

# Working paper



Forests and the climate – manage for maximum wood production or leave the forest as a carbon sink?

Conference 12–13 March, 2018



## Table of Contents

Introduction .....	3
The carbon cycle and forest-climate interactions: principles and considerations .....	4
Assessing the climate effects of forestry and biomass production: the outcome depends on questions asked and how these are answered .....	8
The importance of considering economic and ecosystem feedbacks as a basis for carbon policy .....	13
Comparison of selection systems and rotation forestry system: conditions for biomass extraction, carbon balances and climate effects .....	20
A principal choice—manage forests for wood production or leave the forest as a carbon sink: carbon balances and climate effects .....	25
Climate effects of forestry and substitution of carbon-intensive materials and fossil fuels – a country level study for Sweden .....	30
The climate impact of forestry extends beyond its carbon budget .....	33
Bioenergy in the energy system – now and in the future .....	42

## Introduction

This conference was organized by The Royal Swedish Academy of Agriculture and Forestry, The Royal Swedish Academy of Sciences, and The Royal Swedish Academy of Engineering Sciences on 12–13 March 2018, with the purpose to establish a shared view regarding some basic principles concerning the role of forests in climate mitigation and adaptation, which is needed for scientists to provide good advice to policy-makers.

The Paris Agreement sets ambitious targets for climate mitigation, which require transformation of the production and consumption systems that generate greenhouse gas (GHG) emissions, mainly due to fossil fuel use. Bioenergy is currently the largest renewable energy source used in the EU. Most Member States have, in absolute terms, increased their use of forest biomass for energy towards meeting their Year 2020 renewable energy targets.

The interaction of forests with the climate system is complex. Climate change affects forests, and at the same time forests and forest products industries play important roles in the GHG balance, in that they sequester and store carbon and displace fossil fuels and other products, which would otherwise cause GHG emissions. Forests can also affect the climate in other ways, for example, by modulating the share of incoming sunlight that is reflected into space (instead of warming the earth surface).

The scientific literature provides a variety of views on how different forests and forest management options can be adapted to climate change – and there are also divergences in view on how they affect the climate. One reason for this diversity of opinion is that scientists assess climate change mitigation and adaptation in the forest sector from different perspectives and entry-points – all of which have their merits. The different contexts of the analyses that are performed exert a strong influence on the formulation of the research questions, as well as on the methods and assumptions related to critical parameters that are then applied. This in turn has a decisive impact on the results and conclusions. The ongoing and vigorous debate on these topics among experts often leads to confusion among decision-makers and citizens.

While mitigation and adaptation are two sides of the same coin, special focus in this was on forests and forest management for climate change mitigation. The aim was to:

- facilitate a dialogue about the roles of forests and forest management in climate change mitigation, to advance scientific understanding of the topic and clarify divergent views and their underlying rationales;
- identify knowledge gaps and priorities for future research and data collection, with the aims of improving scientific understanding and supporting policy development of relevance to forest management in the context of climate change mitigation and adaptation; and
- produce and disseminate a state-of-the-art view of forests and climate that reflects the outcomes of the exchanges of opinions and areas of agreement that emerge from the conference.

The first one and a half days were in the form of an expert workshop followed by a half-day session where the outcomes of the workshop were presented and discussed together with industry representatives, government officials, policy-makers, and politicians.

Before the conference the invited presenters had kindly contributed descriptions of their respective presentation topics, which now have been updated, see below. There has been no strict requirement concerning format for the contributions and they therefore differ in style. As a complement to this working paper a publication will be produced where conclusions and knowledge gaps will be stated.

This conference was possible owing to financial support from The Swedish Foundation for Strategic Environmental Research, Mistra, The Swedish Research Council Formas, the Swedish Energy Agency, and Chalmers University of Technology.

## The carbon cycle and forest-climate interactions: principles and considerations

*Werner Kurz, Dr. Senior Research Scientist, Canadian Forest Service, Canada*

The goals of the Paris Agreement will be very difficult to achieve and require substantial reductions in the emissions from the burning of fossil fuels. Most countries that have submitted their Nationally Determined Contributions (NDCs) to the UNFCCC secretariat have indicated that the land sector, and in particular forests, will play a role in achieving the desired greenhouse gas (GHG) emission reductions. Together, reductions in emissions and increases in sinks can move the earth system towards the necessary balance of emissions and removals, and ideally towards net negative emissions in the latter part of this century. However, the proposed pathways towards this goal are based on ‘heroic assumptions’ about the scale at which certain mitigation activities such as bioenergy with carbon capture and storage (BECCs) will be implemented. Moreover, the proposed pathways often lack clarity on how limited resources, such as land and biomass will be deployed. Even if the greenhouse gas balance can be managed to achieve net negative emissions, uncertainties remain about the impacts on the climate system of associated changes in land cover and biophysical characteristics which can affect non-GHG components of the climate system.

Globally, forests are large carbon sinks that remove about one quarter to one third of anthropogenic GHG emissions from the atmosphere (Pan et al., 2011, Le Quéré et al., 2016). What is less certain is how the impacts of climate change, human activities and natural ecosystem processes such as aging and disturbances, will affect the sustainability of the current sink (Kurz et al., 2008, Nabuurs et al., 2013). Research therefore is focussing on forest sector climate change mitigation strategies that can contribute to reductions in national GHG emissions and increases in sinks (Smyth et al., 2014, Lundmark et al., 2014, Werner et al., 2010). Ideally, such mitigation strategies are also aligned with other objectives, including adaptation to climate change, socio-economic and sustainable development goals, and other desired outcomes (Lemprière et al., 2017, Xu et al., 2017).

Analyses of forest sector climate change mitigation options need to be based on a systems perspective that takes into consideration carbon stock changes and emissions and removals in forest ecosystems, harvested wood products, and the changes in emissions resulting from the use of wood products instead of other emissions-intensive materials such as concrete, steel and plastics (Kurz et al., 2016, Lemprière et al., 2013, Nabuurs et al., 2015). Biomass can also be used to substitute for fossil fuels, but whether or not bioenergy use contributes to real GHG emission reductions is highly dependent on national circumstances, the origin and alternate fate of the biomass, the type of energy sources that are substituted, and the time horizon over which the assessment is conducted (Smyth et al., 2017a, Laganière et al., 2017).

The design of mitigation options should be based on reported impacts on the atmosphere that are not affected by simplifying, policy-based accounting assumptions. The assumptions of “instant oxidation” of harvested wood products and “carbon neutral” bioenergy are both simplifications that contribute to a discrepancy between atmospheric impacts and reported (or accounted) impacts. To be climate effective, forest-sector based mitigation strategies need to be informed by estimates of the impacts on the atmosphere.

To evaluate and rank alternative climate change mitigation options in the forest sector, options need to be compared against a “business-as-usual” baseline which must include realistic representation of the age-dependence of forest growth rates (e.g. Smyth et al., 2014, Xu et al., 2017). As forests age, carbon accumulation rates diminish first in biomass pools and subsequently in dead organic matter and soil carbon pools. Moreover, in many ecosystem types, cumulative disturbance risk increases with forest age.



Therefore an apparent trade-off exists between strategies aimed at maximising the amount of carbon that is stored in forests (maximise stock size) and the amount of carbon that is annually removed from the atmosphere by forests (maximise removals)(Kurz et al., 2016). While forest management decisions are not based on carbon objectives alone, and while the optimum strategies must be regionally-differentiated, in principle, active forest management, silvicultural actions, protection against fire and insects, can all be designed such that carbon removal from the atmosphere is increased, where appropriate. Such strategies will include ongoing harvest and removal of carbon from the forest, and the harvested wood can then be deployed to increase carbon storage outside the forest and to substitute for other emissions-intensive products (Smyth et al., 2017b). The IPCC concluded that “In the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fibre or energy from the forest, will generate the largest sustained mitigation benefit.” (Nabuurs et al., 2007).

The alternative assumption, that a strict conservation strategy will result in increased carbon stocks, is not sustainable (forests will age), is vulnerable to reversal due to climate change impacts (such as fire), and eliminates opportunities for GHG emission reductions through the use of wood products and biomass. A 100-year conservation experiment in National Parks in Canada provides an example of the vulnerabilities of carbon stocks to natural disturbances (Sharma et al., 2013).

The debate over forest management strategies that will contribute to emission reductions needs to be informed by tools that assist in the evaluation of options, risks, costs and outcomes with regard to desired future conditions. As the urgency to address climate change increases, the values and desired outcomes of increasingly urban populations may shift. Recognition of the climate benefits of forest management may result in willingness to compensate land owners (including public owners) for ecological services provided by forests, payments which in turn may provide resources that can enhance forest management. Analyses have demonstrated that GHG reduction benefits are achieved through wood uses that increase carbon retention in long-lived wood products, and deployment of such products to substitute for steel, concrete and plastics (Smyth et al., 2014, Werner et al., 2010, Xu et al., 2017). At every stage from harvest to processing of timber, to construction and end-of-life disposal, a portion of the biomass and wood remains for which the best possible use is the production of bioenergy. Thus, cascading use of wood which includes considerations of the most GHG-effective use options at every stage in the wood life cycle can help achieve GHG reduction goals (Höglmeier et al., 2015).

At present, woody biomass used for bioenergy is almost always a by-product of the production of higher value commodities. With the exception of bioenergy plantations, roundwood is rarely used for the production of bioenergy as higher value options are available. However, national strategies that legislate that certain proportions of energy be derived from woody biomass can distort markets, leading to increased demand for biomass, which in turn may result in reductions in the amount of wood available for long-lived products which both retain carbon out of the atmosphere for much longer and which can have far greater substitution potential. Consequently, such legislated approaches may (inadvertently) reduce the GHG reduction mitigation potential of the forest sector.

Therefore, analyses of global and regional strategies to reduce GHG emissions through the forest sector must include assessments of supply constraints, of opportunities to increase the supply, and must also meet sustainability goals and other desired outcomes.

Using wood and biomass in greenhouse gas reduction strategies requires that forests are managed sustainably. Thus, investments into forest management, monitoring of outcomes, forest protection and regeneration of forests where natural or anthropogenic impacts caused forest loss will all be required. Obtaining and maintaining public support for forest sector based GHG mitigation strategies requires verifiable and credible documentation of the climate benefits of such strategies.

*Action items to reduce knowledge gaps*

- Develop and assess forest sector climate change mitigation strategies, including interactions with, and risks from climate change impacts.
- Identify and quantify the interactions between land management and non-GHG impacts on the earth system, based on realistic assumptions about changes in land surface characteristics.
- Evaluate the potential, costs, and impacts of strategies aimed at protecting forests and enhancing their productivity through active forest management.
- Design bioeconomies that use wood and biomass in climate change mitigation strategies that are based on principles of sustainable land management, cascading wood uses, and high substitution benefits while meeting other socio-economic goals. In particular, strengthen the evidence of substitution benefits through wood use by improving life cycle analyses and the understanding of consumer responses to changes in product availability.
- Develop monitoring programs that determine the GHG benefits of mitigation actions relative to the business-as-usual baseline and that quantify the costs per tonne of CO<sub>2</sub> mitigation and inform the public about the mitigation outcomes.

References

- HÖGLMEIER, K., STEUBING, B., WEBER-BLASCHKE, G. & RICHTER, K. 2015. LCA-based optimization of wood utilization under special consideration of a cascading use of wood. *Journal of Environmental Management*, 152, 158-170.
- KURZ, W. A., SMYTH, C. & LEMPRIÈRE, T. C. 2016. Climate change mitigation through forest sector activities: principles, potential and priorities. *Unasylva*, 67, 3-9.
- KURZ, W. A., STINSON, G., RAMPLEY, G. J., DYMOND, C. C. & NEILSON, E. T. 2008. Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *Proceedings of the National Academy of Sciences*, 105, 1551-1555.
- 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.
- LE QUÉRÉ, C., ANDREW, R. M., CANADELL, J. G., SITCH, S., KORSBAKKEN, J. I., PETERS, G. P., MANNING, A. C., BODEN, T. A., TANS, P. P., HOUGHTON, R. A., KEELING, R. F., ALIN, S., ANDREWS, O. D., ANTHONI, P., BARBERO, L., BOPP, L., CHEVALLIER, F., CHINI, L. P., CIAIS, P., CURRIE, K., DELIRE, C., DONEY, S. C., FRIEDLINGSTEIN, P., GKRTZALIS, T., HARRIS, I., HAUCK, J., HAVERD, V., HOPPEMA, M., KLEIN GOLDEWIJK, K., JAIN, A. K., KATO, E., KÖRTZINGER, A., LANDSCHÜTZER, P., LEFÈVRE, N., LENTON, A., LIENERT, S., LOMBARDOZZI, D., MELTON, J. R., METZL, N., MILLERO, F., MONTEIRO, P. M. S., MUNRO, D. R., NABEL, J. E. M. S., NAKAOKA, S.-I., AMP, APOS, BRIEN, K., OLSEN, A., OMAR, A. M., ONO, T., PIERROT, D., POULTER, B., RÖDENBECK, C., SALISBURY, J., SCHUSTER, U., SCHWINGER, J., SÉFÉRIAN, R., SKJELVAN, I., STOCKER, B. D., SUTTON, A. J., TAKAHASHI, T., TIAN, H., TILBROOK, B., VAN DER LAAN-LUIJKX, I. T., VAN DER WERF, G. R., VIOVY, N., WALKER, A. P., WILTSHIRE, A. J. & ZAEHLE, S. 2016. Global Carbon Budget 2016. *Earth System Science Data*, 8, 605-649.
- LEMPRIÈRE, T. C., KRCMAR, E., RAMPLEY, G. J., A., B., SMYTH, C. E., HAFFER, M. & KURZ, W. A. 2017. The cost of climate change mitigation in Canada's forest sector. *Canadian Journal of Forest Research*, 47, 604-614.
- LEMPRIÈRE, T. C., KURZ, W. A., HOGG, E. H., SCHMOLL, C., RAMPLEY, G. J., YEMSHANOV, D., MCKENNEY, D. W., GILSENAN, R., BEATCH, A., BLAIN, D., BHATTI, J. S. & KRCMAR, E. 2013. Canadian boreal forests and climate change mitigation *Environmental Reviews*, 21, 293-321.

- LUNDMARK, T., BERGH, J., HOFER, P., LUNDSTRÖM, A., NORDIN, A., POUDEL, B., SATHRE, R., TAVERNA, R. & WERNER, F. 2014. Potential roles of Swedish forestry in the context of climate change mitigation. *Forests*, 5, 557–578.
- NABUURS, G.-J., LINDNER, M., VERKERK, P. J., GUNIA, K., DEDA, P., MICHALAK, R. & GRASSI, G. 2013. First signs of carbon sink saturation in European forest biomass. *Nature Climate Change*, 3, 792–796.
- NABUURS, G. J., DELACOTE, P., ELLISON, D., HANEWINKEL, M., LINDNER, M., NESBIT, M., OLLIKAINEN, M. & SAVARESI, A. 2015. A new role for forests and the forest sector in the EU post-2020 climate targets. European Forest Institute.
- NABUURS, G. J., MASERA, O., ANDRASKO, K., BENITEZ-PONCE, P., BOER, R., DUTSCHKE, M., ELSIDDIG, E., FORD-ROBERTSON, J., FRUMHOFF, P., KARJALAINEN, T., KRANKINA, O., KURZ, W., MATSUMOTO, M., OYHANTCABAL, W., RAVINDRANATH, N. H., SANZ SANCHEZ, M. & ZHANG, X. 2007. IPCC Forestry. In: METZ, B., DAVIDSON, O. R., BOSCH, P. R., DAVE, R. & MEYER, L. A. (eds.) *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, USA.: Cambridge University Press.
- PAN, Y., BIRDSEY, R. A., FANG, J., HOUGHTON, R. A., PEKKA, K., KURZ, W. A., PHILLIPS, O. L., SHVIDENKO, A., LEWIS, S. L., CANADELL, J. G., CIAIS, P., JACKSON, R. B., PACALA, S. W., MCGUIRE, A. D., PIAO, S. L., RAUTAINEN, A., SITCH, S., HAYES, D. & WAYSON, C. 2011. A large and persistent carbon sink in the world's forests. *Science*, 333, 988–993.
- SHARMA, T., KURZ, W. A., STINSON, G., PELLATT, M. G. & LI, Q. 2013. A 100-year conservation experiment: Impacts on forest carbon stocks and fluxes. *Forest Ecology and Management*, 310, 242–255.
- SMYTH, C., KURZ, W. A., RAMPLEY, G. J., LEMPRIÈRE, T. C. & SCHWAB, O. 2017a. Climate change mitigation potential of local use of harvest residues for bioenergy in Canada. *Global Change Biology Bioenergy*, 9, 817–832.
- SMYTH, C. E., RAMPLEY, G. J., LEMPRIÈRE, T. C., SCHWAB, O. & KURZ, W. A. 2017b. Estimating product and energy substitution benefits in national-scale mitigation analyses for Canada. *Global Change Biology Bioenergy*, 9, 1071–1084.
- 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.
- WERNER, F., TAVERNA, R., HOFER, P., THÜRIG, E. & KAUFMANN, E. 2010. National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. *Environmental Science & Policy*, 13, 72–85.
- XU, Z., SMYTH, C. E., LEMPRIÈRE, T. C., RAMPLEY, G. J. & KURZ, W. A. 2017. 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.

## Assessing the climate effects of forestry and biomass production: the outcome depends on questions asked and how these are answered

*Annette Cowie, Adjunct Professor, University of New England, Australia*

*Contributor: Göran Berndes, Chalmers University of Technology*

The debate on forests and their role in climate change mitigation is highly polarised: some claim that the greatest contribution is obtained by ceasing logging and conserving forests as carbon stores, while others assert that the greatest benefit is obtained through sustainable management of forests for production of renewable products. With respect to forest bioenergy, the debate ranges from claims that bioenergy is worse than coal, to claims that all bioenergy is carbon neutral. There are a number of reasons for the lack of consensus on climate effects of bioenergy, some relating to features of the bioenergy systems modelled, and some relating to aspects of the analytical methods.

*Amongst forest-based bioenergy systems, the following factors vary widely:*

- Forest species, location (climate, soil type, slope, accessibility), silvicultural management, and markets determine forest growth rate and carbon carrying capacity; forest response to thinning; yield of sawlogs, pulplogs and residues, and therefore the mix of wood products produced and the biomass available for bioenergy.
- Supply chain processes including distance transported, transport method, pre-processing methods (eg in-field chipping; pelletising; torrefaction) make a small but significant difference. Supply chain energy use is usually less than 5% of the product though can rise to around 10% where international transport is involved. There are examples with relatively higher fossil GHG emissions, such as when coal is used as a process fuel when wet feedstocks are used to produce pellets. But fossil fuel use is not an intrinsic characteristic of the system. Other process fuels can be used, such as biomass itself, though this reduces the output of bioenergy products per unit biomass used.
- Alternative fate of biomass. In the case of harvest residues, biomass used for energy may otherwise have decomposed on the forest floor or been burned in the forest; sawmill residues may have been landfilled or used for composite wood products or animal bedding; low quality trees may have been left standing or thinned to waste. Diverting biomass from these alternative fates can have implications for soil carbon and nutrient levels, forest carbon stocks, biodiversity, emissions of methane and smoke particles; some effects are positive and some are negative.
- Energy products produced (electricity, heat, liquid fuels) and associated conversion processes (combustion, gasification, pyrolysis, Fischer-Tropsch etc), with differences in efficiency between technologies and at different scales. Combined heat and power (CHP) plants recover otherwise wasted thermal energy for heating and thereby reach higher overall conversion efficiency than electricity-only plants; larger plants (e.g., biomass co-firing in coal plants) tend to be more efficient than smaller plants, and pre-processing (drying, pelletising, etc) can enhance efficiency. Output of co-products is also relevant.

These factors lead to valid fundamental differences that contribute to variation between studies concerning climate change effects of forest-based bioenergy systems.

Variations also arise from differences in the analytical methods, and these can also have a very large impact on the results of climate change assessments.



*Assumptions applied, especially:*

- Selection and representation of reference energy system, that is, the energy supply assumed to be used if forest bioenergy is not available. Greater benefits are generally seen from displacing coal than natural gas; displacing other bioenergy systems with forest bioenergy gives varying outcomes depending on the characteristics of the other bioenergy system. Beyond direct displacement effects, energy system effects can influence the climate benefits; bioenergy may in some circumstances compete with other renewables, or it may facilitate expansion of other renewables by supplying grid stability. Energy system effects are rarely considered in studies that quantify the climate effects of specific bioenergy products.
- Choice of reference land use, that is, how the land would be managed, and therefore how much carbon it would sequester if biomass was not extracted for bioenergy; what products, if any, would be produced in the reference land use. In different circumstances it may be appropriate to consider that production of wood products would continue, or that the forest would not be harvested, or that it would be converted to farmland. Each option has a very different outcome with respect to the counterfactual carbon stocks and value from displacement of fossil fuels and GHG-intensive building products. For instance, the biomass may come from:
  - managed forest that continues under same management, with residues now used for energy (same output of other forest products and residue extraction causes small forest carbon loss, *ceteris paribus*);
  - conversion of long rotation sawlog forest to shorter rotation biomass plantations (forest carbon loss; changes in other forest product output);
  - conversion of mature unharvested forests into tree plantations (forest carbon loss);
  - tree planting on degraded pastures (carbon gain; possibly other forest product output); or
  - silvicultural operations in previously neglected forests that might otherwise have been converted into pastures (avoided carbon loss).

Vulnerability to fire and pests also varies and should be considered in estimating the mitigation value of the counterfactual scenario.

*Aspects of scope:*

- Spatial boundary of assessment: analysis at stand level, for forests that are clear-felled at harvest, shows greater variation in forest C stocks than analysis at estate (landscape) level. Some studies consider only above-ground biomass stocks, but changes in residue and soil carbon pools can be significant.
- Temporal boundary of assessment: particularly in boreal regions where forest growth is slow and rotations are long, long-term studies (order of 100 years) are needed to understand differences between management regimes, and to discern the effects of climate change on forest carbon dynamics. Studies that start out from the objective to contribute to global temperature stabilisation relate to a century time scale. But studies that focus on short/medium term objectives, such as political targets to reduce GHG emissions, may apply temporal boundaries that prevent full consideration of carbon balances in boreal forests. Another aspect of temporal boundary is the start time: accounting may start at the time the forest is established, or at the time of harvest; giving an initial sequestration, or an initial emission, respectively, for the same forest system.
- Climate forcing factors considered: studies commonly include GHGs covered by the UNFCCC, but other factors, such as albedo and short-lived climate forcers (SLCFs), can be significant in bioenergy systems. While there are agreed methods for quantifying effects of GHGs specified in the Kyoto Protocol, methods for albedo and SLCFs do not have the same level of consensus and availability.

- Sectoral boundary: product-focused studies may consider only the forest and the bioenergy product, but it can be important to consider wood products, which are often the driver of forest management, and their displacement value in the building sector; consideration of the role of bioenergy in the energy sector may reveal opportunities such as solar-biomass hybrid solutions.
- Indirect effects – links between the forestry, energy and building sectors, land use, and consumer behaviour mediated through markets and policy mechanisms can lead to rebound and indirect land use change, which can cause positive or negative leakage. Indirect effects can also result through biophysical and biogeochemical connections such as climate-Earth system feedbacks.

#### *Analytic approach including impact metrics:*

- Impact assessment method used to quantify climate effects: while global warming potential (GWP) calculated over 100 years is the most common metric, the IPCC Fifth Assessment Report also provides values for Global Temperature change Potential (GTP). Approaches that explicitly consider the climate effect of timing of emission and removals have also been proposed.
- Assumptions about the future trajectories of energy demand, land use, competition for biomass, bearing in mind population patterns, development pathways, effectiveness of climate change policies, that affect anthropogenic GHG emissions, influence the background atmospheric GHG concentration and thereby the climate effects of emissions from the studied system.
- Analytical approach: life cycle assessment (LCA) quantifies the environmental impact (such as climate change) across the whole product life cycle; attributional LCA considers just the bioenergy supply chain, while consequential LCA includes indirect effects. While LCA generally focuses on product level analysis, other approaches such as integrated assessment modelling and energy system modelling take a broader, scenario approach.

The appropriate choice of assumptions and methods depends on the context for the studied system and on the question to be answered by the study. Nevertheless, many aspects are subjective.

#### *Scientists disagree on some key aspects related to quantifying climate effects of bioenergy, particularly:*

- The relevant time frame for assessment. Divergence in views can reflect a difference in perspective:
  - One perspective stresses net changes in atmospheric GHG concentrations in the coming 1–2 decades, which may relate to political GHG targets and/or concern about rate of warming or proximity to tipping points
  - Another perspective stresses cumulative net CO<sub>2</sub> emissions over longer time periods, relating to temperature targets and stabilization pathways.
- What scenario to evaluate when judging whether bioenergy is good for the climate:
  - an isolated harvest event where the biomass is used for bioenergy, or
  - a scenario for expanded use of biomass for energy in a country or a large region.
- whether the concept of carbon payback time is useful:
  - If yes, how should it be defined and calculated and how long payback time is acceptable for a bioenergy system (or any other energy option)?
  - Does it depend on the role of bioenergy in the energy system, e.g., would a longer payback time be acceptable if functions are provided that are difficult to provide with other means? Or if the bioenergy system supports the expansion of intermittent renewables by providing dispatchable power?

- The potential to mitigate negative impacts on forest carbon stock through improved forest management.
- How market responses will enhance or diminish the contribution of bioenergy, including by influencing development of forest carbon stocks.
- How policies will affect behaviour of actors.

Scientists may also apparently disagree due to vagueness concerning objectives of studies. Specifically, the “climate change mitigation” objective can be operationalized and evaluated in many ways and should therefore be distinctly specified.

*Three examples of climate change mitigation are:*

- To reduce the GHG intensity of specific products.
- To reduce net GHG emissions to the atmosphere over a specified time period by using forest products instead of more GHG intensive products.
- To promote the phasing out of technologies and infrastructures that cause fossil carbon emissions, which is necessary for keeping fossil sources secured underground.

To conclude, assessing GHG balances and the climate effects of forest bioenergy is essential for informed policy development and implementation. The topic can be approached from different points of view, and methodological decisions and parameter assumptions have a strong influence on the outcome. Results must be interpreted with this in mind.

Involving policymakers and stakeholders in defining policy-relevant research questions (e.g., in defining objectives, scope and selecting reference scenarios) increases the likelihood that results are relevant, interpreted correctly, and useful in the policy development process.

## References

- Berndes, G., Ahlgren, S., Börjesson, P. and Cowie, A.L., 2013. Bioenergy and land use change—state of the art. *Wiley Interdisciplinary Reviews: Energy and Environment*, 2(3), pp.282–303.
- Berndes, G., Abt, B., Asikainen, A., Cowie, A., Dale, V., Egnell G., Lindner, M., Marelli, L., Paré, D., Pingoud, K., Yeh, S. 2016. Forest biomass, carbon neutrality and climate change mitigation. From Science to Policy 3. European Forest Institute.
- Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B. and Woess-Gallasch, S., 2009. Energy-and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, conservation and recycling*, 53(8), pp.434–447.
- Cowie, A., Berndes, G. and Smith, T., 2013. On the timing of greenhouse gas mitigation benefits of forest-based bioenergy. *IEA Bioenergy Executive Committee statement*, 4. <http://www.ieabioenergy.com/publications/on-the-timing-of-greenhouse-gas-mitigation-benefits-of-forest-based-bioenergy/>
- Gustavsson, L., Karjalainen, T., Marland, G., Savolainen, I., Schlamadinger, B. and Apps, M., 2000. Project-based greenhouse-gas accounting: guiding principles with a focus on baselines and additionality. *Energy policy*, 28(13), pp.935–946.
- Koponen, K., Soimakallio, S., Kline, K.L., Cowie, A. and Brandão, M., 2017. Quantifying the climate effects of bioenergy—Choice of reference system. *Renewable and Sustainable Energy Reviews*.
- Lamers P, Junginger M (2013) The 'debt' is in the detail: A synthesis of recent temporal forest carbon analyses on woody biomass for energy. *Biofuels, Bioproducts & Biorefining*, 7, 373–385.

- Miner, R.A., Abt, R.C., Bowyer, J.L., Buford, M.A., Malmsheimer, R.W., O'Laughlin, J., Oneil, E.E., Sedjo, R.A. and Skog, K.E., 2014. Forest carbon accounting considerations in US bioenergy policy. *Journal of Forestry*, 112(6), pp.591-606.
- Sathre, R., and O'Connor, J. (2010). Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science & Policy* 13, 104-114.
- Schlamadinger, B., Apps, M., Bohlin, F., Gustavsson, L., Jungmeier, G., Marland, G., Pingoud, K. and Savolainen, I., 1997. Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems. *Biomass and Bioenergy*, 13(6), pp.359-375.
- Sedjo R, Tian X (2012) Does wood bioenergy increase carbon stocks in forests? *Journal of Forestry*, 110, 304–311.
- Ter-Mikaelian, M.T., Colombo, S.J. and 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), pp.57-68.

## The importance of considering economic and ecosystem feedbacks as a basis for carbon policy.

*Robert Abt, NC State University and Karen Abt, USDA Forest Service*

*Contributors: Justin Baker, Research Triangle Institute; Göran Berndes, Chalmers University; Madhu Khanna, University of Illinois; Sarah Ohrel, US Environmental Protection Agency; Brent Sohngen, The Ohio State University; Birger Solberg, Norwegian School of Life Sciences*

### *Abstract*

This paper summarizes the importance of incorporating indirect leakage effects from markets using a bioeconomic modeling approach. It is not a review of the literature—it is a first principles discussion of how leakage occurs and can be captured with a bioeconomic approach. Bioeconomic modeling is the scientifically accepted basis for carbon policy, and there is a large and growing scientific literature of sophisticated linked economic and biophysical models driving comprehensive assessments. This paper concludes with a discussion of why one particular set of outcomes (positive carbon leakage), plausible under certain conditions, seem to be more controversial and subject to challenge.

### *Carbon Leakage*

In a carbon-offset project example, if harvest is restricted in one forest type, but harvest simply shifts to other forest types, it is a primary or activity-shifting leakage. For small-scale carbon-offset projects, it is difficult to control leakage, which can reduce or even more than outweigh carbon gains recorded within a project boundary. One of the early applications of bioeconomic analysis of international leakage estimated that regional forest conservation efforts could transfer up to 95 % of removals to other countries through market impacts (Gan and McCarl, 2007). A recent study of effects of changes in round wood harvests in Norway showed that about 60–100% of the harvest change in Norway is offset by an opposite change in the rest of the world. Such leakage rates vary over time, wood category, background scenario, and the size of the harvest change (Kallio & Solberg).

The significance of carbon leakage was recognized in the 1990s but were rarely considered in assessments of bioenergy systems until in the 2000s (Chum et al., 2011). Searchinger et al. (2008) published concerns in Science about global scale indirect land use change (ILUC) driven by biofuel policy. This and other papers provided a catalyst for using bioeconomic models as a basis for policy. They also brought attention to the limitations of attributional life-cycle-analysis (aLCA) as a basis for policy; which does not consider economic concepts of market response and changes in behavior. Increased attention to dynamic effects provided a catalyst for using bioeconomic models and consequential LCA (cLCA) as a basis for policy. Consequential means expansion of the LCA boundary for any reason, but in this case to include market feedbacks.

From an economist's perspective, the same phenomena could be described as the incorporation of dynamic GHG accounting into existing economic trade models, especially those focused on land use in the agricultural and forest sectors. (e.g. IIASA, FASOM-GHG, GLOBIOM).



#### *Linking biophysical and economic models*

Just as the composition of our atmosphere results from a long history of society's exploitation of fossil fuels, the extent, management, and composition of our current forest resources result from our past utilization and exploitation of these resources. For much of this history, local values interacting with local forest conditions determined forest utilization, preservation or neglect. Today, local markets and policies are increasingly driven by global demands, trade policies, and environmental concerns. The relationship between atmospheric and forest carbon is a perfect example of how progress can only be measured at large scales over long time frames by incorporating the full bioeconomy.

The European Union (EU) moved toward this perspective less than a decade ago. Associated with the 2009 EU Renewable Energy Directive (Directive 2009/28/EC) and the Directive to reduce indirect land use change for biofuels and bioliquids (Directive (EU) 2015/1513), the European Commission (EC) commissioned several bioeconomic studies including the first general equilibrium analysis. More recently, the IEA Bioenergy Copenhagen workshop in 2014 concluded; *“(ii) studies that quantify greenhouse gas balances should adopt a full life cycle, comprehensive system view and preferably use information and data from biophysical and socio-economic modelling studies that consider market effects [and] several alternative scenarios”* (Cowie et al. 2017, page 1).

The U.S. does not have a formal biogenic carbon energy policy, but the US Environmental Protection Agency has addressed carbon accounting. A Science Advisory Board was formed to discuss carbon accounting frameworks under the Clean Air Act. That process is ongoing but the 2016 SAB report recommended that, “An integrated modeling approach that captures biophysical and economic dynamics is appropriate to estimate . . . the additional effect of bioenergy demand on CO<sub>2</sub> emissions.”

#### *Food vs Fuel and Bioethanol and Negative Carbon Leakage*

One of the early commissioned EU studies was “Global Trade and Environmental Impact Study of the EU Biofuels Mandate” by Al-Riffai, Dimaran, and Laborde in 2010. This study identified that ILUC effects were potentially significant but also uncertain. A follow-up study used an updated version the MIRAGE-Biof CGE model that considered the 27 EU member state national plans and revised biofuel demand scenarios. The key conclusion from this exercise was that over two-thirds of the direct emission savings are lost when considering ILUC effects. A later study commissioned by the EC (Valin et al. 2015) used IIASA's global partial equilibrium model GLOBIOM, which covers the agriculture, forestry and bioenergy sectors. This study showed that LUC impacts and GHG performance varied significantly depending on feedstock and geographic location. The study also showed that results are sensitive to a number of assumptions about deforestation and peatland conversion patterns, degree of vegetable oil substitution, substitution effects of coproducts, yield development and yield response.

A key conclusion from the study was that a given biofuel pathway is not associated with one permanent ILUC effect, since ILUC may change with different policy design, baseline development, or timeframe.

The early concerns about using first generation biofuels based on bioeconomic models set the context for how land use change and leakage entered the scientific and policy conversations.

Relative scarcity (price) depends on the cost of supply versus the willingness to pay relative to substitute goods and services. Increased scarcity raises relative prices, which gives producers the incentive to produce more, and consumers an incentive to find substitutes. Using corn for a bioenergy feedstock raises the price of corn, which raises the demand for corn cropland. Expanding corn acreage for fuel either displaces

existing corn directly or leads to conversion of non-crop land to crops. As was mentioned above, results are sensitive to several factors. For the corn ethanol case, the assumed productivity increases (technical change) associated with higher corn prices is critical. In this debate, land use effects were often discussed as one-to-one transfers of acres between providing food or fuel. Expansion of cropland into any other land use was usually a carbon negative. The science was more complicated and nuanced (see Figure 2), but the contrast with results from bioeconomic analysis of forest carbon is important. [see *Ricardian land use theory footnote below*].

#### *Forest Carbon Accounting and Potential Positive Leakage*

Another of the early EU commissioned studies (Havlik et al. 2011), which also used the GLOBIOM model, found significant ILUC effects that suggested that second generation (woody) biofuels had a distinct advantage over first generation (crop-based) biofuels with ILUC effects being positive for the former and negative for the latter.

Positive carbon leakage results from increasing returns to timberland from increased demand for forest products. Lubowski et al. (2008) concluded in their analysis of U.S. forestland:

*“...we identified the rise in timber net returns as the most important factor driving the increase in forest areas between 1982 and 1997. This is consistent with reports that the increase in forests largely involved timberland acreage.”*

Higher rents increase forestland area, but they also lead to intensified management and higher sequestration rates. Figure 1 in the appendix shows the history of increasing inventories in the southern U.S. and Sweden as demand for wood increases. Observed plantation growth rates in the U.S. South increased by an average of 1 % per year between 1990 and 2014. (US Forest Service –Forest Inventory and Analysis Database).

Plantations can also displace naturally regenerated forest. This creates a carbon stock/sequestration tradeoff if carbon stocks are higher on the displaced slower growing forest. In some cases, managed forests have both higher carbon stocks at maturity and higher of sequestration rates than naturally regenerated forests (Figure 3).

Expansion of plantations into pasture or scrubland is expected to increase carbon stocks. If forest area expanded into agriculture, it would compete for the less productive land, which would lessen price and leakage effects in the agriculture sector. [see *Ricardian land use theory below*].

#### *Complementary Carbon Sequestration and Biomass Energy Policies*

As shown in the historical data, carbon sequestration from higher growth does not have to come at the expense of carbon stock. Favero et al. (2017) consider the benefits of combining carbon sequestration policies with biomass energy with carbon capture and storage to limit long-term radiative forcing. They found that the combined policy was more effective than either policy alone.

A recent working paper by Baker et al. (2018) uses a detailed global forest market model to examine the relationship between bioenergy expansion and sequestration incentives. It also finds that a combination of biomass energy expansion and forest sequestration payments have complementary effects and potentially better carbon outcomes than either policy individually.

The contrast between these results and the Gan and McCarl paper, cited earlier, are consistent and noteworthy. In Gan and McCarl, preserving carbon stocks by creating reserves leads to harvest leakage to other countries. This largely negates net carbon storage gains. In the Favero et al. and Baker et al. papers, economic incentives for both biomass energy and carbon sequestration led to better carbon outcomes. Increasing rents to forestland can lead to higher sequestration and carbon stocks due to intensive management and forest expansion.

*Translating bioeconomic analyses of forest carbon into policy*

Agreement on a conceptual bioeconomic approach does not simplify the research task nor make it easier to translate results from a suite of bioeconomic models, each with a range of outcomes, into concise policy recommendations. Forests vary by growth rates, age at maturity, ownership objectives, regulations, biodiversity, and accessibility. Finally, location determines access to markets and types of forest products with different emission profiles affected by increased demand for bioenergy.

Bioeconomic analyses often estimate carbon positive net effects resulting from increased demand for wood that are consistent with the historical development of markets and forest carbon stocks, especially in areas where forests markets are responsive. However, these results often seem to cause controversy. For example, scientific discussions of the U.S. EPA biogenic carbon accounting framework are currently stalled—in part due to a debate on the merits of economic models as a basis for policy.

*Why do positive forest carbon results from bioeconomic analysis seem more controversial?*

This paper concludes with a discussion of why one particular set of outcomes (positive carbon leakage), plausible under certain conditions, seem to be more controversial and subject to challenge.

*Bioeconomic models require another order of magnitude of assumptions*

Linked economic and biophysical models require additional layers of *explicit* assumptions but positing a future without market feedbacks requires a particular set of *implicit* economic assumptions. Ignoring implicit assumptions and their likelihood might reduce variability in model results, but it will not improve model accuracy or strengthen its basis for policy.

Ultimately the role of these models is to increase our understanding of these complex systems and to help guide policy toward better choices. This requires full consideration of bioeconomic dynamics, explicit consideration of uncertainty and full disclosure of the implications of this uncertainty for policy.

*Economists cannot predict the short run, why should we believe long run forecasts*

First, because long-term dynamics of key macroeconomics drivers like GDP have less variability than short run variables tied to business cycles, economists are better at predicting the long-run. Second, forest stocks change slowly and given data on age class structure and growth, long-term supply trends for wood are straightforward to project. Analysis of increased variance in results due to changing climate or episodic events is relatively straightforward.

Most importantly, however, accuracy of the reference or baseline projection is not a prerequisite for a policy relevant model. It is more important to capture the direction and scale of the marginal effect of a new policy on forest and atmospheric carbon outcomes. Given the complex interrelationships in the bioeconomic system, these outcomes are not likely to be independent, but direction and scale of policy impacts may be robust across a range of specific economic outcomes. Uncertainty in results should be characterized and effectively communicated to policy makers.

*You trust what you can see*

In a carbon-offset program that limits harvest in a specific location which results in negative leakage, it is easy to identify the trees that were not harvested, but hard to identify the harvest elsewhere caused by project leakage. Market response to increasing price can result in positive land use leakage. It is easy to identify the harvest, but it is hard to identify area not lost to land use change caused by project leakage

The same perspective applies to growth/sequestration versus harvest, where both are empirically validated. Harvest of forests leads to visible aesthetic and ecological implications, leading to more angst when a forest is harvested than when, say, a corn field is harvested. Seeing the benefit while believing there is loss elsewhere is more comforting than seeing the loss and trusting there is gain elsewhere.

*Confirmation-bias: models results seem wrong, so the assumptions must be wrong*

At some level, we all choose what to believe. The concept that harvesting trees and using them for energy can lead to a future with more forest carbon and less atmospheric carbon is not intuitive. Faced with a wide array of uncertain model results, it is human nature to favor science that matches your intuition. For example, there is considerable evidence that skepticism of anthropogenic climate change is not related to less understanding of climate science. Internal biases are not easily changed by science.

*Climate policy has an asymmetric loss function.*

Some bioeconomic forest carbon projections have relatively positive forest and atmospheric carbon outcomes. Even if the more optimistic projections are valid, rational policy choices might be conservative simply to avoid catastrophic outcomes. It is critical, however, to separate a conservative policy choice based on the best available information from a skepticism of science that leads to more optimistic outcomes. For scientists, careful scrutiny of fully informed models leads to better understanding of the systems we are modeling. Science based policy requires the same.

## References

- Al-Riffai, P., B. Dimaranan, D. Laborde. 2010. Global Trade and Environmental Impact Study of the EU Biofuels Mandate. IFPRI Final Report. 125pp.
- Baker, J.S., C.M. Wade, B. Sohngen, S. Ohrel, A. Fawcett. 2018. Potential Complementarity of Forest Carbon Sequestration Incentives and Biomass Energy Expansion. RTI Working Paper. Available from the J. Baker.
- Chum, H., A. Faaij, J. Moreira, G. Berndes, P. Dhamija, H. Dong, B. Gabrielle, A. Goss Eng, W. Lucht, M. Mapako, O. Masera Cerutti, T. McIntyre, T. Minowa, K. Pingoud, (2011). Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Cowie, A., Brandão, M., Fritsche, U., Berndes, G., Junginger, M., Smith, T. 2017. Forests, bioenergy and climate change mitigation: report of a workshop held 19-20 May 2014, Copenhagen. IEA Bioenergy, Task 38, Task 40, Task 43.
- Favero, A., R. Mendelsohn, B. Sohngen. 2017. Using forests for climate mitigation: sequester carbon or produce woody biomass? Climatic Change 144:195-206
- Fox, Thomas R., Eric J. Jokela, and H. Lee Allen. 2007. The Development of Pine Plantation Silviculture in the Southern United States. Journal of Forestry. Oct/Nov pp. 337-347
- Gan, J., B. McCarl. 2007. Measuring transnational leakage of forest conservation. Ecological Economics (64):423-432.
- Havlik, P., U. Schneider, E. Schmid, B. Hannes, F. Steffena, S. Rastislav, A. Kentaro, DeCara, S., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., Obersteiner, M. 2011. Global land use implications of first and second-generation biofuel targets. Energy Policy 39:5690-5702.
- Kallio, M. and Solberg, B. 2018. Leakage of forest harvest changes in a small open economy: case Norway, Scandinavian Journal of Forest Research, DOI: 10.1080/02827581.2018.1427787
- Lubowski, R.N., A.J. Plantinga, R.N. Stavins. 2008. What drives Land-Use Change in the United States? A National Analysis of Landowner Decisions. Land Economics 84(4):529-550.
- Plevin, R.J., M.A. Delucchi, and F. Creutzig. 2014. Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation Benefits Misleads Policy Makers. Journal of Industrial Ecology 18(1):73-83

- Searchinger, T, Heimlich, R, Houghton, R, Dong F, Elobeid, A, Fabiosa, J F, Tokgoz, S, Hayes, D J, and Yu, T (2008) *Factoring Greenhouse Gas Emissions from Land Use Change into Biofuel Calculations*. Science(319)1238-1240.
- Valin, H., Peters, D., van den Berg, M., Frank, S., Havlik, P., Forsell, N., Hamelinck, C. 2015. The land use change impact of biofuels consumed in the EU. Quantification of area and greenhouse gas impacts. Study commissioned by the European Commission. Ref. Ares (2015) 4173087 - 08/10/2015
- Woltjer, G., Daioglou, V., Elbersen, B., Ibanez, G.B., Smeets, E. González, D.S., Barnó, J.G. 2017. Study report on reporting requirements on biofuels and bioliquids stemming from the directive (EU) 2015/1513. Report prepared for the European Commission under contract number ENER/C1/SER/2015-438/4/SI2.735083.

#### *Ricardian land use theory and the implications for carbon positive leakage.*

Indirect land use change estimates can be misleading if land use is considered a zero-sum game, i.e. additional acre of forestland requires loss of one acre of crop land and *vice versa*. This implicitly assumes land is equally productive.

The economic (Ricardian) view of land use recognizes that rural land uses tend to follow a productivity gradient, which implies smaller than average impacts on production and prices when land is converted. For example, the most valuable crops will be on the most productive land for that crop. If more land were required, the displacement would tend to follow the productivity spectrum. An example progression might be less productive cropland, pastureland, managed forestland, natural forestland, and scrubland. In this setting increasing the value of a crop could lead intensification of crop management and at the margin a conversion of less productive cropland, pasture or forestland into crops.

Similarly, increasing the value of forestland could lead to an increase in forestland area and increased intensity of forest management. For example, plantations could displace natural forest with carbon stock/sequestration tradeoffs if carbon stocks are higher on the displaced slower growing natural forest. If forest area expanded into agriculture land, it would be marginal agriculture land with lessened production or price impacts in the agriculture sector. Plantation expansion into less productive forestland could expand both the carbon stock and sequestration of the forestland. Both of these are examples of positive carbon indirect leakage.

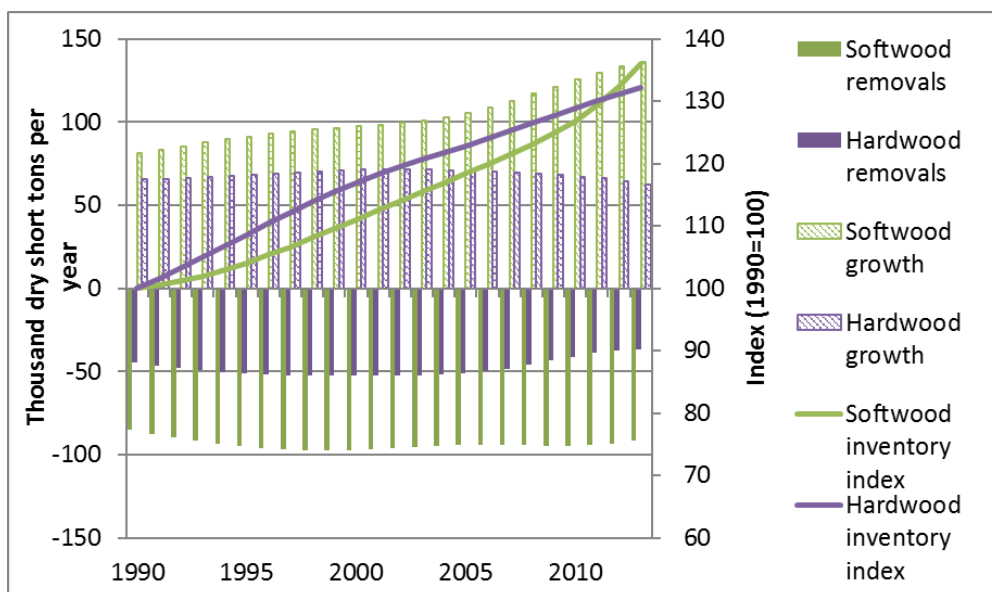


Figure 1A. Southern U.S. growth, removal, and inventory trends over the last 25 years. (U.S. Forest Service FIA database)



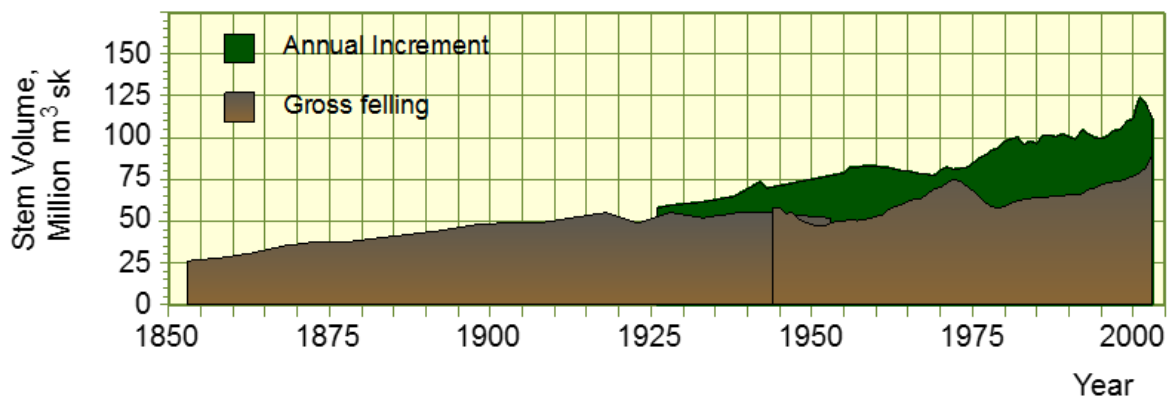


Figure 1B. Sweden's history of increasing removals and net growth.

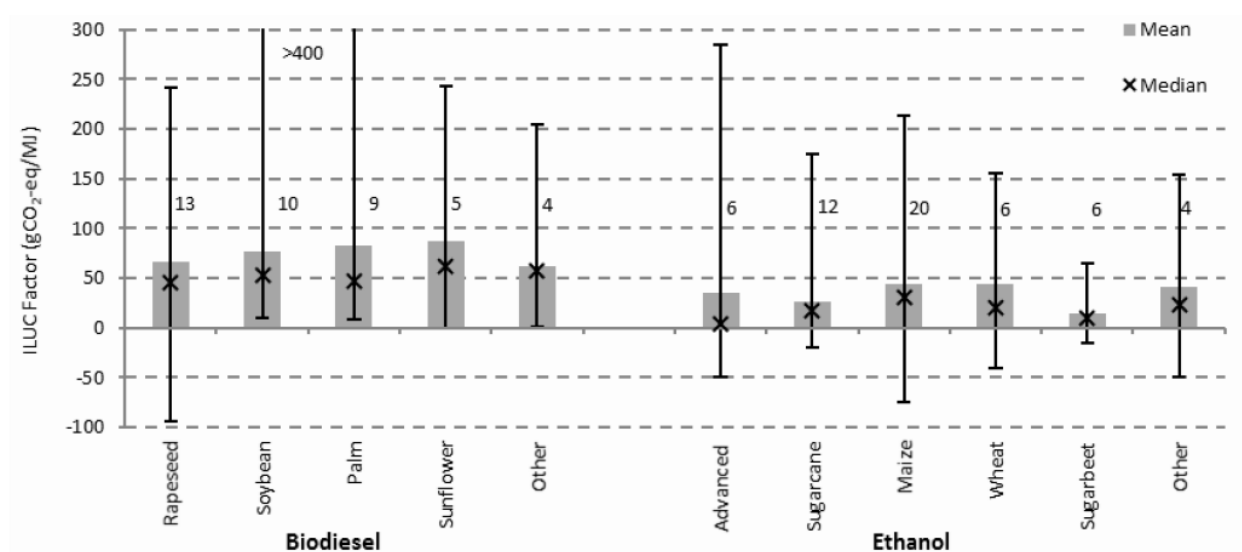


Figure 2. Summary of ILUC factors found in literature for biodiesel and ethanol. Grey bars: Mean, Black crosses: Median, Whiskers: Maximum-Minimum, number of studies quantifying ILUC factors written above each column. All ILUC factors have been harmonized to represent a 20 year amortization period. Note: a given study may include multiple scenarios or feedstocks. Source: Woltjer et al., 2017.

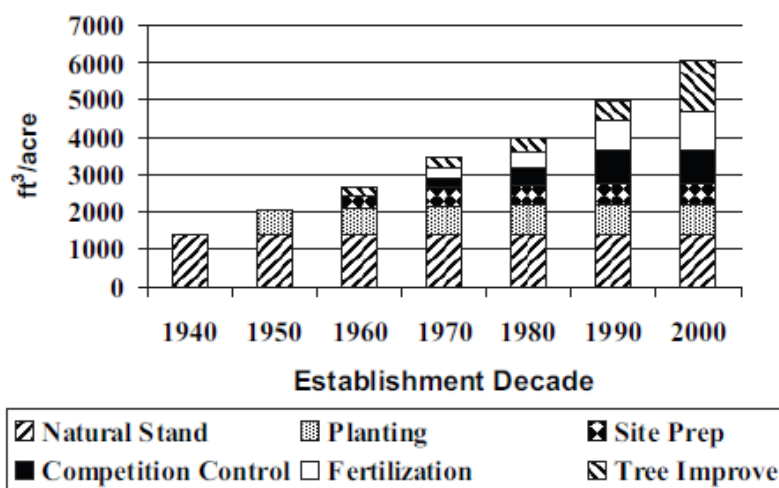


Figure 2. Estimated total yield and contributions of individual silvicultural practices to productivity of pine plantations in the southern United States from 1940 to 2000.

Figure 3. Source: Fox, Thomas R., Eric J. Jokela, and H. Lee Allen. 2007. The Development of Pine Plantation Silviculture in the Southern United States. *Journal of Forestry*. Oct/Nov pp. 337-347

## Comparison of selection systems and rotation-forestry system: conditions for biomass extraction, carbon balances and climate effects

*Johan Bergh, Professor, Linné University, Sweden*

*Contributors: Sauli Valkonen, Natural Resources Institute Finland (Luke); Lars Lundqvist, Swedish University of Agricultural Sciences; Anders Lindroth, Lund University; Tomas Lundmark, Swedish University of Agricultural Sciences*

Tree growth provides an efficient means of removing CO<sub>2</sub> from the atmosphere and producing raw materials to replace the use of fossil fuels. Forests in themselves are also large carbon stores and increased standing volume also means less CO<sub>2</sub> in the atmosphere. Similarly, forest products with a long life-time contribute to climate change mitigation by storing carbon for a period of time relevant from a climate change mitigation perspective. However, short-lived products do not carry this advantage. Thus, the forest sector has two principal options for contributing to climate change mitigation - fossil fuel substitution and carbon storage - both associated with relatively low costs. An important difference is that the displacement of fossil fuels results in a permanent benefit while the carbon storage option is temporary, i.e., the benefit lasts only until the stored carbon is released back to the atmosphere.

Forestry in Sweden today is largely based upon rotation-forestry systems with even-aged forest stands and a balanced stand age distribution on the landscape level. The carbon dynamics of rotation-forestry systems include a significant net amount of biomass carbon removal out of the forest at final harvest, emissions of CO<sub>2</sub> during the regeneration phase (mainly from logging residues and soil, more pronounced when site preparation is applied) and then rapid net carbon gain in young stands with substantial setbacks in thinnings. Net carbon gain is high after canopy closure in more mature stand (20-100 yrs), while it decreases in over-mature stands and finally approaches zero or slightly negative/positive. An alternative management principle is the selection system, with uneven-aged, structurally more complex forest stands and diversely structured and continuously maintained forest cover. The cyclic final harvest-and-regeneration pattern in rotation-forestry is replaced by a harvesting cycle with lighter partial harvests occurring with shorter intervals, where a major part of the stand is always retained. Currently this system is barely on practice in Sweden, but could be an alternative for future. The carbon dynamics of selection systems include a net biomass carbon removal out of the forest at selection harvests and a relatively stable net carbon gain in the uneven-aged stands. Site preparation is seldom applied, and the respective carbon release from the soil is avoided in contrast to the clear-cutting and regeneration stage in rotation forestry. A change in silvicultural system could bring a range of changes in regeneration practices, forest structure, biomass production, harvest and forest disturbance, which must be considered when analysing carbon balance for the two management systems.

### *Discussion within the group*

The uptake of CO<sub>2</sub> in the forest is determined by photosynthesis, while the emissions of CO<sub>2</sub> originates from autotrophic (from plants) and heterotrophic (decomposition) respiration. The balance between these processes determine the net carbon stock change (NEP), which should be equal to net ecosystem exchange (figure 1).

The group agree that NEE (and/or NEP) is a good approximation for CO<sub>2</sub>-uptake and capacity to store CO<sub>2</sub> per unit time = sink strength (Luyssaert et al., 2007). This should also be related to biomass production n a long-term perspective (even if NEE and biomass productions is not exactly the same). The group agrees that increased production are in general positive for overall carbon balance since it increase the CO<sub>2</sub>-uptake and

allows us to harvest more forest biomass for long-term carbon storage. The group also acknowledge the importance of substitution of fossil fuels and products associated with higher carbon emissions such as many construction materials.

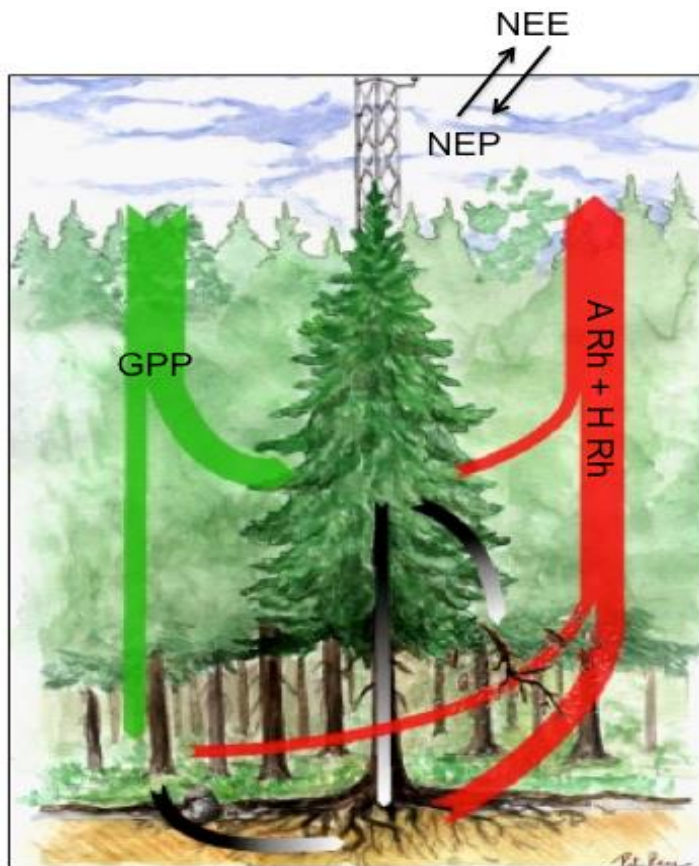


Figure 1. *GPP = Gross Primary Production The uptake of  $\text{CO}_2$  through photosynthesis.*

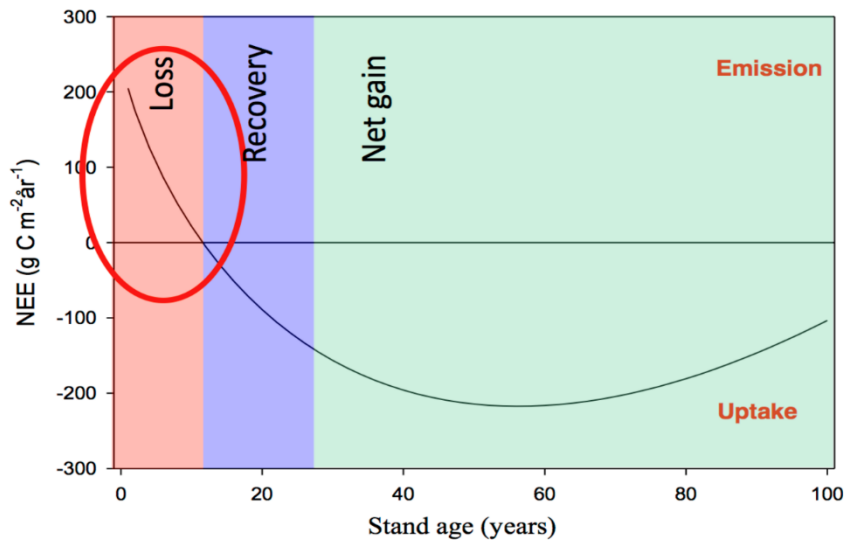
*NPP = Net Primary Production:  $\text{GPP} - \text{autotrophic respiration (A Rh)}$  by plant. The total production of biomass and dead organic matter in a year.*

*NEP = Net Ecosystem Production:  $\text{NPP} - \text{heterotrophic respiration (H Rh)}$  by decomposition of litter, dead wood and soil. It is equal to net carbon stock change.*

*NEE = Net Ecosystem Exchange Another way to measure NEP by integrating the fluxes of  $\text{CO}_2$  into and out of the vegetation.*

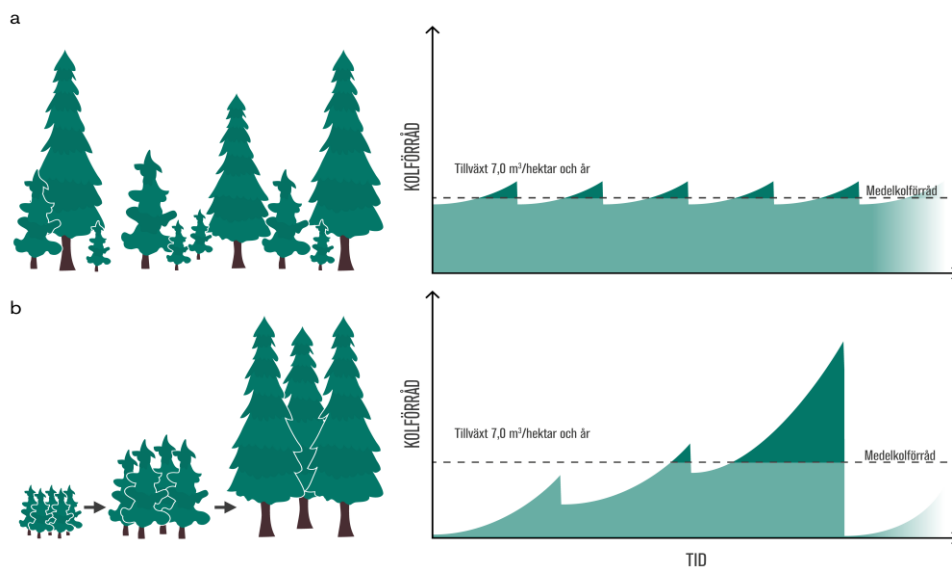
Another discussion is whether selection systems are better compared with rotation forestry in terms of carbon balance, based on the large emissions of  $\text{CO}_2$  in clear-fellings and the consecutive years after until young stands turn to a sink instead. The loss of  $\text{CO}_2$  creates a “debt” (figure 2) and it takes several years before the debt is “paid off”. Figure 2 is based on five “Eddy-flux” sites across Sweden (Lindroth et al. 2009) and all of them are even-aged stands managed by rotation forestry. One major weakness is that similar measurements have not been conducted in multi-layered stand with selection forestry yet and therefore no direct comparisons have been possible. One Norwegian study shows that carbon storage capacity is 10-15 % larger in rotation forestry than selection forestry for a 81 year period (Nilsen & Strand, 2013)

In the same time production is higher in rotation forestry, especially during the second half of the rotation period and also the mean production are higher for rotation forestry, according to literature studies, when these systems are compared. We don't know, however, if the  $\text{CO}_2$ -uptake/NEE/NEP is larger as a mean for a whole rotation period.



One process/hypothesis a number of scientists claim can differ between the two silvicultural systems is heterotrophic respiration and slower decomposition of organic matter in multi-layered stands compared with rotation forestry (Noormets et al, 2015), which imply higher storage of carbon in the soil. No scientific evidence has been shown this far but in the same time the hypothesis cannot be rejected. A recent study indicated that the two systems may not differ very much in this respect, except that carbon release is much greater if site preparation is applied, and the gap tends to persist for decades (Simola 2017). Site preparation is applied on most clear-fellings in rotation forestry but seldom needed in selection management.

According to field studies in Sweden and Finland, there is no difference in mean carbon stock between the systems with a long-term perspective even if there are larger fluctuations in rotation forestry.



*Differences between rotation forestry and selection system needed to consider:*

*Advantage for rotation forestry in terms of carbon balance:*

- Extraction of forest residues is possible
- Use of genetical improved plant material for enhanced productivity
- Higher production by 10-20 % in rotation forestry (Lundqvist, 2017)
- Better possibility to change tree species in rotation forestry
- Forest area directly suitable for selection forestry without stand conversion is currently less than 5 % of total forested area. It is, however, much more land available for transformation from even age stands to selection systems
- Large losses in production and carbon balance to transfer even-aged stands to selection systems during 30-50 years (Drössler et al, 2014)

*Advantage selection systems in terms of carbon balance:*

- Site preparation with increased CO<sub>2</sub> emissions is avoided
- Disease and damage risks are considered smaller than in rotation forestry, mostly in respect to moose, storm damage, voles, weevils (Nevalainen, 2017)
- Will the decomposition curve of forest residues, stumps and organic matter differ between the systems (harvest in rotation forestry vs incremental thinnings in selection systems), where heterotrophic respiration and slower decomposition of organic matter leads to higher storage of carbon in the soil in selection system (Noormets et al, 2015)
- Field vegetation might differ between the systems and be important for NEP and soil C storage

*Take home message*

- 1) After discussions we finally agreed that no one can claim that selection systems or rotation forestry is much better than the other in terms of overall carbon balance. Better to focus on other strategies to mitigate climate change.
- 2) NEE and NEP is a good approximation for CO<sub>2</sub>-uptake and capacity to store CO<sub>2</sub> per unit time = sink strength
- 3) We agree upon that increased production is beneficial for climate mitigation, since it increase the CO<sub>2</sub>-uptake and allows us to harvest more forest biomass and use it for long lived products, such as building constructions.

## References

- Drössler, L., Nilsson, U., Lundqvist, L., 2014. Simulated transformation of even-aged Norway spruce stands to multi-layered forests: an experiment to explore the potential of tree size differentiation. *Forestry* 87, 239–248. <http://dx.doi.org/10.1093/forestry/cpt037>.
- Lindroth, A., Lagergren, F., Grelle, A., Klemetsson, L., Langvall, O., Weslien, P., Tuulik, J., 2009. Storms can cause Europe-wide reduction in forest carbon sink. *Glob. Change Biol.* 15, 346–355.
- Lundqvist, Lars. "Tamm Review: Selection System Reduces Long-term Volume Growth In Fennoscandic Uneven-aged Norway Spruce Forests." *Forest ecology and management* 391(2017): 362-375. doi: 10.1016/j.foreco.2017.02.011



- Luyssaert, S., Inglisma, I., Jung, M., Richardson, A.D., Reichstein, M., Papale, D., Piao, S.L., Schulze, E.D., Wingate, L., Matteucci, G., Aragao, L., Aubinet, M., Beer, C., Bernhofer, C., Black, K.G., Bonal, D., Bonnefond, J.M., Chambers, J., Ciais, P., Cook, B., Davis, K.J., Dolman, A.J., Gielen, B., Goulden, M., Grace, J., Granier, A., Grelle, A., Griffis, T., Grunwald, T., Guidolotti, G., Hanson, P.J., Harding, R., Hollinger, D.Y., Huttyra, L.R., Kolari, P., Kruijt, B., Kutsch, W., Lagergren, F., Laurila, T., Law, B.E., Le Maire, G., Lindroth, A., Loustau, D., Malhi, Y., Mateus, J., Migliavacca, M., Misson, L., Montagnani, L., Moncrieff, J., Moors, E., Munger, J.W., Nikinmaa, E., Ollinger, S.V., Pita, G., Rebmann, C., Roupsard, O., Saigusa, N., Sanz, M.J., Seufert, G., Sierra, C., Smith, M.-L., Tang, J., Valentini, R., Vesala, T., Janssens, I.A., 2007. CO<sub>2</sub> balance of boreal, temperate, and tropical forests derived from a global database. *Glob. Change Biol.* 13, 2509–2537
- Nevalainen S. (2017). Comparison of damage risks in even- and uneven-aged forestry in Finland. *Silva Fennica* vol. 51 no. 3 article id 1741. 28 p. <https://doi.org/10.14214/sf.1741>
- Nilsen P., Strand L. T. (2013). Carbon stores and fluxes in even- and uneven-aged Norway spruce stands. *Silva Fennica* vol. 47 no. 4 article id 1024. 15 p.
- Noormets, A.; Epron, D.; Domec, J.C.; McNulty, S.G.; Fox, T.; Sun, G.; King, J.S. 2015. Effects of forest management on productivity and carbon sequestration: A review and hypothesis. *Forest Ecology and Management*. 355: 124-140.17 p. <http://dx.doi.org/10.1016/j.foreco.2015.05.019>
- Simola, H. 2018. Persistent carbon loss from the humus layer of tilled boreal forest soil. *European Journal of Soil Science* 69: 303-314.

## A principal choice—manage forests for wood production or leave the forest as a carbon sink: carbon balances and climate effects

Gert-Jan Nabuurs, Professor, Wageningen University, The Netherlands

### Initial remarks

- Role of forest management in mitigating climate change has been studied and evaluated often,
- Outcomes depend very much on what part of the forest-wood products-energy chain has been included.
- Depends on time span, initial situation
- Which region of the world
- Biophysical effects; ref. to presentations by Luyssaert and Kalliokoski

(These remarks may be supported by short literature overview)

A concern expressed in the debate is that the wood demand for bioenergy may rise enormously, threatening the existence of forests. But bioenergy is typically a side-product of forest harvesting and wood processing, and sustainable forest management (SFM) principles provide safeguards against overharvesting where such principles are applied.

Considering market realities, SFM requirements and existing regulations around bioenergy, it is highly unlikely that a paradigm shift will take place towards large scale cutting of forests solely for bioenergy.

Given the multitude of forest functions, the question implied in the presentation title – *Manage forests for production or leave as a carbon sink?* – **this is not the question !**

It can be reformulated to:

- Where should we do what?
- How to create “the best” incentives?

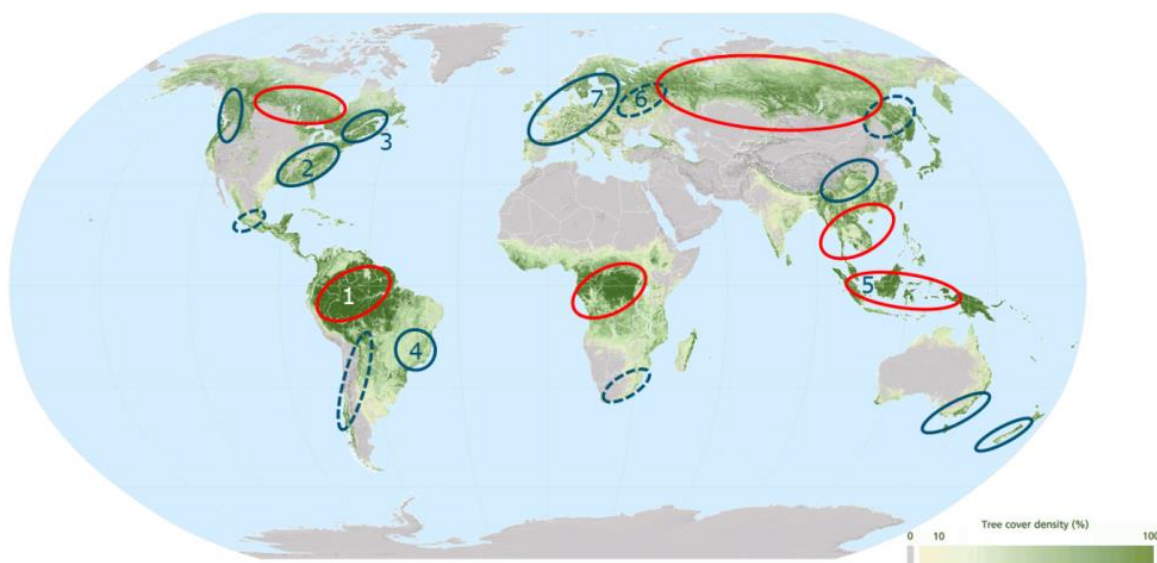


Fig. 1. FAO world forest map. Blue encircled are those regions where some form of sustainable management takes place and where harvest could be increased for products and energy. Blue dashed circles are those regions where an increased sustainable harvest could be developed in the longer term, e.g. on the basis of 2<sup>nd</sup> rotation forest or tropical secondary forests. Red circles are areas with large tracts of primary forests and/or a high rate of deforestation occurs i.e., regions more suited to ‘n management’ or forest restoration.

As a complement to earlier presentations – that may show hectare scale analyses and the principles of mitigation effects – continental analyses will be provided including examples in pictures.

Woody biomass resources are limited and the total forest resource is small compared to the global energy system. Consequently, the forest sector's contribution to the global energy supply will be limited. Yet, sustainably managed forests can make a substantially larger contribution than today.

Taking EU as an example, EU woody biomass now covers 6% of EU primary energy use. It is possible to increase this to 10–11%. As shown in Fig 2, European countries find a good balance between active management and still maintaining a carbon sink.

In the past, the European forest sector has responded to increased demand for sawnwood and paper by expanding forests and intensifying management to increase wood production. Similarly, the likely response to increased bioenergy demand will be to devise management approaches that enable biomass production for energy in conjunction with supply of sawlogs and pulpwood.

Yet, in association with renewable energy considerations, countries focus very much on harvesting additional wood and biomass (which is possible sustainably in some regions, see Fig.3). But this requires investing upfront in regeneration, better techniques, schooling and capacity building.

Thus, climate Smart Forestry is needed that (i) maintains productivity; (ii) adapts forests to climate change; and (iii) mitigates climate change (through whole chain)

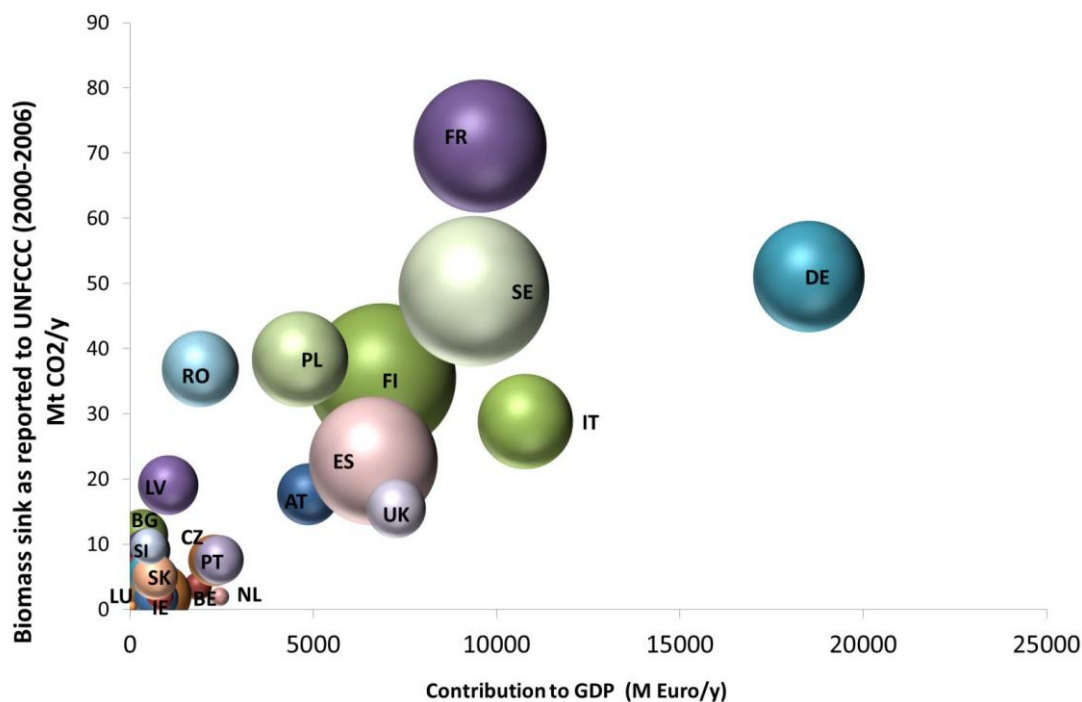
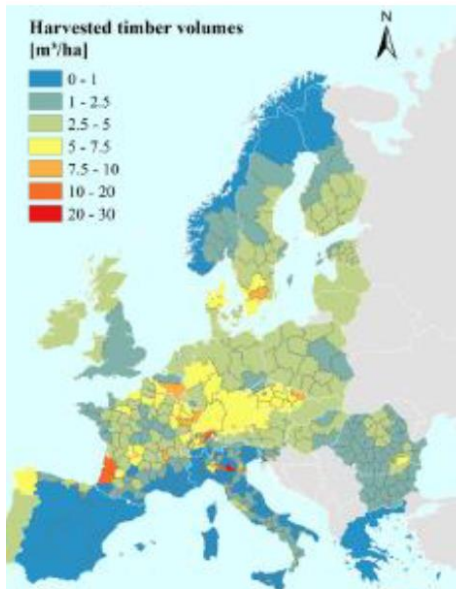


Fig. 2. Europe: X axis is contribution of national forest sector to GDP. Size of bubble is size of forest area (Source: Nabuurs et al. 2015)

## Harvesting: Countries differ !



Resources in Europe: possible to increase harvest sustainably with 100-150 million m³/y.

Without any carbon debt.

This also requires investing in forest management, knowledge etc

EFISCEN modelling (Nabuurs & Schelhaas 2017, Levers et al. 2014)

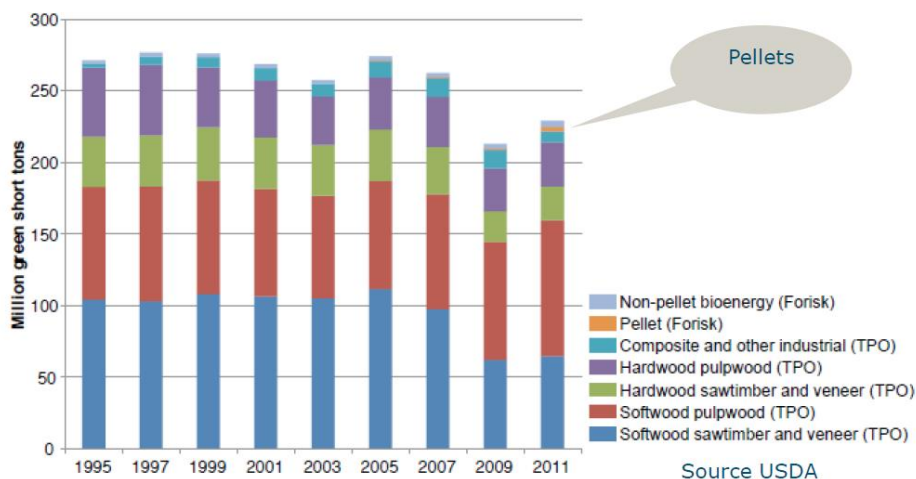
7

Fig. 3. The diversity in management amongst countries has to lead to different approaches in Climate Smart Forestry

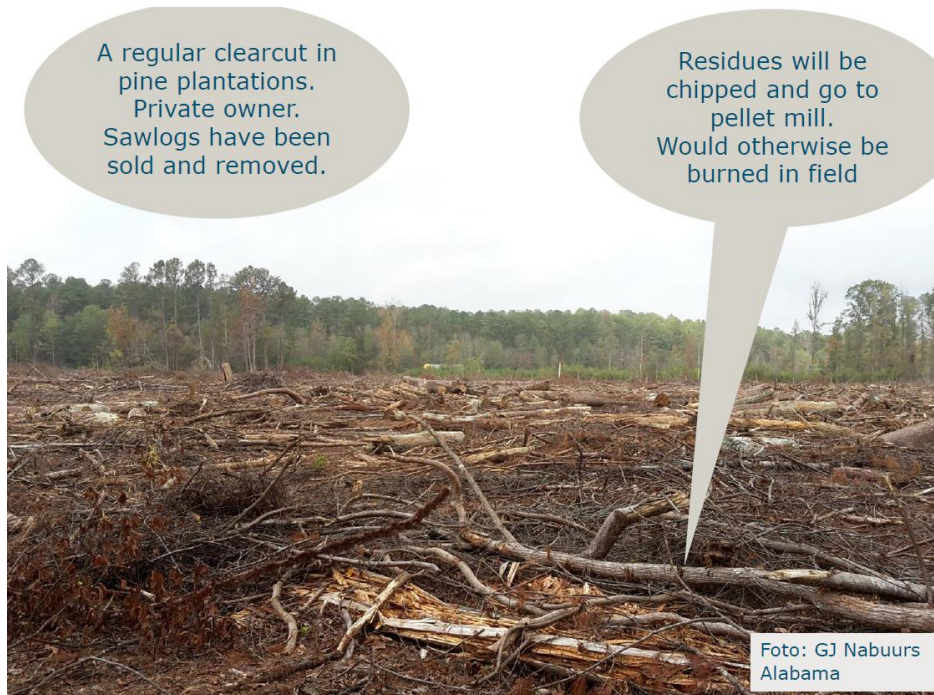
Pellet production in perspective: often portrayed as ‘gigantic’ but it is still only very small fraction.

## Timber product output SE USA

- Pellet output now ~10 million tonnes (UNECE 2017)
- On total product output of 230 million tonnes







Continental scale analyses of CSF are needed, but the debate is politicised. Still better and more regional analyses needed.

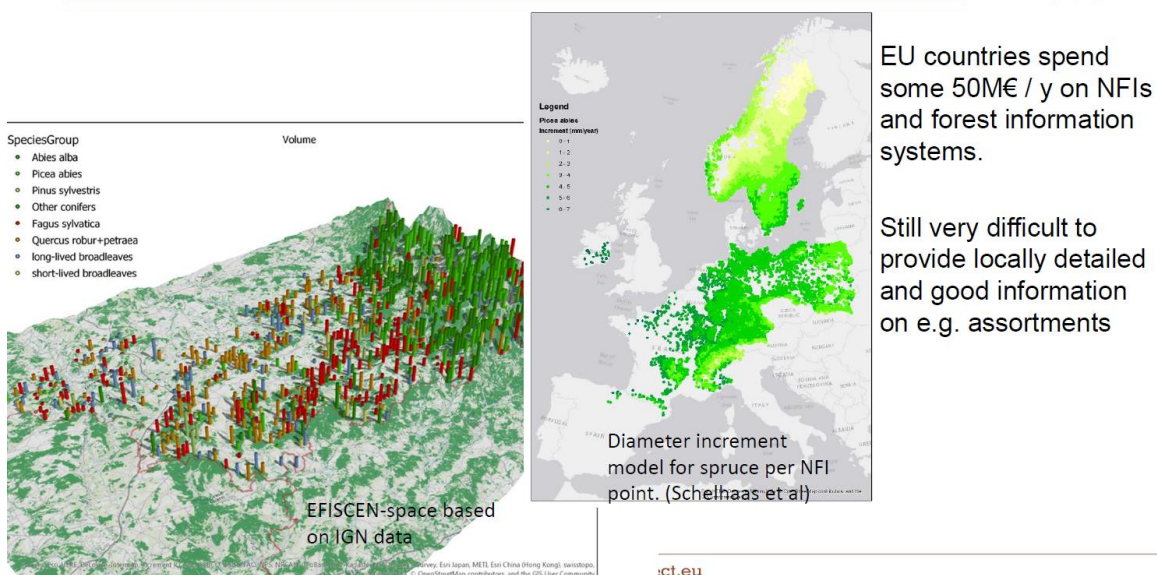
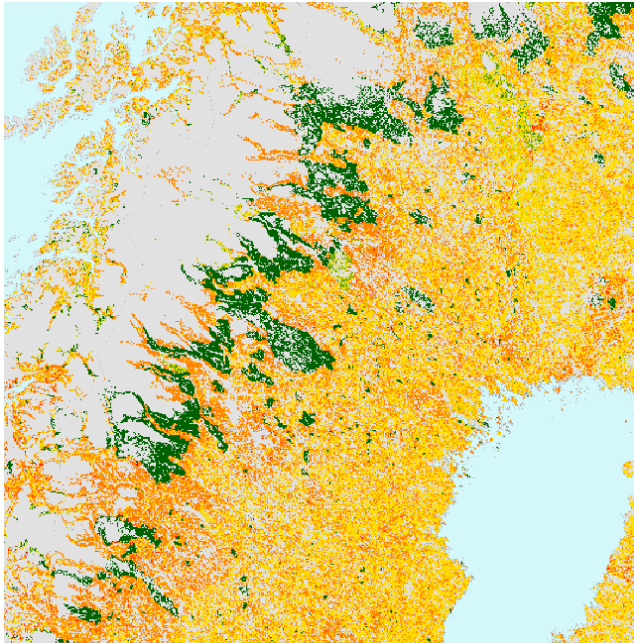


Fig: It is now possible to simulate and take into account local circumstances in forestry modelling all over Europe. Based on ~200,000 NFI plots. Dealing with forest owner characteristics, steep slopes, nature conservation, road access, etc. see example below where dark green is a strict reserve, light green and yellow are multifunctional forms, and orange hints at a more intensive management form.





## Climate effects of forestry and substitution of carbon-intensive materials and fossil fuels – a country level study for Sweden

*Leif Gustavsson, Professor, Linné University, Sweden<sup>1</sup>*

*Contributors: Roger Sathre<sup>3</sup>, Ambrose Dadoo<sup>3</sup>, Mattias Lundblad<sup>2</sup>, UnibenTettey<sup>3</sup> and Nguyen Le Truong<sup>3</sup>*

A topic of active discussion in Sweden is how forests should be managed. Specifically, there is much interest in how forest resources should be used effectively to mitigate climate change. Forests can play several roles in carbon emission reduction strategies, for example as a reservoir for storing carbon and as a source of renewable energy and material. To better understand the linkages and possible trade-offs between different forest management strategies, there is a need for integrated analysis where both sequestration of carbon in growing forests and the effects of substituting carbon intensive products within society are included.

In this presentation, we analyse the climate effects of directing forest management in Sweden towards enlargement of the set-aside area in forests, or towards increased forest production, relative to the current forest management over 100 years. We consider various scenarios of forest management and biomass use, and we estimate the carbon balances of the forest systems and their climate impacts in terms of radiative forcing.

The presentation is built on three general forest management scenarios: Business as usual (BAU), Set-aside, and Production. The BAU scenario reflects current forestry practices. In the Set-aside scenario, the protected area is doubled at the starting year of the simulation and then kept constant while all other settings are equal to BAU. In the Production scenario a higher forest productivity is achieved through more intensive management. Each forest management and harvest extraction scenario combination provides a supply of biomass raw materials to be used in the building and energy sectors. Different building construction and energy system scenarios are considered.

We ensure that the same services are delivered to society in the different forest management scenarios. In the Production scenario, more biomass is harvested compared to the BAU, increasing the potential production of timber buildings and bioenergy. In the Set-aside scenario, the harvest is less compared to BAU, decreasing the potential production of timber buildings and bioenergy. With less production of timber buildings and bioenergy, the construction of concrete buildings and use of fossil fuels need to increase to deliver the same amount of service to society.

Simulations of forest development and biomass harvest were made with the Heureka Regwise simulator, which is a forecast tool for forests and forestry on a large scale regional level. The core of the tool is simulation models for the tree-layer: growth, mortality and ingrowth. Models for individual trees simulate height growth in young stands (mean height < 7 m), and basal area for established stands (mean height ≥ 7 m). It also includes models for management, harvest, effect of climate change, and storm fellings. Input data for the simulations came from Swedish National Forest Inventory permanent and temporary plots. Simulations were made in 20 five-year intervals for each scenario; these results were then linearly interpolated and used as annual input data for further modelling.

Soil carbon stock changes in mineral soils were estimated with the Q-model. This is a soil decomposition model based on the continuous quality theory, where organic material entering the soil is decomposed over time in cohorts with specific initial qualities for needles, fine roots, branches, coarse roots, stumps, and stems.

The building construction scenarios include modern prefabricated concrete construction, prefabricated modular timber and cross-laminated timber building systems. A prefabricated concrete frame building in Växjö, Sweden (latitude 56°87'37"N; longitude 14°48'33"E) adapted to meet the Swedish passive house criteria, is used as reference building and is redesigned in detail with prefabricated modular timber and cross-laminated timber building systems. The building is 6 storeys high and has a total of 24 apartments, comprising 1–3 rooms with a total heated floor area of 1686 m<sup>2</sup>. The full lifecycle implications of the building versions are considered excluding the operation phase, as the building versions are designed to have the same operating energy use. We consider complete materials and energy chains, including the primary energy used to extract, process, and transport the required materials, and taking into account material losses and efficiencies of fuel cycles and conversion and distribution systems. We also consider calcination and carbonation carbon flows linked to cement-based materials. The service life of each building version is assumed to be 80 years. At the end-of-life of the building, steel is assumed to be recycled as scrap for production of new steel, concrete is crushed into aggregate and exposed to the atmosphere to increase carbonation during four months and then used for below-ground filling, while wood is recovered and used for energy. For comparison, a 4-storey high residential building with a different architectural design is also analysed.

There is a large potential for biomass to be used in the electricity, heating, and transportation sectors, replacing fossil energy. The shares of fossil fuels and renewable energy in the European Union in 2014 were about 72 % and 14 % (bioenergy: 9.1 %; hydro: 2.0 %; others: 2.6 %), respectively. In comparison, of the global primary energy use in 2014, fossil fuels, biomass and nuclear constituted about 81 %, 10 % and 5 %, respectively, giving a fuel dependence of 96 %. Increased use of bioenergy may help reduce the dependence on fossil fuels and mitigate the integration of wind and solar in renewable energy systems. Here, harvest residues from forest thinning and final fellings as residues from wood processing and building construction and demolition are assumed to be used for bioenergy. Net CO<sub>2</sub> emissions from bioenergy systems are compared to those from fossil energy systems that provide the same services. Each bioenergy scenario has a corresponding fossil energy system that makes equivalent products based on coal or fossil gas for cogeneration of heat and electricity or diesel oil for transportation. For biomass used for bioenergy an international transport of 1000 km is included in the analysis.

In the first 20 years of the analysis, the differences between the scenarios were small when bioenergy was assumed to replace fossil coal. After this initial period, a strategy aimed at high forest production, high residue recovery rate, and high efficiency utilization of harvested biomass gave most climate benefits which also increased over time. At the end of the analysed period, the effect of setting aside more forest for carbon storage resulted in higher total emissions, also compared to the reference, due to lower forest harvests leading to higher carbon emissions from the energy and material systems.

The climate benefits are significantly reduced if bioenergy replaces fossil gas, and take longer to manifest. Replacing gas, the Set-aside scenario gave climate benefits during the first 20-50 years compared to the Production scenario, but after 50 years the Production scenario with high residue recovery rate gave clear climate benefits that increased over time, compared to the Set-aside scenario. Using biomass to replace liquid motorfuels further reduced the climate benefits of the Production scenario compared to the Set-aside scenario. The assumed type of wood building system or the type of residential building has a rather small impact on the results.

In this analysis, the climate implications of bioenergy and wood construction are considered in a holistic life-cycle system perspective. The analysis is based on detailed description of forest systems and technical systems, where a landscape perspective is used to consider the dynamics of productive forests in Sweden. All significant annual flows of CO<sub>2</sub> to and from the atmosphere are considered, but not other climate effects such as albedo. Hence, the cumulative radiative forcing is calculated based on annual net CO<sub>2</sub> emissions to the atmosphere. The timespan of 100 years appears to be long and technological development may change

the results, but still only about one forest rotation period is included in the analysis. In longer timespans the climate benefit of the Production scenario is expected to further increase compared to the Set-aside scenario, as the carbon stock in the set-aside forest may reach a dynamic steady state, while the forest in the Production scenario continues to produce biomass that can be harvested and used for bioenergy and materials.

Key factors steering the results are forest management, amount of harvested biomass, use of forest biomass and replaced non-wood products and fuels, end-of-life management of building materials and timespan of the analysis.

In summary, active forest management with high harvest and efficient forest biomass utilization with replacement of carbon-intensive non-wood products and fuels appear to provide significant climate benefits, compared to setting aside forest land and storing more carbon in the forest and reducing the amount of harvest biomass.

---

1) Department of Built Environment and Energy Technology, Linnaeus University, Växjö, Sweden

2) Department of Soil and Environment, Swedish University of Agricultural Sciences, Uppsala, Sweden

3)

## References

Gustavsson, L., Haus, S., Lundblad, M., Lundström, A., Ortiz, C.A., et al. Climate change effects of forestry and substitution of carbon-intensive materials and fossil fuels. *Renewable & Sustainable Energy Reviews* 67 (2017) 612-624.

Gustavsson L. and Truong, N.L. Bioenergy pathways for cars: Effects on primary energy use, CO<sub>2</sub> emission and energy system integration. *Energy* 115 (2016) 1779-1789.

Sathre, R., Gustavsson, L., and Truong, N.L. Climate change effects of electricity production fuelled by coal, forest slash and municipal solid waste with and without carbon capture. *Energy* 122 (2017) 711-723.

Tetty, U.Y.A., Dodoo, A. and Gustavsson, L. Effect of different frame materials on the primary energy use of a multi-storey residential building in a life cycle perspective (manuscript).

Ongoing work by Dodoo, A., Gustavsson L., Sathre, R., Tetty, U.Y.A. and Truong, N.L.

## The climate impact of forestry extends beyond its carbon budget

*Tuomo Kalliokoski, University of Helsinki, Department of Forest Sciences*  
*Sebastiaan Luyssaert, Wageningen University, Department of Ecological Sciences*

*Contributor: Jaana Bäck, University of Helsinki, Department of Forest Sciences)*

### *Context*

The Paris Agreement aims at limiting the increase in global temperature to well below 2 degrees. Parties aim to reach global peaking of greenhouse gas emissions as soon as possible and to undertake rapid reductions thereafter, in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the middle of this century. The implicit causality made in the Paris Agreement is thus that irrespective of how emission reductions are realized, they will result in a global temperature decrease. While the Paris agreement focuses on GHGs, it is critical to consider also non-GHG forcers since climate change mitigation strategies may otherwise be ineffective or even counterproductive. Climate effects, other than GHG-related, include changes in the surface albedo, evapotranspiration, surface roughness and the production of biogenic volatile organic compounds (BVOC) which have an effect on the number and quality of aerosols formed in the atmosphere. Secondary organic aerosols (SOA) can serve as a cloud condensation nuclei which connects forest management to the most uncertain climate effect, i.e., cloud formation in the lower atmosphere which has potentially large negative impact on global warming (IPCC 2013).

Contrary to the small land area required to reduce the emissions from fossil fuel burning is the substantial land area, i.e. 30% of the global ice-free land, that is required to reduce the emissions from deforestation and enhance the forest carbon sink. Prior to presenting forestry as a pathway for mitigating climate change and creating legal frameworks to support its use, it should be robustly established that carbon-based forest management genuinely results in cooling even after taking changes in surface properties and processes into account. This requires that for any land-based activity aiming at climate change mitigation: (1) non-GHG forcers should be considered in the assessment, (2) various assessment frameworks such as life cycle analyses (LCA) need to extend the scope to consider non-GHG forcers of the reference the land-based approach will be compared against.

### *Which part of the atmosphere should become cooler?*

The Paris Agreement aims at a global cooling but does not specify where in the atmosphere this cooling should occur. From a planetary point of view, global cooling will be achieved when reducing the imbalance of the radiative forcing at the top of the atmosphere. Reducing the top of the atmosphere imbalance between incoming and outgoing radiation guarantees that less heat will be trapped in the Earth's oceans and atmosphere. Even after a reduction of the imbalance of the radiative forcing at the top of the atmosphere the boundary layer climate – as experienced by the biosphere – could considerably change. An example of this is the proposal to inject aerosols in the stratosphere to increase the reflected incoming radiation. Where this would result in a decrease of the radiative imbalance at the top of the atmosphere, surface radiation, near-surface temperature and precipitation may change as well.



Humans and the ecosystems they rely on, largely depend on the near surface temperature which encompasses the skin temperature of the soil as well as the air temperature in the lower 2 m of the atmosphere. Even if humanity fails to mitigate climate change and thus lets the imbalance in top of the atmosphere radiation further increase, changes in surface properties and processes due to LULUCF may redistribute the heat away from the surface. Consequently, reducing the near surface temperatures could be a beneficial outcome of forest management but does not necessarily imply that the objectives of the Paris Agreement, i.e., limiting the increase in global temperature to well below 2 degrees, are met.

When a climate mitigation claim is made, it should, therefore, be specified which components of the climate system are expected to change.

#### *Net climate effects of afforestation and deforestation*

The climate effects of afforestation and reforestation are rather well understood both from observational (Bright et al. 2017; Lee et al. 2011; Li et al. 2015; Luyssaert et al. 2014; Zhao and Jackson 2014) and modeling studies (Arora and Montenegro 2011; Bala et al. 2007; Bathiany et al. 2010; Davin and de Noblet-Ducoudré 2010). Whereas afforestation in the tropics cools the surface climate from enhanced transpiration together with C sequestration outweighing the warming effect associated with the albedo change (Arora and Montenegro 2011; Davin and de Noblet-Ducoudré 2010; Li et al. 2015; Da Rocha et al. 2009), afforestation warms the surface climate through snow masking in the boreal zone (Arora and Montenegro 2011; Bala et al. 2007; Betts 2000; Li et al. 2015; Swann et al. 2010), transitioning from cooling to warming in the temperate zone (Li et al. 2015). These general responses imply that the combined biogeochemical and biophysical effects of tropical afforestation are expected to cool the climate. Afforestation in the boreal zone is currently expected to result in a biogeochemical cooling but a biophysical warming. However, these analyses do not include the cooling effect of SOAs which may change the net balance of afforestation towards cooling also under temperate and boreal conditions.

Although the biological and physical processes underlying these insights are well understood, the climate effect has typically been assessed for idealized model simulations which quantified the effects for extreme rather than realistic afforestation scenarios. When more realistic scenarios were applied the temperature effect of afforestation decreased substantially (Arora and Montenegro 2011).

#### *Net climate effects of forest management*

Contrary to the effects of afforestation and deforestation, little is known about the climate effects of forest management including the effects of human-induced tree species changes and silvicultural strategies (Erb et al. 2017; Luyssaert et al. 2014; Naudts et al. 2016) – despite the fact that management is explicitly mentioned in both the Kyoto Protocol and the Paris Agreement. When managing the carbon budget of a forest, interventions such as thinnings, species changes, and selective cuttings, to mention a few, result in also changes in the surface properties and processes of the forest that were unintended by the forest management. For example, a thinning aims at stimulating growth of the remaining trees but will unintentionally also change the albedo and transpiration. The near surface temperature effects of these unintended changes have been reported to be of the same magnitude as the temperature effects of afforestation and deforestation (Luyssaert et al. 2014), although the biogeochemical effects will most likely be smaller. The accumulating evidence thus suggests that ignoring biophysical interactions – as is currently the case in the Kyoto Protocol and the Paris Agreement – could result in mitigation projects that provide little climate benefit or, in the worst case, are counterproductive (Marland et al., 2003; Jackson et al., 2008; Naudts et al., 2016).

### *Finnish boreal forest case*

Active forest management and increased harvests for more intensive use of wood are frequently proposed to be a climate-friendly solution for the urgently needed shift from fossil fuels towards renewables. In this case study with a focus on Finland, we analyse the net radiative forcing (RF) effect of CO<sub>2</sub> (including tree biomass, soil carbon, harvested wood products, and products and energy substitution), surface albedo and forest related aerosols both at stand scale and in different harvesting scenarios of Finnish forests (50 %, 65 %, 100 % and 130 % of current annual increment, CAI). We selected this case study because it focusses on boreal forest and it is one of the few studies including the effects of plant-induced aerosols but because of the method applied, the analysis did not fully account for changes in atmospheric radiation transfer, e.g., longwave radiation and changes in atmospheric emissivity.

Forest growth of single-species stands of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and silver birch (*Betula pendula*) was simulated using the empirical stand-level tool called MOTTI (Salminen et al. 2005). Simulations were repeated for different harvesting scenarios and for different site fertility indices (infertile-medium fertile-fertile) over 100 years assuming a continuation of the current climate. Litter input into soil was calculated by multiplying simulated biomass compartments and turnover rates in MOTTI with biomass expansion factors (BEF) used in the Finnish greenhouse gas inventory (Official Statistics of Finland 2017). The soil decomposition model YASSO07 (Tuomi et al. 2011) was used to simulate soil carbon dynamics from the obtained litter inputs. The carbon stocks of harvested wood products and their decay over time were computed combining the timber harvest assortment information that MOTTI simulates with species-specific product distributions and life cycle information. Storage of carbon in wood products was based on lifecycle categories with exponential decay, given in Karjalainen et al. (1994). The avoided CO<sub>2</sub> emissions related to wood utilization were computed separately for harvested sawlogs and pulpwood (Table 1) based on the substitution factors of individual studies listed in Sathre and O'Connor (2010).

Table 1. The substitution factors used in the calculation of the avoided emissions. The avoided CO<sub>2</sub> emissions related to wood utilization were computed separately for harvested sawlogs and pulpwood. For sawnwood, the substitution factors of individual studies listed in Sathre and O'Connor (2010) were used as data points to compute the average values for avoided carbon emissions per carbon in raw material. Data values that referred to individual products were discarded as they were considered to be case dependent. The uncertainty range of the values was calculated for each species from the individual studies reported in Sathre and O'Connor (2010). Pulpwood was assumed to substitute mainly plastic packaging products and energy.

Harvested wood	Substitution factor (kg C kg rawwood <sup>-1</sup> )
Scots pine logwood	0.91 ± 0.57
Norway spruce logwood	0.91 ± 0.56
silver birch logwood	0.82 ± 0.51
Pulpwood	0.695

The resulting dynamic CO<sub>2</sub> balance (CO<sub>2</sub> in trees, soil and HWP, as well as avoided emissions) was coupled with CO<sub>2</sub> atmospheric life time function (IPPC 2007) and following changes of radiative forcing (RF) was derived by the methodology of Lohila et al. (2010).

Surface albedo of different forest types was estimated for an area located in central Finland based on MODIS MCD43A3 blue-sky albedos (Schaaf et al. 2002) and forest resource data produced by the Natural Resources Institute Finland (Tomppo et al. 2008). Regression models were used to estimate the tree species specific forest albedos for different volume thresholds utilizing information on the fractional covers of different forest types within the MODIS pixels (Kuusinen 2014). The resulting albedo values were translated into net shortwave radiation at the TOA using ECHAM5 radiative transfer model (Roeckner et al. 2003).

The impacts of forest BVOC emissions on the secondary aerosol concentrations, in more detail on particle size distributions, were modelled with the SOSAA model (Boy et al 2011). From the modelled size distributions, the radiative forcing in TOA due to aerosol-radiation interactions (scattering of solar radiation) and due to aerosol-cloud interactions (the cloud albedo effect, Kurtén et al. 2003) was estimated. The description of the modelled SOSAA stands was based on MOTTI simulations and BVOC emission potentials for different species were derived from both field and laboratory measurements (Hakola et al 2001, 2012, 2016). The simulated aerosol loading for the atmospheric boundary layer column was then employed to estimate the direct and indirect aerosol induced RF. The indirect effect, which dominates the aerosol radiative effects, is based on the method by Kurtén et al. (2003). This calculation did not account for the feedbacks, such as the altered BVOC emissions due to the increased cloud albedo (feedbacks presented e.g. in Kulmala et al 2014).

By using the age and species distributions from the recent forest inventory data (The Finnish Statistical... 2014), the single-species stand level results were upscaled to the entire forest area of Finland. The scenario reducing the harvest levels to 65% of CAI corresponds the current harvest level and was thus used as a reference for the other scenarios. In order to obtain the targeted harvest level, the recommended site-specific age of final harvest was delayed from the recommended age when needed. The resulting forest dynamics were coupled with stand level values of RF changes due changes in CO<sub>2</sub>, surface albedo and aerosols at different stand ages in order to obtain total RF changes of Finnish forest area up to 2050.

Our case study showed that under current climate conditions, the change of RF due to forest management on stand-level surface albedo (warming effect) and SOAs (cooling effect) almost offset each other (Fig. 1).

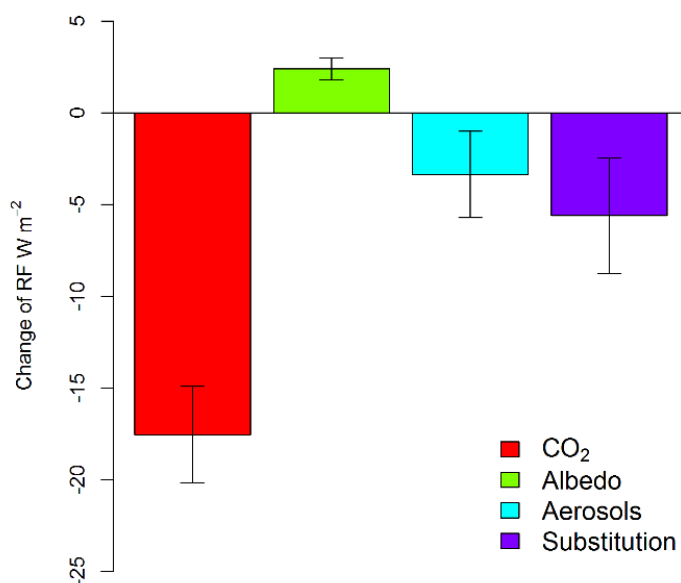


Figure 1. The changes in radiative forcing (RF, W m<sup>2</sup>) of the different radiative factors considered for a Norway spruce stand during 100 years.

Avoided emissions, through product and energy substitution, may cumulate rapidly if high substitution factors, indicating a large share of long lasting wood products, are used in the analysis. Our values for sawnwood could be seen as rather conservative and factor for pulpwood approaches the value of energy substitution. In fact, most of the carbon in harvested wood has been estimated to return to the atmosphere in less than five years (Soimakallio et al 2016), even when accounting for long-lived timber products.

Simulations for both nutrient poor and nutrient rich sites showed that both carbon sequestration and VOCs production were higher at the more fertile site suggesting a positive correlation between site fertility and net cooling effect was found. Substantial uncertainty surrounding the quantitative link between VOC emissions and cloud production (including the potential climate feedbacks) prevents us from drawing more firm conclusions. Furthermore, although there are BVOC measurements for Norway spruce and silver birch, long-term data of BVOC production are available only for Scots pine. Hence, results related to other tree species, especially in case of deciduous trees, should be used cautiously and regarded more as illustration of the dynamics not so much to quantify the net effects.

Following, the change in RF due to different harvest scenarios was quantified for a forest landscape representing the present day state of the Finnish forests. At the landscape level, the sign of RF of the different radiative components changed according to whether the harvest level was higher or lower than the current level of harvesting (65 % of CAI, Fig. 2). Increased harvests produced shorter rotation times and thus more open areas due to increased amount of final harvests (clearcuts). Thus negative albedo (cooling) and positive aerosol (warming) forcing was observed in these harvesting schemes. Also the relative importance of different effects changed depending on the harvest level. However, the trade-off between storing carbon either in the ecosystem or in wood products had the largest impact on the net climate effect of each scenario. The product substitution impact was also larger than biophysical impacts. After accounting for the radiative components under study, the net radiative forcing due to changes of surface albedo and SOAs was almost negligible in the proposed management scenarios (Fig. 2).

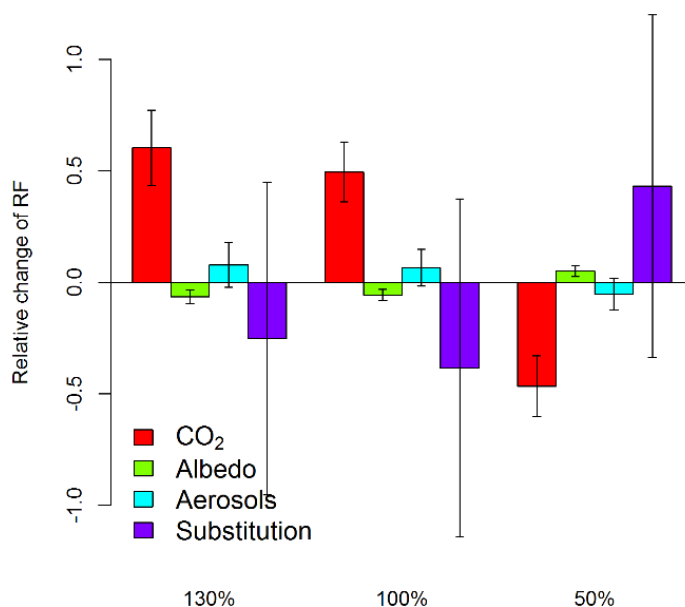


Figure. 2: Relative contribution of different factors to the average change of net global radiative forcing (RF) in 50 years due to different harvest levels (50 – 130 % of current annual increment, CAI) of Finnish forests relative to the current harvest level (65 % of CAI). Analysis was done in the current climate. CO<sub>2</sub> includes carbon sequestered in trees, soil and forest products.

Our landscape level analyses support the earlier findings (Hudiburg et al 2012, Valade et al 2017) that a reduction in the forest carbon stock due to increased harvests is difficult to compensate through substitution. In terms of the mean curve in Fig. 3, the largest cooling was obtained for the scenario implementing the lowest harvest regime, i.e., 50 % of current annual increment. As our analysis shows, harvests corresponding the annual increment of Finnish forests (100 % of CAI) may result in about equal climate mitigation response as the current harvest level (65% of CAI) or the lowest harvest scenario (50 % of CAI), provided that wood products produce high substitution by displacing only products like cement and steel. In theory, the losses in the forest C-stock due to high harvesting levels could be thus offset by assuming very (unrealistically?) high substitution factors.

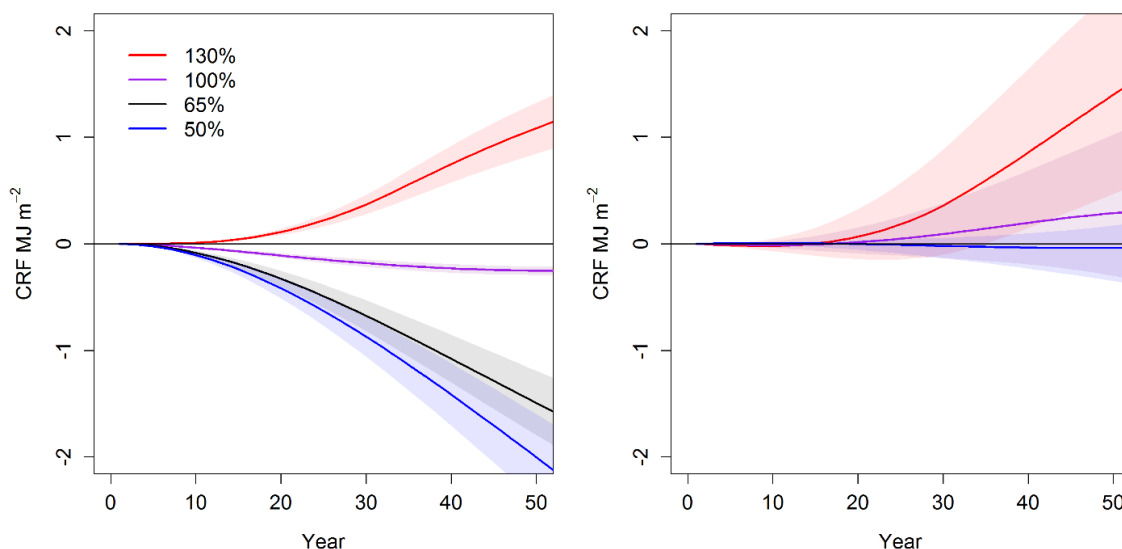


Figure. 3: Simulated development of the net global cumulative radiative forcing (CRF, MJ) due to different harvest intensities of Finnish forests (2% of the boreal forest area) relative to their present state in the current climate. Left panel) excluding avoided emissions from product and energy substitution and right panel) the total impact including substitution relative to a reference harvest level at 65% of the present current annual increment (CAI, present harvest level). Different colors represent varying harvest levels given as a percentage of present CAI in Finland in 2013 and the shaded area represents the estimated uncertainty.

The case study showed that combining intensive harvests with increased use of wood for bioenergy or wood products storing carbon only a short time (like paper, cardboard etc.) is unlikely to result in the climate change mitigation within the timeframe needed to restrict global warming under 2°C.

#### *Disagreement in the research community, ideas about reasons for disagreements*

Making forest management contribute to the objectives of the Paris Agreement requires that, if the harvest level is increased, wood products should replace fossil products of high greenhouse gas emissions (with the whole product chain taken into account), and that carbon content of wood product should be stored as long as possible, and only in the end, wood could be used for energy purposes (Finnish Climate Panel 2015). In short-term (10-30 years), increased use of boreal forests for bioenergy and short-lived products is thus questionable from a climate perspective. In medium term (50-100 years), current levels of forest use will likely cause more climate benefits than the increased forest use with current portfolio of wood products. In long term, the climate impacts of forest based bioenergy are better than the climate impacts of fossil fuels. However, even the long term impacts include implicitly the assumptions that the growth of forests will not be weakened in the future, and that the substitution is permanent. Further, the effects of potentially very cost-efficient climate warming mitigation by alternative management scenarios such as continuous cover forestry where carbon stocks are sustained over time were not evaluated in this case study.



The implications of the current insight that forest management most likely has only a small net climate effect has been intensively debated. Nevertheless, a small net effect does not need to imply that forest management itself has no role to play in climate mitigation. On the contrary, forest management only has a small net climate effect once the forest cover is preserved and this objective may strongly depend on appropriate forest management.

### *Knowledge gaps*

The principles of the biophysical effects is rather well understood, and the qualitative processes are not under discussion. Quantifying the impact of forest management remains challenging because the net effect is the small residual of several large gross changes with opposite effects. Owing to the substantial uncertainty on each of the gross changes, the signal to noise ratio of the net changes appears to be unfavorably small. Nevertheless, the results of analyses quantifying net climate effects confirm the need for holistic evaluations of the climate impacts rather than pure carbon based analysis when assessing the potential role of forest management in climate change mitigation.

The field has seen an evolution from more simple site-level assessments accounting for carbon and albedo to more integrative studies, accounting for carbon, different wood uses, substitution, albedo, transpiration, roughness, cloud feedbacks, emissivity and emission scenarios. As none of the radiative components dominate the radiative balance under all conditions, increasing the complexity of the assessment did not allow to establish the sign of the net effect; the sign remains uncertain owing to the substantial uncertainty of the gross effects. With an increase in the number of processes being accounted for the net effects appears to be small; be it a cooling or a warming. Since the first –incomplete– studies of the net climate effects, researchers have been warning that cooling through increased C-sinks in forests and wood products could be off-set by the biophysical effects. The latest –more complete– studies on the topic, including this case study, could neither validate nor invalidate this concern. Verifying the large-scale climate effect of forest management and change therein is likely not yet possible with the available scientific tools and instruments, in particular due to insufficient understanding of the complex climate feedbacks.

Although all radiative components come still with substantial uncertainties, we believe that the radiative forcing from BVOC emissions and subsequent transformation is the only remaining term that could have a large scale effect on the quantification of the net climate effect of a currently established forest stand. Clouds and aerosols continue to contribute the largest uncertainty to estimates and interpretations of the Earth's changing energy budget (IPCC 2013). Even if the formation of particles large enough to act as cloud condensation nuclei (CCN) is caused by the growth of aerosol particles due to BVOC emissions from forests, the activation of the CCN i.e. the cloud formation can only take place when the air mass containing these CCN is uplifted high enough, in the case of Finland this requires for example a low-pressure system. The true impact on radiative forcing will, therefore, be very different depending on where and above which kind of Earth surfaces the cloud droplets will be forming and transported. Understanding how forest management affects cloud formation thus requires that the differential effect of tree species selection and silvicultural approaches on BVOC is understood. At present the understanding of the relation of BVOC emissions with environmental drivers is improving, but the specific knowledge on emissions in relation to factors that are important when forest management options are considered (species, stand structure, stand age, harvest protocols) is still lacking.

Reducing the uncertainty of the other radiative terms will require a better understanding of the effects of forest management on the surface properties, for example, how does surface albedo vary with stand age, stand structure, species (Otto et al. 2015, Hovi et al 2016, Kuusinen et al 2014, 2016).

Although some of the direct effects of forest management could be observed at experimental sites, e.g., surface albedo, surface temperature, or BVOC emissions, quantifying the climate effect of these direct changes strongly relies on models. Given the small magnitude of the effects of changes in forest management on the global scale, these effects are at present difficult to verify.

## References

- Arora and Alvaro Montenegro. 2011. "Small Temperature Benefits Provided by Realistic Afforestation Efforts." *Nature Geoscience* 4(8):514–18. Retrieved (<http://www.nature.com/doi/10.1038/ngeo1182>).
- Bala et al. 2007. "Combined Climate and Carbon-Cycle Effects of Large-Scale Deforestation." *Proceedings of the National Academy of Sciences* 104(16):6550–55. Retrieved (<http://www.pnas.org/cgi/doi/10.1073/pnas.0608998104>).
- Bathiany et al. 2010. "Combined Biogeophysical and Biogeochemical Effects of Large-Scale Forest Cover Changes in the MPI Earth System Model." *Biogeosciences* 7(5):1383–99.
- Betts 2000. "Offset of the Potential Carbon Sink from Boreal Forestation by Decreases in Surface Albedo." *Nature* 408(6809):187–90.
- Boy et al. 2011. SOSAA – a new model to simulate the concentrations of organic vapours and sulphuric acid inside the ABL- Part 1: Model description and initial evaluation, *Atmos. Chem. Phys.*, 11, 43–51.
- Bright et al. 2017. "Local Temperature Response to Land Cover and Management Change Driven by Non-Radiative Processes." *Nature Climate Change* 7(4):296–302. Retrieved (<http://www.nature.com/doi/10.1038/nclimate3250>).
- Davin and de Noblet-Ducoudré. 2010. "Climatic Impact of Global-Scale Deforestation: Radiative versus Nonradiative Processes." *Journal of Climate* 23(1):97–112.
- Erb et al. 2017. "Land Management: Data Availability and Process Understanding for Global Change Studies." *Global Change Biology* 23(2):512–33. Retrieved (<http://doi.wiley.com/10.1111/gcb.13443>).
- Seppälä et al. 2015. Climate impacts of forest use and carbon sink development. Finnish Climate Panel Report 4/2015. The Finnish Statistical Yearbook of Forestry. (Metsäntutkimuslaitos, Tampere, 2014), pp. 426.
- Hakola et al. 2001. Variation of the VOC emission rates of birch species during the growing season, *Boreal Environ. Res.*, 6, 237–249.
- Hakola et al. 2012. Annual variations of atmospheric VOC concentrations in a boreal forest, *Boreal Environ. Res.*, 14, 722–730.
- Hakola et al. 2017. Terpenoid and carbonyl emissions from Norway spruce in Finland during the growing season, *Atmos. Chem. Phys.*, 17, 3357–3370, <https://doi.org/10.5194/acp-17-3357-2017>.
- Hovi et al. 2016 Quantifying the missing link between forest albedo and productivity. *Biogeosciences*, 13, 6015–6030.
- Hudiburg et al. 2011. "Regional Carbon Dioxide Implications of Forest Bioenergy Production." *Nature Climate Change* 1(8).
- IPCC, 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* F. T. Stocker et al. Eds. (Cambridge Univ. Press, Cambridge, 2013), pp. 1535.
- Jackson et al. 2008. "Protecting Climate with Forests." *Environmental Research Letters* 3(4):44006. Retrieved (<http://stacks.iop.org/1748-9326/3/i=4/a=044006?key=crossref.2cd20c3cc54d529a187f7976faf78424>).
- Karjalainen et al. 1994. Role of wood-based products in absorbing atmospheric carbon, *Silva Fenn.*, 28, 67–80.
- Kulmala et al. 2014. CO<sub>2</sub> induced terrestrial climate feedback mechanism: From carbon sink to aerosol source and back. - *Boreal Env. Res.* 19 (suppl. B): 122–131.
- Kurtén et al. 2003. Estimation of different forest-related contributions to the radiative balance using observations in southern Finland, *Boreal Environ. Res.*, 8, 275–286.
- Kuusinen 2014. Boreal forest albedo and its spatial and temporal variation, *Dissertationes Forestales*, 179, 48 pp.
- Kuusinen et al. 2016. Structural factors driving boreal forest albedo in Finland. *Remote Sensing of Environment* 175: 43–51.
- Lee et al. 2011. "Observed Increase in Local Cooling Effect of Deforestation at Higher Latitudes." *Nature* 479(7373):384–87. Retrieved (<http://www.nature.com/doi/10.1038/nature10588>).
- Li et al. 2015. "Local Cooling and Warming Effects of Forests Based on Satellite Observations." *Nature Communications* 6:6603. Retrieved (<http://www.nature.com/doi/10.1038/ncomms7603>).
- Lohila et al. 2010. Forestation of boreal peatlands: Impacts of changing albedo and greenhouse gas fluxes on radiative forcing, *J. Geophys. Res. Biogeo.*, 115, DOI: 10.1029/2010JG001327.
- Luyssaert et al. 2014. "Land Management and Land-Cover Change Have Impacts of Similar Magnitude on Surface Temperature." *Nature Climate Change* 4(5) :389–93.
- Marland et al. 2003. The climatic impacts of land surface change and carbon management, and the implications for climate-change mitigation policy. *Climate Policy* 3: 149–157.
- Naudts et al. 2016. "Europe's Forest Management Did Not Mitigate Climate Warming." *Science* 351(6273):597–600. Retrieved (<http://www.sciencemag.org/cgi/doi/10.1126/science.aad7270>).
- Official Statistics of Finland (OSF): Greenhouse gases [e-publication]. ISSN=1797-6065. Helsinki: Statistics Finland [referred: 20.3.2017]. Access method: [http://www.stat.fi/til/khki/index\\_en.html](http://www.stat.fi/til/khki/index_en.html)
- Otto et al. 2014. "Forest Summer Albedo Is Sensitive to Species and Thinning: How Should We Account for This in Earth System Models?" *Biogeosciences* 11(8):2411–27.
- Da Rocha et al. 2009. "Patterns of Water and Heat Flux across a Biome Gradient from Tropical Forest to Savanna in Brazil." *Journal of Geophysical Research: Biogeosciences* 114(1):1–8.
- Roeckner et al. 2003. The atmospheric general circulation model ECHAM5 - Part1. Max Planck Institute Report No. 349.
- Salminen et al. 2005. Reusing legacy FORTRAN in the MOTTI growth and yield simulator, *Comput. Electron. Agric.*, 49, 103–113.
- Sathre. and O'Connor. 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution, *Environ. Sci. Policy*, 13, 104–114.
- Schaaf et al. 2002. First operational BRDF, albedo nadir reflectance products from MODIS, *Remote Sens. Environ.*, 83, 135–148.
- Swann et al. 2010. "Changes in Arctic Vegetation Amplify High-Latitude Warming through the Greenhouse Effect." *Proceedings of the National Academy of Sciences* 107(4):1295–1300. Retrieved (<http://www.pnas.org/cgi/doi/10.1073/pnas.0913846107>).
- Tomppo et al. 2008. Combining national forest inventory field plots and remote sensing data for forest databases, *Remote Sens. Environ.*, 112, 1982–1999.

Tuomi et al. 2011. Wood decomposition model for boreal forests, *Ecol. Mod.*, 222, 709-718.

Valade et al. 2017. “Sustaining the Sequestration Efficiency of the European Forest Sector.” *Forest Ecology and Management* 405(September):44–55. Retrieved (<http://www.sciencedirect.com/science/article/pii/S0378112717302128>).

Zhao and Jackson. 2014. “Biophysical Forcings of Land-Use Changes from Potential Forestry Activities in North America.” *Ecological Monographs* 84(2):329–53.

## Bioenergy in the energy system – now and in the future

Filip Johnsson, Professor, Chalmers University of Technology, Sweden

Contributors: Henrik Thunman and Göran Berndes, Chalmers University of Technology, Göteborg, Sweden

### *The challenge from a fuel-mix perspective*

Over the last decade the common narrative in the energy policy context and in the public debate has been that there is a robust growth in Renewable Energy Sources (RES), and in particular in Non-Hydro Renewable Energy Sources (NHRES). Although these have undergone rapid expansion, massive investments are at the same time made in technologies and infrastructure that use fossil fuels, which still account for the major share in global primary energy supply. The large expansion of renewables has in fact, so far, not resulted in any reduction in the fossil-fuel share of primary energy consumption, which remains at 80%. Figure 1 gives the overall trend in global consumption of fossil fuels, NHRES, hydro and nuclear power from 1972 to 2014, as well as the required reduction in fossil fuel use to limit global warming to well below 2°C, assuming 1) a halving in global CO<sub>2</sub> emissions every decade from 2020<sup>1</sup> up to 2050 as suggested by Rockström et al. (2017), 2) emissions factors from (IEA 2017) and 3) that the ratio between coal, oil and gas is maintained at current level (a change in ratio would only marginally change the shape of the curve) – see Johnsson et al., 2017 for details. From Figure 1 it can be concluded that a highly *disruptive change in both reductions in the use of fossil fuels and in investments in alternatives* to fossil fuels (e.g., biomass, wind, solar, hydro and nuclear) is required to approach near zero emissions around 2050.

The current fossil dominated energy system constitutes a system which relies on carbon-based fuels that are transportable and storable. This is also the case for biomass, which then differs from other NHRES in that it contains carbon and can readily be used to produce transportable and storable fuels that can be used instead of fossil based fuels in vehicles and to provide dispatchable energy (as opposed to wind and solar technologies, which are non-dispatchable). Synthetic carbon-based fuels produced from variable renewable electricity (VRE) and a carbon source (e.g., the atmosphere or biogenic flue gases) may become important but costs are uncertain and large-scale application seems unlikely within the next decades.

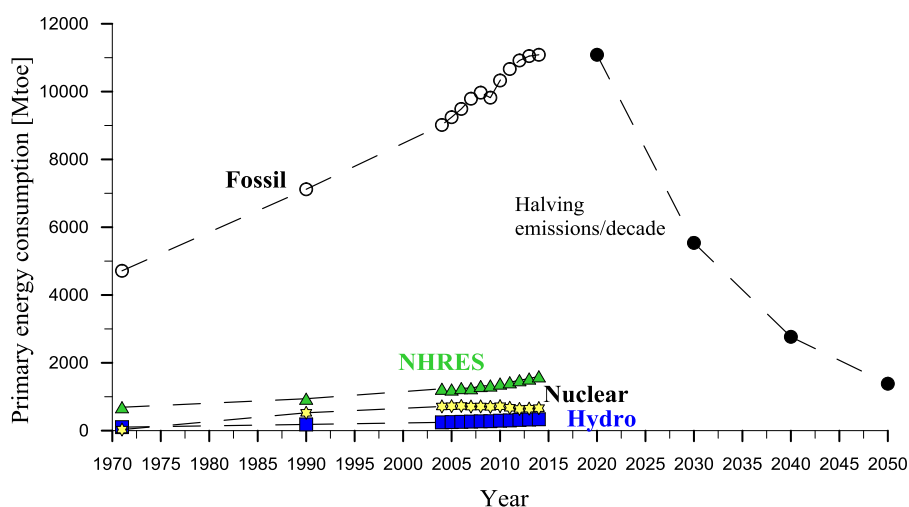


Figure 1. The development in primary energy consumption from fossil fuels, NHRES, hydro and nuclear, from 1972 to 2014. The filled symbols are approximations of the reduction in fossil-fuel consumption required if halving the gross anthropogenic carbon-dioxide emissions every decade in line with “the Carbon Law” proposed by Rockström et al. (2017) – here assuming constant ratio between coal, oil and gas, not considering any offsetting by CCS or from land-use change. From Johnsson et al. (2018).

Studies that use integrated assessment models or techno-economic energy systems models show that if the world succeeds in limiting global warming to well below 2°C (in line with the Paris agreement) the energy system will eventually (from mid-century and beyond) to a large part rely on non-dispatchable NHRES, mainly in the form of wind and solar technologies, i.e. VRE generation. Modeling studies also show that the value of carbon based fuels, which do not contribute to increasing atmospheric GHG concentrations, will increase since these will be increasingly important for balancing increasing amounts of VRE and for meeting energy demand in sectors and uses where carbon based fuels will be difficult to substitute, most notably in the aviation sector. As a consequence – and also indicated by energy systems modelling – biomass demand for energy (with and without associated carbon capture and storage to produce negative emissions) is expected to grow significantly if the world moves towards limiting warming to 2°C or below. Which – and how much - fuel uses that will be provided based on biomass will vary over time, depending on willingness to pay and the character of biomass supply systems.

Considering the needed ramp-up of renewable energy shown in Figure 1, it is clear that we are facing a formidable challenge and it is reasonable to assume that there will be trade-offs to handle, related to the implementation of bioenergy as well as other RES options. The attractiveness of using forest fuels depends on whether the feedstock originates from areas where forest management follows sustainable forest management principles ensuring healthy and productive forests. However, we do not discuss possible conflicts with other sustainability goals in this chapter, which focus on climate effects.

Concerning climate effects of forest-derived bioenergy, Box 1 combines two principal criteria to define the climate effect of forestry derived biomass. These include spatial and temporal perspectives and were put forward in a joint report from the Swedish Energy Agency, the Swedish Forest Agency, the Swedish Environmental Protection Agency and the Swedish Board of Agriculture. The temporal and spatial perspectives correspond well with those inherent in pathways towards meeting temperature targets and we argue that these perspectives are appropriate when addressing national climate change mitigation strategies and principal aspects of forest management as well as technology choices in energy, industry and transport. The influence of spatial and temporal scale in evaluations of bioenergy systems is further discussed in other chapters (especially by Cowie et al.).

*Box 1. Criterion for a positive climate effect from use of forestry derived biomass in the energy system. Based on two criteria proposed in a joint report from the Swedish Energy Agency, the Swedish Forest Agency, the Swedish Environmental Protection Agency and the Swedish Board of Agriculture (Black-Samuelsson et al., 2017).*

Together, the bioenergy supply-chain emissions (e.g., harvesting, transportation and processing) and possible forest carbon losses within a certain region (typically a country) over a longer time-perspective, as a consequence of forest management to produce biomass for energy along with other forest products, should be small compared to the carbon content in the fossil fuels replaced by the biomass. Changes in biospheric carbon stock are taken into account when territorial emissions and removals of greenhouse gases are reported under the UN Climate Convention, the Kyoto Protocol and EU regulations.

The perspective presented here emphasizes the importance of defining and agreeing on what system is targeted in the long term – say until emissions should be zero or near zero – and associates to this long-term perspective when addressing the climate effects of mobilizing biomass over time to meet the long-term biomass demand. It is believed that this can be done in principle, even if one cannot foresee exactly what technologies will be available in a distant future.

Figure 2 provides a schematic illustration of future use of carbon based (RES) fuels, not directly originating from fossil oil, gas or coal, over the decades until GHG emissions have to be zero. With increased requirement on lowering the fossil-fuel emissions, there is an increase in the value of carbon based fuels without net emissions of carbon to the atmosphere.



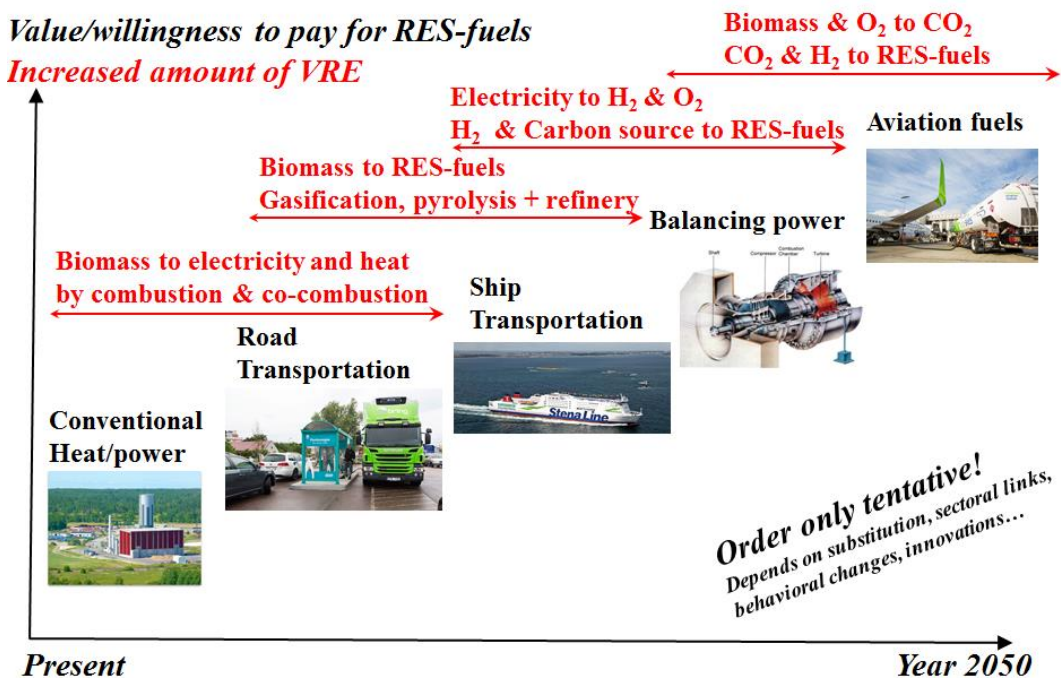


Figure 2. A schematic illustrating the value of carbon based fuels (denoted “RES-fuels”) without net-emissions to the atmosphere in a world that moves in line with what fulfills the Paris agreement.

As indicated above, an energy system with zero or near zero carbon emissions will have large amounts of VRE, to fulfill direct use of electricity, but also for production of renewable energy carriers such as hydrogen for industry and possibly also transportation fuels. Thus, the electricity generation system will be transformed:

*from the present system which constitutes a thermally dominated system resting on base-load electricity generation, with the fuel cost dominating the electricity generation cost and with relatively stable wholesale electricity prices,*

*to a system dominated by VRE with near-zero generation cost, where the cost is dominated by investment costs and with volatile wholesale prices and for which production of energy carriers, storage of electricity and flexible demand can be means to dampen volatility.*

It is reasonable to assume that VRE based electricity will have to also play a role as fueling the transportation and industry sectors, i.e. both directly (direct powering of vehicles, combined with energy storage) and indirectly by means of electrofuels, including hydrogen for industrial use. Exemplifying with the electricity generation system, Figure 3 provides a representative scenario of how the European electricity generation mix can be transformed to a near-zero CO<sub>2</sub> emission system.

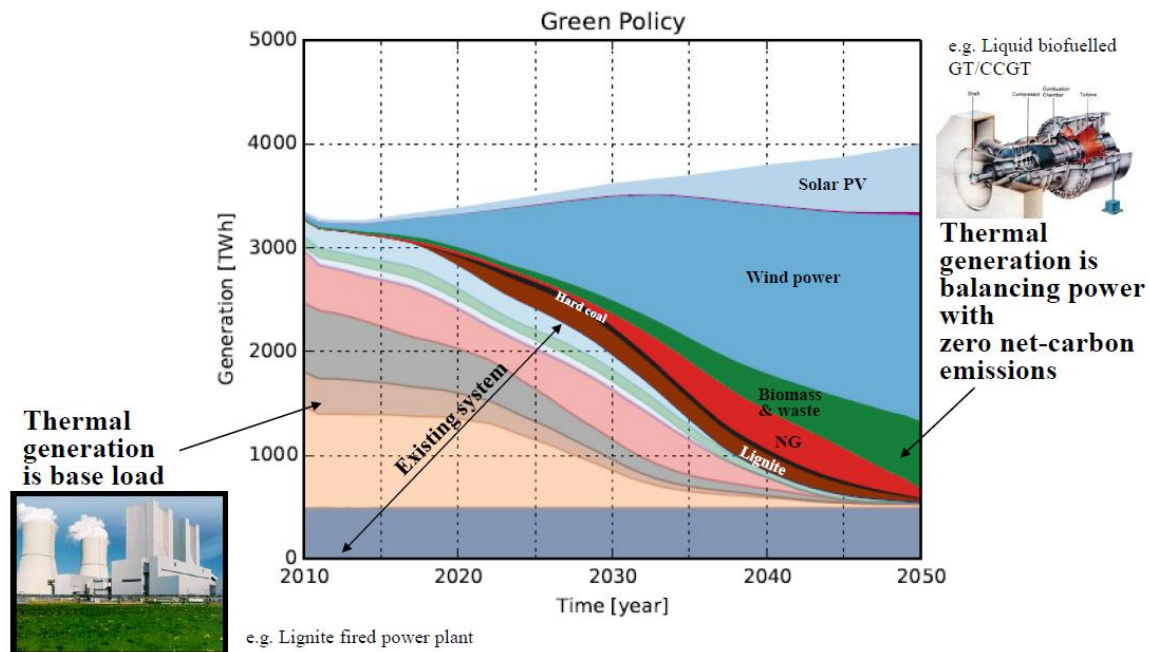


Figure 3. Transformation of the European electricity system for a scenario ("Green policy"), which fulfills near-zero CO<sub>2</sub> emissions (99 % reduction compared to 1990 levels) and with a target of 100 % renewable electricity generation by Year 2050. In the case of thermal generation that use biomass fuels, "zero net-carbon emissions" corresponds to a situation where the use of these fuels yields no systematic increase in atmospheric GHG concentrations over time. From modeling by the ELIN model of EU27+Switzerland+Norway (see Odenberger et al. 2009 for model details).

### Bioenergy in the energy system – from present to long term

#### Present

Bioenergy is currently the largest renewable energy source used in the EU. Yet, most of the bioenergy is currently used in biomass-rich countries such as Sweden and Finland and used for production of locally controlled and regulated commodities such as heat and electricity. This is even more so for forestry biomass. There have been significant efforts to introduce various support schemes and to fund research activities to promote development of more advanced biomass-conversion technologies for production of second generation biofuels. Yet, these activities have so far not resulted in market conditions stable enough to overcome the risk and cost associated with introduction of these technologies.

Much of the research on advanced biofuel technologies is therefore still carried out at small scale in different research laboratories. As in many areas it is not a technical limitation that prevents large scale demonstration of advanced biomass conversion processes, but rather lack of economic incentives. An obvious challenge is that periods of low fossil-fuel prices for transportation (e.g., lower gasoline prices) make it more difficult get alternative fuels into the market. Yet, the target is that demands for fossil fuels should be reduced and eventually be zero, which will result in that their prices also approach zero. Thus, stimulation of biomass technologies and other renewables must be followed by pricing of CO<sub>2</sub> emissions at a sufficiently high level (directly – e.g. in the form of EU-ETS – or indirectly by means of emission performance standards or renewable-fuel share quota). As for electricity generation and large-scale industrial processes (e.g. steel, chemical and cement), CCS is an option allowing continued use of fossil fuels, but CCS requires a sufficiently high pricing of CO<sub>2</sub> emissions.

Another characteristic of biofuels compared to heat and power is that it is not a local commodity. Due to this, local biofuel subsidies intended to promote development of large-scale advanced biofuel production have sometimes resulted in “initial market killing” by imports of biofuels, or raw fuels that can be converted to biofuels by relatively simple processes. These raw biofuels can be transported around the world to meet demand defined by local targets and thereby outcompete development of advanced biofuels before these reach a sufficiently large market penetration.

#### *Short term – accelerate development*

Short term actions must on one-hand ensure that biomass markets are created at a reasonable low-risk and on the other hand prepare for next generation biomass fuel technologies. Thus, in the short term, increased use of biomass for heat and electricity production could be motivated, since this will offer low-risk options for establishing a biomass-supply market where such do not exist. An example could be introduction of biomass in existing energy infrastructure such as biomass-fired CHP plants, co-firing biomass in coal power plants and the use of torrefied biomass in steel production to replace part of the coal used. When it comes to processes for production of higher value biomass energy carriers such as liquid fuels, there are significant lead times in the development, demonstration and implementation of the conversion technologies and it is of uttermost importance to start demonstrating these processes already now. As mentioned above, a major part of the activities is carried out in laboratory and small scales. In order to take development to the next step, it is urgent to provide common markets with similar subsidy schemes in larger regions, like Europe and Northern America, to accelerate demonstration and commercialization of biomass processes for production of advanced fuels and other energy carriers. From a technology provider perspective, it is important that a market on a longer term can be envisioned by the technology providers. For large-scale processes it critical that it is possible to see a potential market of, say, at least some 20-30 production plants for technology providers (and society) to take the risk to promote the development for such processes. If no such market can be foreseen, the development will stop at the demonstration stage (and must be funded to a large extent by governmental funding).

#### *Intermediate term – towards zero emission systems*

If society is serious about climate-change mitigation it is of uttermost importance that a fossil-fuel strategy is developed. This must be the case both for countries with large assets of fossil fuels but also considering import of goods from fossil-fuel rich countries to countries and regions with little fossil fuels. Since the fossil fuel use in countries such as China and India is indirectly and in part generated by consumption of imported goods in the fossil-fuel lean countries and regions, emissions are redistributed amongst nations (cf. Raupach et al., 2014) and, thus, it seems important that a fossil-fuel supply strategy must involve countries which import goods from fossil-rich countries (e.g. EU import of Chinese consumer goods). Piggot et al. (2017) conclude that fossil-fuel supply strategy is to a considerable extent lacking in the Nationally Determined Contributions (NDCs), i.e. the documents in which the countries describe how they intend to reduce their GHG emissions. A fossil-fuel strategy will lead to that solid-fuel plants (coal and lignite) and associated infrastructure (e.g. solid fuel handling) will have to close, or shift fuel to biomass (although implementation of CCS may somewhat lower the rate for this). Such transformation can open for introduction of biomass fuels, especially such based on forest residues and other “difficult” biogenic waste fractions.

Although all scenarios on how the energy system can be transformed to comply with climate targets (Paris agreement) yield large shares of wind and solar power, it is important to realize that biomass fueled technologies cannot be substituted by wind and solar power. Even in scenarios with very high amounts of wind and solar, biomass has a key role to secure supply of electricity. The introduction of the advanced biofuel production can take advantage of existing infrastructure. In developed regions with the EU region as an example, existing sites for thermal plants will be sufficient for accommodate future thermal plants, such as biomass plants for electricity or biofuel production and power plants with CCS. At these sites there are also valuable infrastructure as well knowledge and experience from thermal processes. Thus, although it is most likely difficult to establish Greenfield sites, existing sites can be transformed for production of biomass-based electricity and fuels. In addition, these sites can be used for production of raw bio-oil which

is subsequently transported to chemical and refinery industries for production of chemicals and liquid transportation fuels. Thus, an intermediate step is to convert fossil-fuel power plant sites to biomass-processes. A relatively large scale of biomass plants is a prerequisite for cost-efficient and environmentally friendly conversion of low grade biomass such as residues from forest industry and other waste woods (e.g. demolition wood).

#### *Long term – towards negative emissions*

On the longer term, biomass will likely be used where carbon based fuels are difficult to replace and where the resulting CO<sub>2</sub> emissions are difficult to capture. Aviation, long-distance ship transport and long-haul road freight are examples of such applications, reflecting that carbon-based fuels will have a higher value in these sectors than, for example, in road transportation where electrification is an alternative on the longer term. In addition, in a biomass constrained market, biomass for energy will obviously also compete with other uses of biomass such as for material production. However, bio-based materials can, once they reached their end of life be used for energy purposes (when not possibly to recycle).

Research shows that stabilize warming to well-below 2°C will most likely require net-negative emissions during the second half of the century. To reach net-negative emissions will require a combination of forestry and other land-use management, application of capture and storage of CO<sub>2</sub> from biomass conversion (BECCS), and possibly Direct Air Capture (DAC).

With respect to BECCS, this will compete with other uses of renewable carbon where alternatives are difficult to find, including balancing power to increase the value of VRE. In principle, application of BECCS may also allow for some use of fossil fuels in sectors where substitution to renewable fuels or feedstocks is difficult.

#### *Conclusions*

A discussion on the current and future role of biomass in the energy system is provided. If the world moves in line with the Paris agreement to limit global warming to well-below 2°C, the following can be concluded with respect to biomass, including such derived from forests:

- Biomass demand will raise, resulting in increased competition of the biomass resource and best practice of biomass use will vary depending on local conditions. Therefore, detailed regulation, such as imposing strict cascading principles or restricting eligibility for bioenergy to specific feedstocks (e.g., excluding all roundwood, irrespective of size or quality) may prevent effective management of forest resources to economically meet multiple objectives, including climate change mitigation and adaptation.
- The long-term perspective inherent in pathways towards meeting temperature targets matches relatively well the time perspective in forest management planning and thereby emphasize a long-term view on changes in forest carbon stocks.
- Carbon-based fuels, which do not contribute to systematic increases in atmospheric GHG concentrations, will be increasingly valuable over time. The biomass will be sourced by the sectors/actors that have the highest willingness to pay.
- It is important to accelerate the development of advanced biofuel technologies to ensure implementation of those in the medium and in the longer term.
- On the long term, i.e., second half of this century and later, biomass may play a key role in establishing net-negative greenhouse-gas emissions by means of BECCS, which are likely to be required if limiting warming to 2°C or below.
- BECCS will compete with other uses of renewable carbon where alternatives are difficult to find, including aviation fuels and other uses where carbon capture is not feasible.

---

1) Year 2020 emissions have been set equal to Year 2014 emissions.

#### References

- Black-Samuelsson S, Eriksson H, Henning D, Janse G, Kaneryd L, Lundborg A och Niemi Hjulfors L. 2017. (in Swedish) Bioenergi på rätt sätt – om hållbar bioenergi i Sverige och andra länder. Report by Skogsstyrelsen, Energimyndigheten, Jordbruksverket och Naturvårdsverket. Rapport 10, Skogsstyrelsen. 2017.
- IEA, 2017, World Energy Outlook, 2017 edition.
- Johnsson, F., Kjärstad, J., Rootzén, J., “The threat to climate change mitigation from the abundance of fossil fuels – immediate need for disruptive change in trends”, submitted to Climate Policy, 2017.
- Odenberger, M., Unger, T., Johnsson, F. Pathways for the North European electricity supply (2009) Energy Policy, 37 (5), pp. 1660-1677.
- Piggot, G., Erickson, P., Lazarus, M., van Asselt, H., Addressing fossil fuel production under the UNFCCC: Paris and beyond, Stockholm Environmental Institute, Working Paper No. 2017-09.
- Raupach, M.R., Davis, S.J., Peters, G.P., Andrew, R.M., Canadell, J.G., Ciais, P., Friedlingstein, P., Jotzo, F., van Vuuren, D.P., Quéré, C.L., Sharing a quota on cumulative carbon emissions, Nature Climate Change, 21 SEPTEMBER 2014 | DOI: 10.1038/NCLIMATE2384.
- Rockström, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakicenovic, N., Schellnhuber, H.J., “A roadmap for rapid decarbonization - Emissions inevitably approach zero with a “carbon law, Science, 24 March 2017, Vol 355, ISSUE 6331, pp1269-1271.