for the carbon balance of forest bioenergy since multiple sources in the literature link the carbon benefits of forest bioenergy to its capacity to limit deforestation in the southeastern United States.

In general, where we do find a link between bioenergy demand and forest management responses, it is weaker than assumed in the bioenergy literature. Overall, we find that most assumptions on forest management changes in these studies cannot be justified by the available evidence. The historical evidence better supports studies that assume little or no change in forest management—and these studies tend to estimate longer carbon payback times and lower climate benefits than the literature reviewed in depth here.

Our findings indicate that policies that only promote bioenergy from forest biomass without conditional requirements on forest management practices most likely do not deliver GHG benefits over a reasonable timeframe. Climate mitigation from bioenergy can be ensured only if policies require biomass to be additional, leading to improved land carbon balance, either through increased sustainable collection of harvesting residues or through stimulating additional growth such as on previously unused, nonforested land.

For bioenergy policies to provide any meaningful carbon benefit, it is necessary to couple the demand for forest biomass with specific measures to improve forest management to increase carbon stocks and biomass output simultaneously. Our specific recommendations are:

- Provide support only for additional biomass that is produced without reducing growing carbon stocks. This includes:
  - Additional collection of logging residues—treetops and small branches, not stumps or small trees—at sustainable levels that do not significantly adversely impact soil organic carbon or biodiversity.
  - Additional harvesting of trees killed by pests and infections.
  - Additional production of biomass on unused land with low carbon stocks, for example abandoned agricultural land, although establishing new forest plantations would achieve benefits mainly in the longer term.
- If stemwood or whole trees from existing forests are harvested for bioenergy, it is not clear that climate mitigation can be achieved even with aggressive forest management improvements. However, if these resources are to be incentivized for reasons beyond climate mitigation, the carbon debt can be somewhat reduced by requiring or encouraging:

- Collection of wood from multiple rounds of thinning at early to middle stages of growth, provided that the operations are additional and are carried out under proper silvicultural guidelines.
- Selection of faster-growing species for replanting harvested areas. However, a holistic view should always be applied to assess consequences on ecosystem health, resilience, and biodiversity.
- Increased fertilization rates and extent, placing great care to account for all related GHG emissions and to minimize negative impacts on ecosystems and waterways.

# REFERENCES

Abt, K.L., Abt, R.C., Galik, C.S., & Skog, K.E. (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 (General Technical Report SRS-202). Retrieved from U.S. Forest Service – Southern Research Station https://www.srs.fs.usda.gov/pubs/47281

Agostini, A., Boulamanti, A.K., & Giuntoli, J. (2014). Carbon accounting of forest bioenergy. Conclusions and recommendations from a critical literature review [JRC Scientific and Policy Report nr. EUR 25354]. Retrieved from European Union Publications https://publications.europa.eu/en/publication-detail/-/publication/e6c29d5b-2bef-4ec4-93f5-c3f672af0b47

Alkama, R. & Cescatti, A. (2016). Climate change: Biophysical climate impacts of recent changes in global forest cover. *Science*, *351(6273),* 600 – 604.

Bernier, P. & Paré, D. (2013). Using ecosystem $CO_2$ measurements to estimate the timing and magnitude of greenhouse gas mitigation potential of forest bioenergy. *GCB Bioenergy, 5,* 67 – 72. doi: 10.1111/j.1757-1707.2012.01197.x

Bertills, U. & Nasholm, T. (2000). Effects of Nitrogen Deposition on Forest Ecosystems, Report 5067, Swedish Environmental Protection Agency. Retrieved from Swedish EPA http://swedishepa.se/Documents/publikationer/620-6137-2.pdf

Booth, M. (2018). Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy. *Environmental Research Letters* 13: 035001. doi: 10.1088/1748-9326/aaac88 of residues burned for bioenergy

Bradburn, K. (2014). 2014 CANBIO Report on the Status of Bioenergy in Canada. Retrieved from CANBIO http://www.fpac.ca/publications/2014_CanBio_Report.pdf

British Columbia Ministry of Forests and Range. (2006). Timber tenures in British Columbia: Managing public forests in the public interest. Retrieved from https://www.for.gov.bc.ca/ftp/dpg/external/!publish/!web/tenures/timber-tenures-2006.pdf

Brunberg, T. (2010). "Skogsbränsle: metoder, sortiment och kostnader 2009. [Forest fuel: methods, assortment and costs]" Skogforsk. Retrieved from https://www.skogforsk.se/kunskap/kunskapsbanken/2010/Skogsbransle-metoder-sortiment-och-kostnader-2009/

Camia, A., Robert, N., Jonsson, R., Pilli, R., Garcia-Condado, S., Lopez-Lozano, R. van der Velde, M. et al. (2018). Biomass production, supply, uses and flows in the European Union. First results from an integrated assessment [JRC Science for Policy report nr. EUR 28993]. Retrieved from European Union Publications https://publications.europa.eu/en/publication-detail/-/publication/358c6d4b-1783-11e8-9253-01aa75ed71a1

Cintas, O., Berndes, G., Cowie, A.L., Egnell, G., Holmström, H., & Ågren, G.I. (2016). The climate effect of increased forest bioenergy use in Sweden: Evaluation at different spatial and temporal scales. *WIREs Energy and Environment, 5,* 351 – 369. doi: 10.1002/wene.178.

Cintas, O., Berndes, G., Hansson, J., Poudel, B.C., Bergh, J., Börjesson, P., … Nordin, A. (2017). The potential role of forest management in Swedish scenarios towards climate neutrality by mid century. *Forest Ecology and Management, 383,* 73 – 84. doi: 10.1016/j.foreco.2016.07.015.

Copley, A. (2018). *Wood Bioenergy Update: Q1 2018*. Retrieved from Forisk http://forisk.com/blog/2018/02/05/wood-bioenergy-update-q1-2018/

Cortini, F., Comeau, P.G., Boateng, J.O., & Bedford, L. (2010). Yield implications of site preparation treatments for lodgepole pine and white spruce in Northern British Columbia. *Forests, 1,* 25 – 48. doi: 10.3390/f1010025.

Dale, V.H., Kline, K.L., Parish, E.S., Cowie, A.L., Emory, R., Malmsheimer, R.W., … Wellisch, M. (2017), Status and prospects for renewable energy using wood pellets from the southeastern United States. *GCB Bioenergy, 9,* 1296 – 1305. doi: 10.1111/gcbb.12445.

Dale, V.H., Parish, E., Kline, K.L., & Tobin, E. (2017). How is wood-based pellet production affecting forest conditions in the southeastern United States? *Forest Ecology and Management, 396,* 143 – 149. doi: 10.1016/j.foreco.2017.03.022.

Duden, A.S., Verwij, P.A., Junginger, H.M., Abt, R.C., Henderson, J.D., Dale, V.H., … van der Hirst, F. (2017). Modeling the impacts of wood pellet demand on forest dynamics in southeastern United States. *Biofuels Bioproducts & Biorefining, 11,* 1007 – 1029. doi: 10.1002/bbb.1803.

Ecological Framework of Canada. (n.d.) Ecozone and Ecoregion Descriptions. Retrieved from http://ecozones.ca/english/zone/index.html

Egnell, G. & Björheden, R. (2016). Options for increasing biomass output from long-rotation forestry. *WIREs Energy and Environment, 2(4),* 465 – 472. doi: 10.1002/wene.25.

Ekstrom, H. (2017). *Almost 50% of the fiber feedstock for wood pellet plants in the US South was industry and forest residues in the 1Q/17, up from 33% five years ago.* Retrieved from Wood Resources International LLC http://news.cision.com/wood-resources-international-llc/r/almost-50--of-the-fiber-feedstock-for-wood-pellet-plants-in-the-us-south-was-industry-and-forest-res,c2213284

Elfving, B., Ericsson, T., & Rosvall, O. (2001.) The introduction of lodgepole pine for wood production in Sweden – a review. *Forest Ecology and Management,* 141: 15-29. doi: 10.1016/S0378-1127(00)00485-0.

Emilsson, S. (2006). *International Handbook: From Forest Extraction of Forest Fuels to Ash Recycling.* Retrieved from Swedish Forest Agency http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=Recash_International_Handbook_Final2006_EN.pdf

Energimyndigheten. (n.d.). Production of unprocessed primary forest fuels of domestic origin by fuel type, GWh, 2013-. Retrieved from http://pxexternal.energimyndigheten.se/pxweb/en/Produktion%20av%20of%C3%B6r%C3%A4dlade%20tr%C3%A4dbr%C3%A4nslen/-/EN0122_3.px/?rxid=2317b153-6985-401d-96e3-354d614f9cde

Environment and Climate Change Canada. (2018). *Clean fuel standard regulatory design paper.* Retrieved from https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/clean-fuel-standard-regulatory-design-paper-2018-en.pdf

European Academies Science Advisory Council (EASAC). (2017). Multi-functionality and sustainability in the European Union's forests [EASAC policy report 32]. Retrieved from European Academies Science Advisory Council https://easac.eu/publications/details/multi-functionality-and-sustainability-in-the-european-unions-forests/

European Commission. (2016). Commission staff working document. Impact Assessment. Sustainability of Bioenergy, accompanying the document Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast). Retrieved from https://eur-lex.europa.eu/resource.html?uri=cellar:1bdc63bd-b7e9-11e6-9e3c-01aa75ed71a1.0001.02/DOC_1&format=PDF

European Parliament & Council of the European Union. (2009). 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. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?%20qid=1467128713306&uri=CELEX:32009L0028

European Parliament & Council of the European Union. (2018). Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). Official Journal of the European Union, L 328/82, 21 December 2018. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L200.

EUROSTAT. (n.d.). *Supply, transformation and consumption of renewables and wastes*. Retrieved from https://ec.europa.eu/eurostat/data/database

FAOSTAT. (n.d.). Forestry Production and Trade. Retrieved from http://www.fao.org/faostat/en/#data

Galik, C.S. & Abt, R.C. (2016). Sustainability guidelines and forest market response: an assessment of European Union pellet demand in the southeastern United States. *GCB Bioenergy, 8,* 658 – 669. doi: 10.1111/gcbb.12273.

Giuntoli, J., Caserini, S., Marelli, L., Baxter, D., & Agostini, A. (2015). Domestic heating from forest logging residues: environmental risks and benefits. *Journal of Cleaner Production, 99,* 206 – 216. doi: 10.106/j.clepro.2015.03.025.

Government of British Columbia. (n.d.a). Provincial Inventory. Retrieved from https://www2.gov.bc.ca/gov/content/environment/climate-change/data/provincial-inventory

Government of British Columbia. (n.d.b). Forests for tomorrow. Retrieved from https://www2.gov.bc.ca/gov/content/environment/natural-resource-stewardship/land-based-investment/forests-for-tomorrow

Government of British Columbia. (n.d.c). Summary data - Change in silviculture treatments. Retrieved from https://catalogue.data.gov.bc.ca/dataset/indicator-summary-data-trends-in-silviculture-in-b-c-/resource/33055c65-ac86-4612-a4e8-bda7e1973830

Government Offices of Sweden. (2019). Sweden's draft integrated national energy and climate plan. Retrieved from https://www.government.se/reports/2019/01/swedens-draft-integrated-national-energy--and-climate-plan/

Hallsby, G., Ulvcrona, K.A., Karlsson, A., Elfving, B., Sjörgen, H., Ulvcrona, T., & Bergsten, U. (2015). Effects of intensity of forest regeneration measures on stand development in a nationwide Swedish field experiment. *Forestry*, 88: 441-453. doi: 10.1093/forestry/cvp010.

Hammel, D. (2015). *Bioenergy in Europe Threatens North American Wetland Forests.* Retrieved from Natural Resources Defense Council (NRDC) https://www.nrdc.org/experts/debbie-hammel/bioenergy-europe-threatens-north-american-wetland-forests

Hedwall, P.-O., Gong, P., Ingerslev, M., & Bergh, J. (2014). Fertilization in northern forests – biological, economic and environmental constraints and possibilities. *Scandinavian Journal of Forest Research*, 29:4, 2014. doi: 10.1080/02827581.2014.926096.

Howard, J.L. & Jones, K.C. (2016). U.S. timber production, trade, consumption, and price statistics, 1965-2013. USDA Forest Service, Forest Products Laboratory, Research Paper FPL-RP-679. Retrieved from https://www.fs.usda.gov/treesearch/pubs/50895

Industrial Forestry Service Ltd. (2015). Wood based biomass in British Columbia and its potential for new electricity generation. Retrieved from BC Hydro https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/regulatory-planning-documents/integrated-resource-plans/current-plan/rou-characterization-wood-based-biomass-report-201507-industrial-forestry-service.pdf

Jeffries, H.M. & Leslie, T. (2017). *Historical perspective on the relationship between demand and forest productivity in the US South.* Retrieved from Forest2Market Inc. https://www.forest2market.com/hubfs/2016_Website/Documents/20170726_Forest2Market_Historical_Perspective_US_South.pdf

Jonker, J.G.G., Junginger, M., & Faaij, A. (2014). Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States. *GCB Bioenergy, 6,* 371 – 389. doi: 10.1111/gcbb.12056.

Jonker, J.G.G., van der Hilst, F., Markewitz, D., Faaij, A.P.C., & Junginger, H.M. (2018). Carbon balance and economic performance of pine plantations for bioenergy production in the Southeastern United States. *Biomass and Bioenergy, 117,* 44 – 55. doi: 10.1016/j.biombioe.2018.06.017.

Jonsson R. & Rinaldi, F. (2017). The impact on global wood-product markets of increasing consumption of wood pellets within the European Union. *Energy,* 133, 864 – 878. doi: 10.1016/j.energy.2017.05.178.

Laganière, J., Paré, D., Thiffault, E., & Bernier, P.Y. (2017). Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests. *GCB Bioenergy, 9,* 358 – 369. doi: 10.1111/gcbb.12327.

Lang, A. (2016). *Wood Bioenergy Update: Q1 2016*. Retrieved from Forisk http://forisk.com/blog/2016/02/25/wood-bioenergy-update-q1-2016/

Legislative Assembly of British Columbia. (2002). Forest and Range Practices Act [SBC 2002] Chapter 69. Retrieved from http://www.bclaws.ca/civix/document/id/complete/statreg/02069_01

Lemprière, T.C., Krcmar, E., Rampley, G.J., Beatch, A., Smyth, C.E., Hafer, M., & Kurz, W.A. (2017). Cost of climate change mitigation in Canada's forest sector. *Canadian Journal of Forest Research, 47,* 604 – 614. doi: 10.1139/cjfr-2016-0348.

Lemprière, T.C., Kurz, W.A., Hogg, E.H., Schmoll, C., Rampley, G.J., Yemshanov, … Krcmar, E. (2013). Canadian boreal forests and climate change mitigation. *Canadian Journal of Forest Research, 21,* 293 – 321. doi: 10.1139/er-2013-0039.

Lindahl, K.B., Stens, A., Sandstrom, C., Johansson, J., Lidskog, R., Ranius, T., & Roberge, J.M. (2017). The Swedish forestry model: More of everything? *Forest Policy and Economics* 77: 44-55. Retrieved from https://www.sciencedirect.com/science/article/pii/S1389934115300605

Lundmark, H., Josefsson, T., & Ostlund Lars. (2013). The history of clear-cutting in northern Sweden – driving forces and myths in boreal silviculture. *Forest Ecology and Management,* 307: 112-122. doi: 10.1016/j.foreco.2013.07.003.

Lundmark, T., Bergh, J., Hofer, P., Lundström, A., Nordin, A., Poudel, B.C., Sathre, R., … Werner, F. (2014). Potential roles of Swedish forestry in the context of climate change mitigation. *Forests, 5*, 557 – 578. doi: 10.3390/f5040557.

Luyssaert, S., Jammet, M., Stoy, P.C. Estel, S., Pongrantz, J., Ceschia, E., … Dolman, A.J. (2014). Land management and land-cover change have impacts of similar magnitude on surface temperature. *Nature Climate Change, 4,* 389 – 393. doi: 10.1038/NCLIMATE2196.

Matthews, R., Hogan, G., & Mackie, E. (2018). Carbon impacts of biomass consumed in the EU. Supplementary analysis and interpretation for the European Climate Foundation. Retrieved from the European Climate Foundation https://europeanclimate.org/new-report-carbon-impacts-of-biomass-consumed-in-the-eu/

Murray, G. (2018). Canadian Wood Pellet Update. Retrieved from https://www.pellet.org/images/2018-06-08_GordonMurray.pdf

National Conference of State Legislatures. (2019). State renewable portfolio standards and goals. Retrieved from http://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx

National Forestry Database. (n.d.a). Wood supply. Retrieved from http://nfdp.ccfm.org/en/data/woodsupply.php#_ftn2

National Forestry Database. (n.d.b). Harvest. Retrieved from http://nfdp.ccfm.org/en/data/harvest.php

National Forestry Database. (n.d.c). Regeneration. Retrieved from http://nfdp.ccfm.org/en/data/regeneration.php#tab61

Nilsson, U., Fahlvik, N., Johansson, U., Lundström, A., & Rosvall, O. (2011). Simulation of the effect of intensive forest management on forest production in Sweden. *Forests, 2,* 373 – 393. doi: 10.3390/f2010373.

Noss, R.F., Platt, W.J., Sorrie, B.A., Weakley, A.S., Means, D.B., Costanza, J.K., & Peet, R.K. (2015). How global biodiversity hotspots may go unrecognized: lessons from the North American Coastal Plain, *Diversity and Distribution* 21: 236-244. doi: 10.1111/ddi.12278.

Poudel, B.C., Sathre, R., Bergh, J., Gustavsson, L., Lundström, A., & Hyvönen, R. (2012). Potential effects of intensive forestry on biomass production and total carbon balance in north-central Sweden. *Environmental Science & Policy, 15,* 106 – 124. doi: 10.1016/j.envsci.2011.09.005.

Poudel, B.C., Sathre, R., Gustavsson, L., Bergh, J., Lundström, A., & Hyvönen, R. (2011). Effects of climate change on biomass production and substitution in north-central Sweden. *Biomass and Bioenergy, 35,* 4340 – 4355. doi: 10.1016/j.biombioe.2011.08.005.

Sathre, R., Gustavsson, L., & Bergh, J. (2010). Primary energy and greenhouse gas implications of increasing biomass production through forest fertilization. *Biomass and Bioenergy, 34,* 572 – 581. doi: 10.1016/j.biombioe.2010.01.038.

Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., … Yu, T.-H. (2008). Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, *29*, 1238 – 1240. doi: 10.1126/science.1151861.

Skogsstyrelsen (Swedish Forest Agency). (n.d.a). Statistics. Retrieved from https://www.skogsstyrelsen.se/en/statistics/

Skogsstyrelsen (Swedish Forest Agency). (n.d.b). 01. Regeneration method as percentage of logged area by region, regeneration method and 3-year average. Retrieved from http://pxweb.skogsstyrelsen.se/pxweb/en/Skogsstyrelsens%20statistikdatabas/Skogsstyrelsens%20statistikdatabas__Atervaxternas%20kvalitet/JO0311_1.px/?rxid=effee662-86f9-4874-a4e7-dff32e6d7d93

Skogsstyrelsen (Swedish Forest Agency). (2014). Skogsstatistisk årsbok [Forest Statistic Yearbook]. 2014. Retrieved from https://www.skogsstyrelsen.se/globalassets/statistik/historisk-statistik/skogsstatistisk-arsbok-2010-2014/skogsstatistisk-arsbok-2014.pdf

Smyth, C., Kurz, W.A., Rampley, G., Lemprière, T.C., & Schwab, O. (2017). Climate change mitigation potential of local use of harvest residues for bioenergy in Canada. *GCB Bioenergy, 9,* 817 – 832. doi: 10.1111/gcbb.12387.

Smyth, C.E., Smiley, B.P., Magnan, M., Birdsey, R., Dugan, A.J., Olguin, M., … Kurz, W.A. (2018). Climate change mitigation in Canada's forest sector: a spatially explicit case study for two regions. *Carbon Balance Management, 13,* 11. doi: 10.1186/s13021-018-0099-z.

Smyth, C.E., Stinson, G., Neilson, E., Lemprière, T.C., Hafer, M., Rampley, G.J., & Kurz, W.A. (2014). Quantifying the biophysical climate change mitigation potential of Canada's forest sector. *Biogeosciences, 11,* 3515 – 3529. doi: 10.519/bg-11-3515-2014.

Statistics Canada. (2018). Human activity and the environment 2017: Forests in Canada. Retrieved from https://www150.statcan.gc.ca/n1/pub/16-201-x/16-201-x2018001-eng.htm

Statistikdatabas. (n.d.). Annual average prices on delivery logs, SEK per cubic meter solid volume excl. bark by region, assortment and year. Retrieved from http://pxweb.skogsstyrelsen.se/pxweb/en/Skogsstyrelsens%20statistikdatabas/Skogsstyrelsens%20statistikdatabas__Rundvirkespriser/JO0303_1.px/?rxid=39fc1865-c393-4826-8b70-0dd7c217e638

Strange Olesen, A., Bager, S.L., Kittler, B., Price, W., & Aguilar, F. (2015). *Environmental implications of increased reliance of the EU on biomass from the South East US* (Report for the European Commission, Directorate General for the Environment, ENV.B.1/ETU/2014/0043). Retrieved from European Union publications https://publications.europa.eu/en/publication-detail/-/publication/8005fb30-81e9-4399-9b19-01af823fa42d.

Swedish University of Agricultural Sciences. (n.d.a). Forest statistics. Retrieved from https://www.slu.se/en/Collaborative-Centres-and-Projects/the-swedish-national-forest-inventory/forest-statistics/forest-statistics/

Swedish University of Agricultural Sciences. (n.d.b). Figure 3.30 - Mean annual volume increment, annual drain and annual harvest (1954 - date). Retrieved from http://skogsstatistik.slu.se/pxweb/en/OffStat/OffStat__ProduktivSkogsmark__Tillv%C3%A4xt/PS_Tillv%C3%A4xt_tab.px/?rxid=f371330b-e920-432d-858a-6a2c2a3c8d85

Swedish University of Agricultural Sciences. (n.d.c). Productive forest area for different age classes (1923 - date). Retrieved from http://skogsstatistik.slu.se/pxweb/en/OffStat/OffStat__ProduktivSkogsmark__Areal/PS_Areal_%C3%A5ldersklasser_1923_tab.px/?rxid=f371330b-e920-432d-858a-6a2c2a3c8d85

Swedish University of Agricultural Sciences. (n.d.d). Figure 4.8 - Annual felling area by felling type (1957-date). Retrieved from http://skogsstatistik.slu.se/pxweb/en/OvrStat/OvrStat__Avverkning/AVV_%C3%A5rlig_utf%C3%B6rd_r%C3%B6jning_huggningsarter_fig.px/?rxid=c32336fc-c696-4a17-9f2b-274b7f576000

Swedish University of Agricultural Sciences. (n.d.e). Table 3.1 - Productive forest area for different forest types (1983 - date). Retrieved from http://skogsstatistik.slu.se/pxweb/en/OffStat/OffStat__ProduktivSkogsmark__Areal/PS_Areal_best%C3%A5ndstyper_tab.px/?rxid=f371330b-e920-432d-858a-6a2c2a3c8d85

Swedish University of Agricultural Sciences. (n.d.f). Area of comparable land use classes (1923 - date). Retrieved from http://skogsstatistik.slu.se/pxweb/en/OffStat/OffStat__AllMark__Areal/AM_Areal_%C3%A4goslag_trad_1923_tab.px/?rxid=f371330b-e920-432d-858a-6a2c2a3c8d85

Ter-Mikaelian, M.T., Colombo, S.J., & Chen, J. (2015). The burning question: Does forest bioenergy reduce carbon emissions? A review of common misconceptions about forest carbon accounting. *Journal of Forestry, 113(1),* 57-68. doi: 10.5849/jof.14-016.

Ter-Mikaelian, M.T., Colombo, S.J., Lovekin, D., McKechnie, J., Reynolds, R., Titus, B., ... Maclean, H.L. (2015). Carbon debt repayment or carbon sequestration parity? Lessons from a forest bioenergy case study in Ontario, Canada. *GCB Bioenergy, 7,* 704 - 716. doi: 10.1111/gcbb.12198.

U.S. Department of Agriculture, Forest Service. (n.d.a). *Forest inventory and analysis national program, program features, national assessment – Resources Planning Act (RPA).* Retrieved from https://www.fia.fs.fed.us/program-features/rpa/.

U.S. Department of Agriculture, Forest Service. (n.d.b). *Forest inventory and analysis – southern research station: State inventory data status.* Retrieved from https://www.fs.usda.gov/srsfia/states/state_information.shtml.

U.S. Department of Agriculture, Forest Service. (2012). *Timber product output (TPO) reports.* Retrieved from http://srsfia2.fs.fed.us/php/tpo_2009/tpo_rpa_int1.php.

U.S. Department of Agriculture. (n.d.). *Major land uses*. Retrieved from https://www.ers.usda.gov/data-products/major-land-uses.aspx

U.S. Energy Information Administration (EIA). (2016). *Manufacturing facilities with capacity and status, December 2016*. Retrieved from https://www.eia.gov/biofuels/biomass/?year=2016&month=13

U.S. Energy Information Administration (EIA). (2018). *Monthly densified biomass fuel report*. Retrieved from https://www.eia.gov/biofuels/biomass/?year=2018&month=07#table_data

U.S. Environmental Protection Agency (U.S. EPA). (2010). Regulation of fuels and fuel additives: Changes to renewable fuel standard program (p. 14670-14904). Federal Register: EPA-HQ-OAR-2005-0161; FRL-9112-3.

U.S. Industrial Pellet Association. (2015). *Wood supply market trends in the US South*. Retrieved from https://www.forest2market.com/uploads/Forest2Market/documents/US-South-Wood-Supply-Trends.pdf

UNECE. (2018). *Prices*. Retrieved from https://www.unece.org/forests/output/prices.html

United States Congress. (2018). H.R. 1625 – Consolidated Appropriations Act, 2018. Retrieved from https://www.congress.gov/bill/115th-congress/house-bill/1625

Wear, D.N. & Greis, J.G. (2013). *The southern forest futures project.* Retrieved from U.S. Department of Agriculture, Forest Service https://www.srs.fs.fed.us/pubs/gtr/gtr_srs178.pdf

Williams, T. (2018). Recovery: America's giant squirrel back from the brink. Cool Green Science, The Nature Conservancy: https://blog.nature.org/science/2018/07/24/recovery-americas-giant-squirrel-back-from-the-brink/

Wood Pellet Association of Canada. (n.d.). Canadian wood pellet production. Retrieved from https://www.pellet.org/production/production

World Bank Climate Change Knowledge Portal. (n.d.). Temperature. Retrieved from http://sdwebx.worldbank.org/climateportal/index.cfm?page=downscaled_data_download&menu=historical

Xu, Z., Smyth, C.E., Lemprière, T.C., Rampley, G.J., & Kurz, W.A. (2018). Climate change mitigation strategies in the forest sector: biophysical impacts and economic implications in British Columbia, Canada. *Mitigation and Adaptation Strategies for Global Change, 23,* 257 – 290. doi: 10.1007/s11027-016-9735-7.

Zevenhoven, M., Yrjas, P., & Hupa, M. (2010). Ash-forming matter and ash-related problems. In: Handbook of Combustion. Online. Eds.: Lackner, M., Winter, F., Agarwal, A.K., & Lighty, J.S. Part 4. Chapter 14. ISBN: 9783527628148; DOI: 10.1002/9783527628148. Retrieved from: https://onlinelibrary.wiley.com/browse/book/10.1002/9783527628148/toc

# APPENDIX: METHODOLOGY & LIMITATIONS

**Methodology notes:**

1. Correlations in this study are carried out through Excel's Regression tool in the Data analysis package. We consider linear regressions to be statistically significant if $p<0.05$ throughout the study.

2. In this study we use multiple data sources, reporting data in multiple units, requiring us to define several conversion parameters.

    a. Whenever possible we reported data in the unit from the official reporting. However, when necessary, data for wood products in $m^3$ were converted to kg through a fixed density of 450 kg/$m^3$. We consider this conversion to produce a measure of dry mass.

    b. Data provided on an energy basis (e.g. MJ or MWh) were converted to dry mass through a fixed heating value of 19 MJ/kg dry.

    c. Prices for all commodities were corrected by inflation through Consumer Price Index official statistics. Prices in Swedish Kroners (SEK) and Canadian Dollars were then converted to euros (2017).

3. Statistical data from the U.S. Forest Service on forest productivity are in terms of area occupied by forest stands within a certain class of productivity. To make data comparable between different stand compositions, we collated these values into a "productivity index," a single value for each year representing the weighted average of all productivity classes. To do this, we multiplied the average value of productivity within each class by the area occupied by that specific age class. We then averaged over the whole area for all productivity classes. The highest productivity class is simply reported in U.S. Forest Service's Resource P assessments as 8.4 $m^3$/ha/yr. Furthermore, specific statistics for each state report additional productivity classes up to 15.7 $m^3$/ha/yr. Based on the latest data available (U.S. Department of Agriculture, Forest Service, n.d.b), we calculate that 18% of loblolly-shortleaf pine presents a productivity between 8.4–11.5 $m^3$/ha/yr, 9% between 11.6–15.7 $m^3$/ha/yr and 0% above 15.7 $m^3$/ha/yr. Similarly, we find that for hickory-oak stand compositions, only 6% presents productivity between 8.4–11.5 $m^3$/ha/yr, 1% between 11.6–15.7 $m^3$/ha/yr and 0% above. Therefore, we simplify our calculations by considering for our productivity index that the value for the highest productivity class is equal to 11.2 $m^3$/ha/yr for loblolly pine and to 10.6 $m^3$/ha/yr for oak-hickory stands.

    This approach entails several limitations and is not intended to be used for rigorous calculations, but it serves the purpose of grouping multiple data into a single value, which facilitates our analysis.

4. Similarly, we calculated an age-class index for the Swedish forests. This index is also a weighted average of the area of Swedish forests characterized by different age classes. To calculate the index we used as weights the average value for each age class, while for the highest class (160+ years) we simply chose the value of 160 years.

**Limitations of the study:**

1. Our evaluation of the main assumptions in the studies reviewed appears in the summary section for each country. The summary tables list: i) the main assumption identified; ii) the objective trend resulting from statistical data; iii) a qualitative

assessment of the evidence available that the trend may be driven by bioenergy demand; and iv) an explicit link of the trend with the potential consequences for carbon accounting of forest bioenergy. The qualitative assessment is based mainly on the regression analysis results complemented with additional sectoral information as well as by the expertise of the authors and reviewers.

2. In this study we focus solely on carbon accounting of forest bioenergy and its role in mitigating greenhouse gas emissions by substituting fossil fuels. However, it is important to remember that forests and forest management can affect the local and global climate also through bio-geophysical forcers, such as changes in surface albedo and evapotranspiration (Alkama & Cescatti, 2016; Luyssaert et al., 2014). When we mention the potential role of bioenergy in mitigating climate change, though, it should be interpreted strictly as mitigating greenhouse gas emissions.

3. Similarly, forest ecosystems provide many services beyond carbon accumulation and provision of wood products (EASAC, 2017). Some of the silvicultural practices assessed in this report have a positive effect on the carbon balance of bioenergy. Nonetheless, they may have negative trade-offs on other ecosystem services, and vice-versa. Even if outside the scope of this report, we recommend a holistic view when assessing potential environmental impacts of bioenergy.

4. Data referring to the quantity and type of logging residues collected is unfortunately very scarce globally, for several reasons: 1. Economic interest in residues or non-merchantable wood is relatively recent; 2. Once residues are removed from the forest, they are classified as "products" in forest statistics and are often mixed in the definition of "fuelwood," rendering it impossible to distinguish between slash, whose fate would have been to decay, and logs harvested as fuelwood, whose fate would have been to continue growing. As shown in the chapter on Sweden, efforts for better data collection are being put in place, and it will be easier to verify and check these trends in a few years.

5. Data from forest inventory in the United States is collected gradually via sample plots across the country and is produced at different periods in different states. Reports on forest resources are produced every five years as mandated by the U.S. Forest and Rangeland Renewable Resources Planning Act of 1974. These reports form the invaluable basis of the historical data presented in this report for the southeastern U.S. region. However, data collated under a specific report year may not correspond to the status at exactly that year and may not be coherent across all states of the region. For example, the RPA report for 2012 includes mainly data collected in 2009 and 2011. This could introduce a time bias in our regression as the price data are, supposedly, reported more closely to when they were collected. We have tried to account for this in our regression analysis by introducing time lags and checking whether the regression remained significant.

6. On a similar note, price data do not reflect physical quantities and are thus more subject to uncertainty concerning the way they were collected, the services included, the geographical coverage, and other factors. We tried to find the best available data series, but it is possible that differing series could be found in the literature.