Received: 26 May 2019 | Accepted: 9 August 2019

DOI: 10.1111/gcbb.12643

POLICY COMMENTARY

GLOBAL CHANGE BIOLOGY BIOENERGY WILEY

Serious mismatches continue between science and policy in forest bioenergy

Michael Norton[1] | Andras Baldi[2] | Vicas Buda[3] | Bruno Carli[4] | Pavel Cudlin[5] | Mike B. Jones[6] | Atte Korhola[7] | Rajmund Michalski[8] | Francisco Novo[9] | Július Oszlányi[10] | Filpe Duarte Santos[11] | Bernhard Schink[12] | John Shepherd[13] | Louise Vet[14] | Lars Walloe[15] | Anders Wijkman[16]

[1]EASAC Secretariat, German Academy of Sciences Leopoldina, Halle, Germany

[2]Centre for Ecological Research, Institute of Ecology and Botany, Vácrátót, Hungary

[3]Nature Research Centre, Vilnius, Lithuania

[4]Institute of Applied Physics CNR, Florence, Italy

[5]Global Change Research Institute, Academy of Sciences of the Czech Republic, Ceské Budejovice, Czech Republic

[6]Trinity College Dublin, University of Dublin, Dublin, Ireland

[7]Faculty of Biological and Environmental Sciences, University of Helsinki, Helsinki, Finland

[8]Institute of Environmental Engineering, Polish Academy of Sciences, Zabrze, Poland

[9]The Spanish Royal Academy of Sciences, Madrid, Spain

[10]Institute of Landscape Ecology of the Slovak Academy of Sciences, Bratislava, Slovakia

[11]CCIAM-CE3C, Faculty of Sciences, University of Lisbon, Lisbon, Portugal

[12]Faculty of Biology, University of Konstanz, Constance, Germany

[13]National Oceanography Centre, School of Ocean & Earth Science, University of Southampton, Southampton, UK

[14]Netherlands Institute of Ecology, Wageningen, The Netherlands

[15]Division of Physiology, Institute of Basic Medical Sciences, University of Oslo, Oslo, Norway

[16]The Royal Swedish Academy of Sciences, Stockholm, Sweden

Correspondence
Michael Norton, EASAC Secretariat, German Academy of Sciences Leopoldina, Halle, Germany.
Email: Michael.norton@easac.eu

Abstract

In recent years, the production of pellets derived from forestry biomass to replace coal for electricity generation has been increasing, with over 10 million tonnes traded internationally—primarily between United States and Europe but with an increasing trend to Asia. Critical to this trade is the classification of woody biomass as 'renewable energy' and thus eligible for public subsidies. However, much scientific study on the net effect of this trend suggests that it is having the opposite effect to that expected of renewable energy, by increasing atmospheric levels of carbon dioxide for substantial periods of time. This review, based on recent work by Europe's Academies of Science, finds that current policies are failing to recognize that removing forest carbon stocks for bioenergy leads to an initial increase in emissions. Moreover, the periods during which atmospheric CO_2 levels are raised before forest regrowth can reabsorb the excess emissions are incompatible with the urgency of reducing emissions to comply with the objectives enshrined in the Paris Agreement. We consider how current policy might be reformed to reduce negative impacts on climate and argue for a more realistic science-based assessment of the potential of forest bioenergy in substituting for fossil fuels. The length of time atmospheric concentrations of CO_2 increase is highly dependent on the feedstocks and we argue for regulations to explicitly require these to be sources with short payback periods. Furthermore, we describe the current United Nations Framework Convention on Climate Change accounting rules which allow imported biomass to be treated as zero emissions at the point of combustion and urge their revision to remove the risk of these providing incentives to import biomass with negative climate impacts. Reforms such as these would allow the industry to evolve to methods and scales which are more compatible with the basic purpose for which it was designed.

KEYWORDS
carbon accounting, carbon payback period, converting from coal to biomass, forest bioenergy, perverse incentives, policy, renewable energy, zero emissions

1 | INTRODUCTION

In recent years, the production of wood pellets using forest biomass as feedstock has increased, with industry consultants (Hawkins Wright, 2019) estimating that global industrial pellet production will reach 24 million metric tonnes (Mt) in 2019 (equivalent to a feedstock of ~50 million m^3 of wood). Most of the 'industrial' pellet production is for electricity generation which the International Renewable Energy Agency (IRENA, 2019) records under the 'solid biofuels and renewable waste' category. Here, global generating capacity has risen from 52,146 MW in 2009 to 95,687 MW in 2018, with the most rapid increases occurring (over the same period) in the EU (from 15,912 to 24,081 MW) and Asia (from 14,140 to 34,845 MW). Among the pellets produced globally, over 10 million tonnes are traded internationally—primarily between United States and United Kingdom and some other European countries but also to South Korea and Japan from sources such as Vietnam (IEABioenergy, 2017). This expanding biomass pellet business depends largely on its treatment in regulations that classify forest biomass as 'renewable', so that many countries have turned to biomass to meet their renewable energy targets—currently around half of the European Union (EU)'s 'renewable' energy comes from solid biomass (Berndes et al., 2016; Eurostat, 2019), with the amount of electricity generated from biomass increasing annually from 60.7 terawatt-hours (TWh) in 2009 to 94.7 TWh in 2017 (Eurostat, 2019).

The classification of forest biomass as 'renewable' is based on the reasoning that, since biomass carbon came from atmospheric CO_2 and regrowth absorbs CO_2 over time, it can be regarded as 'carbon neutral' with net emissions over the harvesting/regrowth cycle of zero. The 'carbon neutrality' concept is, however, a gross misrepresentation of the atmosphere's CO_2 balance since it ignores the slowness of the photosynthesis process which takes several decades for trees to reach maturity. This has been pointed out repeatedly (e.g. Agostini, Guiintoli, & Boulamanti, 2014; Berndes et al., 2016; Fisher, Jackson, & Biewald, 2012; Holtsmark, 2012, 2013; Mitchell, Harmon, & O'Connell, 2012; Ter-Mikaelian, Colombo, & Chen, 2015; Zanchi, Pena, & Bird, 2012). Nevertheless, its simplicity brought with it political and economic advantages and led to the inclusion of biomass in the European Commission's definition of renewable energy in its 2009 Renewable Energy Directive (RED; EC, 2009), being treated as 'part of the package of measures required to reduce greenhouse gas (GHG) emissions.'

The RED allowed governments to offer renewable energy subsidies to substitute coal in large power stations with biomass (without which the economics would be unfavourable; Walker, Lyddan, Perritt, & Pilla, 2015), creating the market incentive which has led to the rapid expansion in the demand for forest biomass pellets mentioned above. It is thus of considerable concern that scientific analyses indicate that, far from reducing GHG emissions, replacing coal by biomass for electricity generation is likely to initially increase emissions of CO_2 per kWh of electricity as a result of the lower energy density of wood, emissions along the supply chain, and/or less efficient conversion of combustion heat to electricity (see later). The resulting increase in atmospheric concentrations of CO_2 increases radiative forcing and thus contributes to global warming. This initial negative impact is only reversed later if and when the biomass regrows. Research has shown that the time needed to reabsorb the extra carbon released can be very long, so that current policies risk achieving the reverse of that intended—initially exacerbating rather than mitigating climate change. This issue has been pointed out by many authors (e.g. Booth, 2018; Laganière, Paré, Thiffault, & Bernier, 2017; Schlesinger, 2018; Ter-Mikaelian, Colombo, Lovekin, et al., 2015), and, in the specific context of the EU's policy (KNAW, 2017; Searchinger et al., 2018).

The European Academies Science Advisory Council (EASAC) has brought these issues to the attention of the European Commission in its recent reviews and statements (EASAC, 2017, 2018, 2019) and, during the debate on the revision of the EU's RED in 2018, many scientists (e.g. Beddington et al., 2018) argued against the simplistic assumptions of carbon neutrality and treating biomass as renewable. However, the revised directive (REDII) continues to classify biomass in the same way as solar, wind and other categories of renewable energy. Subsidies continue and other countries (including some of the 29 members of the 'Powering Beyond Coal Alliance') see substituting coal by biomass as a step towards mitigating climate change, thus leading to further expansion. In this commentary, we re-emphasize the reasons why current policy is achieving the opposite of that intended, and why the urgency of its revision has increased following the conclusion of the Paris Agreement.

Concern has also been expressed over the effects of increased forest biomass harvesting on ecosystem biodiversity and losing services such as the ecologic regulation of water and nutrient cycles or soil maintenance (e.g. Immerzeel, Verwuij, Hilst, & Faaij, 2014). However, in this overview, we concentrate on the central question of whether industrial use of forest biomass has a positive or negative impact on climate change mitigation and whether this is adequately recognized in renewable energy policy. Our analysis is specifically focused on forest biomass and does not apply to second-generation short rotation crops, perennial rhizomatous grasses and other feedstocks which have very short payback times (e.g. Heaton, Dohleman, & Long, 2008; Liu et al., 2016).

2 | HISTORICAL PERSPECTIVE

Forestry management has historically included bioenergy production along with construction timber, board manufacture, fibre for paper and other products. Branches, bark and other sawmill residues have produced the energy for driers, heating and in some cases local electricity generation. Within the framework of sustainable forest management, this can be seen as making the best use of available resources, where the fuel is from materials for which there is no higher value use (the 'cascade' principle; EC, 2014). Such a forest managed sustainably to maintain a stable or increasing carbon stock can be characterized as producing no net release of carbon and thus 'carbon neutral'.

Arguably, it was such a scenario which was influential when the EU first defined the renewable energies which should be included in the targets for the 2009 RED. Prior to this, another important decision had emerged from the United Nations Framework Convention on Climate Change (UNFCCC) where, following the Kyoto Protocol, rules for accounting for forestry emissions had to be developed. These started with the assumption that the carbon in a forest should be regarded as released when harvested (regardless of the subsequent use). Thus, when it came to accounting for emissions if forest biomass was burned, the carbon emitted should (for accounting purposes only) be regarded as zero because the forestry carbon had already been counted in the 'land use, land-use change, and forestry' (LULUCF) category. This means that accounting treats the emissions from forest biomass used in a power station as zero, so that when the power station, and the country in which it resides report emissions, these are not included. If the biomass is harvested and burned within the same country, accounting should reflect overall emission trends in that country. However, a consequence unforeseen at the time was that this rule creates an opportunity for a country to import biomass, use it for energy production and zero rate its emissions on the assumption that they are recorded in the exporting country's LULUCF statistics. The importing country can thus shift responsibility for reporting its own emissions from forest biomass to the exporting country (McKechnie, Colombo, & MacLean, 2014) and obtain a free ride on that proportion of its emissions originating from imported biomass.

Classifying biomass as renewable has had major consequences. Concerns over the intermittent nature of solar and wind have led governments to seek a 'renewable' supplier of baseload capacity which can be provided by existing infrastructure. This has led to the substitution of coal by imported wood pellets at a number of facilities across the EU (particularly the United Kingdom but also the Netherlands and Denmark). Renewable energy subsidies are considerable; a single UK power station (Drax) received £789 million in 2018 (https://www.drax.com/investors/—accessed May 10, 2019), while the Netherlands recently confirmed €3.6 billion over 8 years to subsidise biomass added to large energy/coal plants (https://www.rvo.nl/subsidies-regelingen/stimulering-duurzame-energieproductie/feiten-en-cijfers/volg-sde—accessed May 10, 2019). With the large investments already made in conversion and associated pellet mills and infrastructure (including bulk marine transport), substantial economic assets are dependent on this economic model continuing, and thus, stakeholder commitment to the climate neutrality argument is strong and likely to have been a factor in countering the scientific arguments presented to the European Parliament.

3 | CURRENT FOREST BIOENERGY AND CLIMATE CHANGE POLICY DEBATE

The EASAC applies the scientific expertise in Europe's 27 science academies to analysing topical issues where science interacts with European policy (www.easac.eu). One such issue was how best to manage sustainably Europe's forests when they were subject to multiple demands, and EASAC (2017) looked at the science underpinning sustainable forest management and the trade-offs between production, protection of biodiversity and responses to climate change. This and subsequent reports (EASAC, 2018, 2019) examined the issue of substituting fossil fuels by forest biomass, and pointed out that:

1. Woody biomass contains less energy than coal (biomass pellets 9.6–12.2 GJ/m^3; coal 18.4–23.8 GJ/m^3; IEABioenergy, 2017), so that CO_2 emissions for the same energy output are higher (110 kg CO_2/GJ for solid biomass, 94.6–96 kg CO_2/GJ for coals in IPCC, 2006). Combined with the energy needs to gather from diffuse sources and intermediate treatment (drying and pelleting), replacing fossil fuels in electricity generation results in significant increases in emissions of CO_2 per kWh. The net effect of switching to biomass is thus usually to increase emissions and thus increase atmospheric levels of CO_2. This is the reverse effect to the original objectives of the RED to 'decrease GHG emissions'.
2. Biomass is treated as renewable because it is assumed that the CO_2 emitted will be reabsorbed. However, burning forest biomass transmits the carbon from the forest stock to the atmosphere within minutes, and there is a carbon 'payback period' between this initial release and a return to forest carbon stocks through regrowth. This payback period may be of the order of years when forestry residues provide the feedstock. However, where additional trees are harvested the payback periods depends on the species and conditions of regrowth which range from decades to centuries (e.g. McKechnie, Colombo, Chen, Mabee, & MacLean, 2011; Nabuurs, Arets, & Schelhass, 2017; Sterman, Siegel, & Rooney-Varga, 2018; Ter-Mikaelian, Colombo, Lovekin, et al., 2015). In some scenarios, the carbon present in the original forest stock may never be recovered. This means that the concept of carbon neutrality is both uncertain and highly time and context dependent.
3. When climate mitigation policies were being developed, the delay in achieving net reductions in emissions was left out of the regulations. However, the Paris Agreement now commits 'to pursue efforts to limit the temperature increase even further to 1.5°C' (https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement—accessed May 10, 2019). Given that the Intergovernmental Panel on Climate Change (IPCC, 2018) projects that average surface temperatures are likely to exceed 1.5°C between 2030 and 2052 on current trends, payback periods of decades increase the risk of overshooting Paris Agreement targets.
4. Assessing the net effects of switching from coal to forest biomass requires an integrated approach whereby carbon flows along the complete life cycle (including combustion emissions) in the bioenergy scenario are compared with carbon flows in the absence of increased harvesting for bioenergy (a reference or counterfactual scenario). Such analyses should include the reduction in the carbon stock of the forests harvested. Many such studies (e.g. Ricardo, 2016; Stephenson & Mackay, 2014; Sterman et al., 2018; Ter-Mikaelian, Colombo, Lovekin, et al., 2015) have shown that only residues from traditional forestry management (i.e. leftovers after use for timber, board, paper etc.) or naturally fast-decaying wood as a result of forest dieback from diseases or fire have payback periods of the order of years. In contrast, increasing forest stock harvesting of stemwood (whether thinnings or clear-cut) increases atmospheric CO_2 levels for decades to centuries depending on the counterfactual scenarios. The UK Department of Energy and Climate Change (DECC, 2014) developed the Biomass Emissions and Counterfactual (BEAC) model to estimate different feedstock payback times. Buchholz and Gunn (2015) applied the BEAC model to a scenario in which 80% of feedstock came from additional biomass harvests in US hardwoods and found emissions of 2,677 kg CO_2-eq/MWh-over double that of coal. Even scenarios with 65% residues and only 35% of additional harvests exceeded emissions from a coal reference scenario.
5. Even the shortest payback periods compare unfavourably with that of solar and wind which offer net CO_2 emission savings within months to a few years (Marimuthu & Kirubakaran, 2013). Biomass is thus relatively ineffective in reducing CO_2 emissions; yet it is treated equally in regulations and in some EU countries, comprises the largest proportion of renewable energy subsidies.
6. Sustainability criteria in the RED regulations include conditions that biomass should achieve a specified percentage of GHG emission savings relative to fossil fuel. This can be easily misinterpreted to mean that switching from coal to wood is immediately climate beneficial. This is found on industry publicity—for instance, Enviva's home page states 'We export our pellets primarily to power plants in the United Kingdom and Europe that previously were fuelled by coal, enabling them to reduce their lifetime carbon footprint by about 80%' (http://www.envivabiomass.com/about/; accessed April 24, 2019). It is seldom pointed out that this merely limits the emissions along the supply chain (from felling, transport, drying and pelleting,

shipping) to less than the emissions from burning coal, and ignores the carbon emissions when the wood is burned.

7. The UNFCCC accounting rules already mentioned allowing an importing country to count emissions from biomass as zero, are based on the assumption that reductions in forest biomass are accounted in the exporting country's LULUCF statistics. Since implementation and verification of the latter vary considerably between countries, the trade-off between reductions in carbon stock and emissions into the atmosphere at the point of combustion lacks transparency. Emissions reporting can thus be highly misleading since the importing country will record biomass emissions as zero and as reducing its national emissions inventory, even though the net effect of switching from coal to biomass pellets may be to increase atmospheric CO_2 levels for decades.

The above considerations led to EASAC recommending that forest biomass should not be regarded as a source of renewable energy under the EU's RED unless the replacement of fossil fuels by biomass leads to net reductions in atmospheric concentrations of CO_2 within a decade or so.

Counterarguments to the above include that the removal of carbon stock from one area of forest should be considered on the landscape scale where (at least in some regions) carbon stock may be increasing. The errors in this approach have already been analysed by Ter-Mikaelian, Colombo, and Chen (2015) and from a policy perspective, the key question is, what are the climate implications for policy options including bioenergy, and those without? As pointed out above (EASAC, 2017; Ricardo, 2016; Stephenson & Mackay, 2014), in the case of the import of pellets from the United States to the United Kingdom, scenarios are dominated by those exacerbating climate change. Moreover, even though some forest carbon stocks have been increasing in Europe and parts of the United States, the Global Forest Resources Assessment (FRA, 2015) estimated that forest carbon stocks globally decreased by 0.22 gigatonnes annually from 2011 to 2015.

4 | A WAY FORWARD

In the above, we have described how applying the simplistic concept of carbon neutrality has led to an expensive policy which is increasing atmospheric levels of CO_2 and worsening rather than mitigating climate change for indeterminate periods of time. The IPCC accounting rules aggregating all forestry-related emissions to the LULUCF category have created a reward for countries importing biomass since, even though overall emissions are likely to have increased as a result of switching from coal to imported biomass, the country can count them as zero and report a reduction. Considerable economic assets are now locked into the converted coal-fired power stations, the transport infrastructure and the forest biomass supply chain which could be stranded if the simplistic assumption of carbon neutrality was corrected. Moreover, energy security, ability to meet renewable energy targets and socio-economic benefits in some areas are key aspects which weigh, as much if not more, in the mind of policymakers than the nuances of the real impacts on climate change. How in this situation might the current policy be reformed to reduce perverse impacts on climate?

The starting point must be for policymakers to have a more realistic science-based assessment of the potential of bioenergy. The improved efficiency in photovoltaics has underlined the inherently low efficiency of exploiting photosynthesis for energy, since the amount of electricity that can be produced from a hectare of land using photovoltaics is at least 50–100 times that from biomass (Fthenakis & Kim, 2009; Geyer, Stoms, & Kallaos, 2013). Indeed, some EU member states have already recognized that biomass electricity has a much higher carbon footprint as a 'renewable' energy than solar and wind, and have set much more stringent standards for future renewable energy subsidies (e.g. OFGEM, 2018). This, however, only affects the conditions on future projects, not the facilities already established and operating. Nor do such trends in Europe appear to be reducing efforts by pellet manufacturers to expand their markets outside Europe; for example, recent market surveys forecast rapid growth in pellet demand in South Korea and Japan founded on the ability under UNFCCC accounting rules to rate the related emissions as zero (https://insights.risiinfo.com/bioenergy-pellet-global-outlook/index.html—accessed July 10, 2019).

The essential reform required for existing and new operators is to limit feedstocks to those that have payback periods compatible with the Paris Agreement targets. As already pointed out, these may include the residues of traditional forest management, or forests subject to dieback or high fire risk. This is a challenge for regulators since the EU's own analyses (Agostini et al., 2014; Strange Olesen, Bager, Kittler, Price, & Aguilar, 2015) found that the amounts of residues available are insufficient (or already used in the forestry supply chain) to support the increased demand from large pellet plants, and that stemwood from trees was the dominant source of biomass for US pellet plants. These conclusions on the limited amounts of residues available are consistent with monitoring by environmental groups which have tracked areas of clear-cut forests to pellet mills (e.g. https://www.nrdc.org/sites/default/files/european-imports-wood-pellets-greenenergy-devastating-us-forests.pdf; https://www.nrdc.org/sites/default/files/global-markets-biomass-energy-06172019.pdf—accessed July 10, 2019). Indeed, the industry's own feedstock reporting acknowledges the limited contribution of residues (for instance, Enviva's track and trace system reports its sources as 17% residues, with softwoods and hardwoods providing 83%; http://www.envivabiomass.com/%20sustainability/track-and-trace/—accessed July 10, 2019).

As noted by the UK Committee on Climate Change (CCC, 2018), avoiding biomass uses which are worse for the climate than fossil fuels requires new international governance systems to be established which regulate out high-risk feedstocks and ensure best practice (e.g. use of organic wastes and genuine agricultural or forestry residues, and certain perennial crops grown on marginal land). Applying stricter governance to limit feedstocks to those with short payback periods may thus have substantial implications for the industry and limit its scale, presenting governments and regulators with a major challenge. Nevertheless, the alternative is to see further expansion in a practice which is not only economically expensive but fails to achieve the core objective of renewable energy policy to reduce GHG emissions.

A key component of new governance systems would be to require operators to publish their assessments of the net effects on atmospheric levels of CO_2 over the full life cycle of their supply chain, including how their feedstock supplies are affecting present and future carbon stocks. Several methodologies for such calculations are available (the UK BEAC model and others recently assessed by Brandao, Kirschbaum, Cowie, & Hjuler, 2019). Some debate continues over the sensitivity of such assessments to the choice of reference (counterfactual) scenarios (e.g. Daigneault, Sohngen, & Sedjo, 2012; Koponen, Soimakallio, Kline, Cowie, & Brandao, 2018) and the role of external factors which might compensate for losses of forest carbon stock—for example, if a bioenergy demand leads to improved forest management and productivity reducing the payback period, or if a 'no bioenergy' scenario led to natural carbon loss through pests, fire or other disturbance. Where such mitigating arguments are used to justify increased harvesting of stemwood, policymakers concerned with ensuring the appropriate use of public subsidies for renewable energy have the means to place the burden of proof on the operator and to also ensure that management systems are in place to deliver any mitigating effects.

Finally, reporting requirements under the UNFCCC are urgently needed which reflect real emissions and their impact on climate, and to remove the current perverse incentives to import biomass arising from the ability to treat them as zero emissions at the point of combustion. In the meantime, the EU should reform its own reporting requirements under its Emission Trading Scheme to ensure that emissions from biomass are fully transparent and reflect real climate impacts. Possible alternative reporting criteria have been suggested (Booth, 2018), which would take into account the payback periods of a facility's feedstocks in determining the proportion of emissions which should be reported, with 'zero emission' limited to facilities which achieve a net reduction in atmospheric CO_2 concentrations in Paris Agreement-relevant timescales.

Reforms such as these would allow the industry to evolve to methods and scales which are more compatible with the basic purpose for which it was designed and supported—to achieve net reductions in GHG emissions. A climate-friendly biomass energy supply chain could still provide an additional income source to forest owners, by providing demand for the low-value intermediate removals from thinning and for other residues, providing incentives to landowners to keep their land as forests, and to keep them healthy and productive. Forestry and its products will continue to have a critical role to play in mitigating climate change, but from a climate change perspective, the optimum use of forests remains to maximize use in construction (lumber and panels), furnishings and other products which capture carbon for long periods (Chen, Ter-Mikaelian, Yang, & Colombo, 2018).

ORCID

Mike B. Jones https://orcid.org/0000-0003-0992-4982

REFERENCES

Agostini, A., Guiintoli, J., & Boulamanti, A. (2014). *Carbon accounting of forest bioenergy*. JRC report EUR 25354. Retrieved from http://publications.jrc.ec.europa.eu/repository/handle/JRC70663

Beddington, J., Berry, S., Caldeira, K., Cramer, W., Creutzig, F., Duffy, P., … van Ypersele, J. P. (2018). *Letter from scientists to the EU parliament regarding forest biomass*. Retrieved from http://empowerplants.files.wordpress.com/2018/01/scientist-letter-on-eu-forest-biomass-796-signatories-as-of-january-16-2018.pdf

Berndes, G., Abt, B., Asikainen, A., Cowie, A., Dale, V., Egnell, G. … Yeh, S. (2016). *Forest biomass, carbon neutrality and climate change*. European Commission. Retrieved from https://ec.europa.eu/jrc/en/publication/forest-biomass-carbon-neutrality-and-climate-change-mitigation

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

Brandao, M., Kirschbaum, M., Cowie, A., & Hjuler, S. (2019). Quantifying the climate change effects of bioenergy systems: Comparison of 15 impact assessment methods. *GCB Bioenergy*, *11*, 727–743. https://doi.org/10.1111/gcbb.12593

Buchholz, T., & Gunn, J. (2015). *Carbon emission estimates for Drax biomass powerplants in the UK sourcing from Enviva Pellet Mills in U.S. Southeastern Hardwoods using the BEAC model*. Pleasanton, CA: Spatial Informatics Group. Retrieved from https://www.southernenvironment.org/uploads/news-feed/SIG_BEAC_calculations_SE_hardwoods_2015-05-27.pdf?cachebuster:11

CCC. (2018). UK Committee on Climate Change. *Biomass in a low carbon economy*. Retrieved from https://www.theccc.org.uk/publication/biomass-in-a-low-carbon-economy/

Chen, J., Ter-Mikaelian, M. T., Yang, H., & Colombo, S. J. (2018). Assessing the greenhouse gas effects of harvested wood products manufactured from managed forests in Canada. *Forestry*, *91*, 193–205. https://doi.org/10.1093/forestry/cpx056

Daigneault, A., Sohngen, B., & Sedjo, R. (2012). Economic approach to assess the forest carbon implications of biomass energy. *Environmental Science & Technology*, *46*, 5664–5671. https://doi.org/10.1021/es2030142

DECC. (2014). *User guide for BEAC model*. Department of Energy and Climate Change. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/336622/BEaC_Model_User_Guide_Instructions.pdf

EASAC. (2017). Multifunctionality and sustainability in the European Union's forests. Report 26. Retrieved from https://easac.eu/fileadmin/PDF_s/reports_statements/Forests/EASAC_Forests_web_complete.pdf

EASAC. (2018). Commentary on forest bioenergy and carbon neutrality. Retrieved from https://easac.eu/publications/details/commentary-on-forest-bioenergy-and-carbon-neutrality/

EASAC. (2019). Forest bioenergy, carbon capture and storage, and carbon dioxide removal: An update. Retrieved from https://easac.eu/publications/details/forest-bioenergy-carbon-capture-and-storage-and-carbon-dioxide-removal-an-update/

EC. (2009). Renewable energy directive. Directive 2009/28/EC – EUR-Lex. Retrieved from https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:en:PDF

EC. (2014). Circular Economy package (COM (2014) 398). Retrieved from http://ec.europa.eu/environment/circular-economy/pdf/circular-economy-communication.pdf

Eurostat. (2019). Renewable energy statistics. Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics

Fisher, J., Jackson, S., & Biewald, B. (2012). *The carbon footprint of electricity from biomass: A review of the current state of science and policy*. Cambridge, MA: Synapse Energy Economics, Inc. Retrieved from http://www.synapse-energy.com/sites/default/files/Carbon-Footprint-of-Biomass-11-056.pdf

FRA. (2015). Food and agriculture organization global forest resource assessment. Retrieved from http://www.fao.org/forest-resources-assessment/past-assessments/fra-2015/en/

Fthenakis, V., & Kim, H. C. (2009). Land use and electricity generation: A life-cycle analysis. *Renewable and Sustainable Energy Reviews*, *13*, 1465–1474.

Geyer, R., Stoms, D., & Kallaos, J. (2013). Spatially-explicit life cycle assessment of sun-to-wheels transportation pathways in the U.S. *Environmental Science and Technology*, *47*, 1170–1176.

Hawkins Wright. (2019). The outlook for wood pellets, Q4 2017. Retrieved from https://www.hawkinswright.com/bioenergy/outlook-for-wood-pellets

Heaton, E. A., Dohleman, F. G., & Long, S. P. (2008). Meeting US biofuel goals with less land: The potential of Miscanthus. *Global Change Biology*, *14*, 2000–2014. https://doi.org/10.1111/j.1365-2486.2008.01662.x

Holtsmark, B. (2012). Harvesting in boreal forests and the biofuel carbon debt. *Climate Change*, *112*, 415–428. https://doi.org/10.1007/s10584-011-0222-6

Holtsmark, B. (2013). The outcome is in the assumptions: Analyzing the effects on atmospheric CO_2 levels of increased use of bioenergy from forest biomass. *GCB Bioenergy*, *5*, 467–473. https://doi.org/10.1111/gcbb.12015

IEABioenergy. (2017). *Global wood pellet industry and trade study 2017*. IEA Bioenergy Task 40. Retrieved from https://www.ieabioenergy.com/publications/global-wood-pellet-industry-and-trade-study-2017/

Immerzeel, D. J., Verwuij, P. A., Van der Hilst, F., & Faaij, A. P. C. (2014). Biodiversity impacts of bioenergy crop production: A state-of-the-art review. *GCB Bioenergy*, *6*, 183–200. https://doi.org/10.1111/gcbb.12067

IPCC. (2006). Chapter 2: Stationary combustion. In *2006 IPCC guidelines for national greenhouse gas inventories*, Energy (Vol. *2*, pp. 20–21). Retrieved from https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf

IPCC. (2018). *Global warming of 1.5°C*. SR15 summary for policymakers. Retrieved from https://www.ipcc.ch/sr15/

IRENA. (2019). *Renewable capacity statistics 2019*. Abu Dhabi: International Renewable Energy Agency. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Mar/IRENA_RE_Capacity_Statistics_2019.pdf

KNAW. (2017). *Biofuel and wood as an energy source – Effect on greenhouse gas emissions*. Royal Netherlands Academy of Arts and Sciences Position paper. Retrieved from https://www.knaw.nl/en/news/publications/position-paper-biofuel-and-wood-as-energy-sources-1

Koponen, K., Soimakallio, S., Kline, K. L., Cowie, C., & Brandao, M. (2018). Quantifying the climate effects of bioenergy – Choice of the reference system. *Renewable and Sustainable Energy Reviews*, *81*, 2271–2280. https://doi.org/10.1016/j.rser.2017.05.292

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. https://doi.org/10.1111/gcbb.12327

Liu, W., Peng, C., Chen, Z., Liu, Y., Yan, J., Li, J., & Sang, T. (2016). Sustainable bioenergy production with little carbon debt in the Loess Plateau of China. *Biotechnology for Biofuels*, *9*, 161. https://doi.org/10.1186/s13068-016-0586-y

Marimuthu, C., & Kirubakaran, V. (2013). Carbon payback period for solar and wind energy project installed in India: A critical review. *Renewable and Sustainable Energy Reviews*, *23*, 80–90. https://doi.org/10.1016/j.rser.2013.02.045

McKechnie, J., Colombo, S., Chen, J., Mabee, W., & MacLean, H. (2011). Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science and Technology*, *45*, 789–795. https://doi.org/10.1021/es1024004

McKechnie, J., Colombo, S., & MacLean, H. L. (2014). Forest carbon accounting methods and the consequences of forest bioenergy for national greenhouse gas emissions inventories. *Environmental Science & Policy*, *44*, 164–173. https://doi.org/10.1016/j.envsci.2014.07.006

Mitchell, S. R., Harmon, M. E., & O'Connell, K. E. B. (2012). Carbon debt and carbon sequestration parity in forest bioenergy production. *GCB Bioenergy*, *4*, 818–827. https://doi.org/10.1111/j.1757-1707.2012.01173.x

Nabuurs, G. J., Arets, E. J., & Schelhass, M. J. (2017). European forests shown no carbon debt, only a long parity effect. *Forest Policy and Economics*, *75*, 120–125. https://doi.org/10.1016/j.forpol.2016.10.009

OFGEM. (2018). *Renewables obligation: Sustainability criteria*. London, UK: Office of Gas and Electricity Markets. Retrieved from https://www.ofgem.gov.uk/system/files/docs/2018/04/ro_sustainability_criteria.pdf

Ricardo. (2016). *Use of North American woody biomass in UK electricity generation: Assessment of high carbon biomass fuel sourcing scenarios*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/600477/PED60674_final_report_270416_Tec_Report_FINAL_v2_AMENDMENTS_ACCEPTED.pdf

Schlesinger, W. (2018). Are wood pellets a green fuel? *Science*, *359*, 1328–1329. https://doi.org/10.1126/science.aat2305

Searchinger, T. D., Beringer, T., Holtsmark, B., Kammen, D. M., Lambin, E. F., Lucht, W., … van Ypersele, J.-P. (2018). Europe's renewable energy directive poised to harm global forests. *Nature Communications*, *9*, 3741. https://doi.org/10.1038/s41467-018-06175-4

Stephenson, L., & MacKay, D. (2014). Scenarios for assessing the greenhouse gas impacts and energy input requirements of using North American woody biomass for electricity generation in the UK. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.696.6944&rep=rep1&type=pdf

Sterman, J., Siegel, L., & Rooney-Varga, J. (2018). Does replacing coal with wood lower CO_2 emissions? Dynamic lifecycle analysis of wood bioenergy. *Environmental Research Letters*, *13*, 015007. https://doi.org/10.1088/1748-9326/aaa512

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*. European Commission ENV.B.1/ETU/2014/0043. Retrieved from http://www.aebiom.org/wp-content/uploads/2016/08/DG-ENVI-study-imports-from-US-Final-report-July-2016.pdf

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*, 57–68. https://doi.org/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. *Global Change Biology Bioenergy*, *7*, 704–716. https://doi.org/10.1111/gcbb.12198

Walker, S., Lyddan, C., Perritt, W., & Pilla, L. (2015). An analysis of UK Biomass Power Policy, US South pellet production and impacts on wood fiber markets. RISI.com. Retrieved from https://docplayer.net/25281897-An-analysis-of-uk-biomass-power-policy-us-south-pellet-production-and-impacts-on-wood-fiber-markets-prepared-for-the-american-forest-paper.html

Zanchi, G., Pena, N., & Bird, N. (2012). Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *Global Change Biology Bioenergy*, *4*, 761–772. https://doi.org/10.1111/j.1757-1707.2011.01149.x

How to cite this article: Norton M, Baldi A, Buda V, et al. Serious mismatches continue between science and policy in forest bioenergy. *GCB Bioenergy*. 2019;11:1256–1263. https://doi.org/10.1111/gcbb.12643