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Current Opinion in Environmental Sustainability

Forest bioenergy at the cost of carbon sequestration?

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Bioenergy from forest residues can be used to substitute fossil energy sources and reduce carbon emissions. However, increasing biomass removals from forests reduce carbon stocks and carbon input to litter and soil. The magnitude and timeframe of these changes in the forest carbon balance largely determine how effectively forest biomass reduces greenhouse gas emissions from the energy sector and helps to mitigate climate change. This paper reviews the impacts of harvest-residue-based bioenergy on the carbon balance of forests and discusses aspects linked to the concept of carbon neutrality. This type of forest bioenergy will reduce the emissions in a long run but near-term reductions depend essentially on the longevity of the residues used.

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Current Opinion in Environmental Sustainability 2013, **5**:41–46

This review comes from a themed issue on **Terrestrial systems**

Edited by **Bojie Fu**, **Martin Forsius** and **Jian Liu**

For a complete overview see the Issue and the Editorial

Received 26 June 2012; Accepted 17 October 2012

Available online 11th November 2012

http://dx.doi.org/10.1016/j.cosust.2012.10.015

Introduction

To mitigate climate change, the European Union has committed itself to, first, a reduction in greenhouse gas (GHG) emissions of at least 20% below 1990 levels and, second, a raise the share of renewable energy to 20% of the EU energy consumption by 2020 [1]. Both targets promote the use of biomass in energy production. An attractive option to meet the growing demand for bioenergy is to increase energy production from forest harvest residues, such as branches, stumps, thinning wood and other residual biomass left behind after forestry operations. Intensification of biomass extraction from forests raises questions about the sustainability and the carbon balance effects of this new practice.

Increasing removal of forest residues for energy use decreases the pool of carbon stored in dead organic matter and litter input to soil [2–5]. The litter input and decomposition of organic matter determine the size of the soil carbon stock, that is the amount of carbon accumulated to the soil, similarly as the growth and removals of biomass determine the carbon stock of trees. Globally, the amount of carbon in soils is twice the amount of carbon in the atmosphere and three times the amount in the vegetation [6]. As an example, Finnish forest carbon stocks, fluxes [7] and the effect of forest harvest residue removal is shown in Figure 1.

Potentially, there is a conflict between climate policies targeting at carbon storage in forests and the increased use of forest-based biomass for energy production [8]. From the perspective of greenhouse gas emissions, there is a trade-off between using forest harvest residues for bioenergy to avoid fossil fuel emission, and adding them to the forest carbon stock. Since the forest harvest residues decompose over time, if left in the forest, this problem also involves an important temporal dimension.

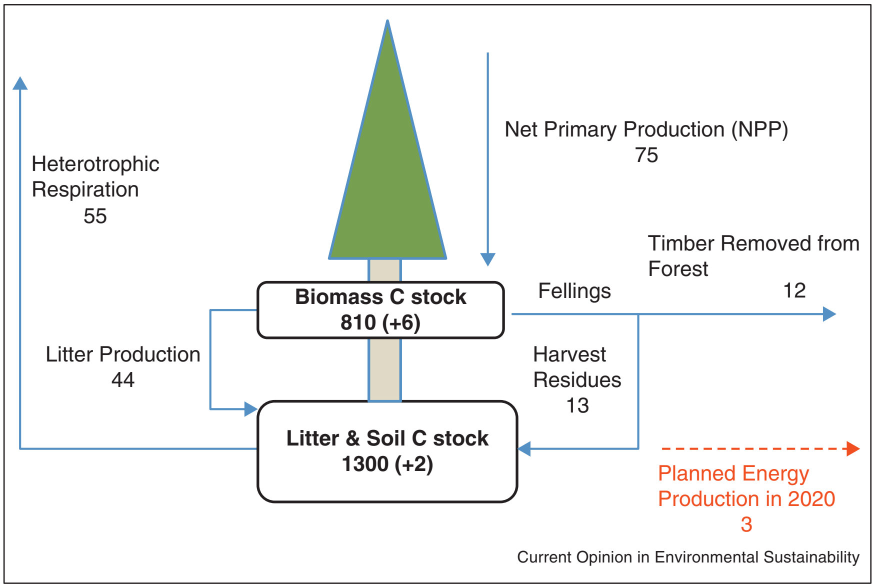
In this synthesis paper, we review the impact of harvest-residue-based bioenergy production on forest soil carbon stocks and discuss aspects linked to the concept of carbon neutrality.

Controversial carbon neutrality

Forest bioenergy is commonly considered as a renewable, carbon neutral energy source. Carbon neutrality refers to achieving net zero carbon emissions by balancing an amount of carbon released with an equivalent amount sequestered or offset, to make up the difference. Forest bioenergy is derived from vegetation that sequesters atmospheric carbon during growth, releases carbon back into the atmosphere when combusted for energy production, and sequesters it once again as the next tree generation develops [9–11]. This is true in the long term as long as conditions do not change but, in the short term, the practice is not necessarily carbon neutral. This is because CO_2 and other greenhouse gases are emitted instantly into the atmosphere when biomass is used in energy production and the development of the next tree generation takes decades.

Researchers have recently remarked that there is a ''critical climate accounting error'' associated with bioenergy production that causes land-use change [12••]. They have questioned the carbon neutrality of renewable biomass because of high indirect greenhouse gas emissions owing to conversion of the forest to an energy crop plantation that may reduce the carbon stocks of biomass and soil and cause thus GHG emissions into the atmosphere [13–15]. GHG emissions resulting from land-use change have been widely studied in the Americas, Southeast Asia and Africa [16–18]. These emissions resulting

Figure 1



Bioenergy and the carbon budget of forests in Finland (carbon stocks in Mt C, annual carbon sink Mt C in parenthesis and fluxes in Mt C/year in the 1990s [7]. Energy production from harvest residues will be increased from nearly zero to 13.5 Mm^3/year by 2020 according to Finnish national energy strategy (red dashed flux). This annual volume, equal to about 3 Mt C/year, represents about one fourth of the total annual harvest residues and is larger than the annual carbon sink of the forest soil in the 1990s.

from changes in carbon stocks are often excluded when assessing climate change mitigation potentials of bioenergy [13,14,19].

Similar land-use-related emissions occur also within the same land-use. The indirect emissions from removing forest harvest residues, and using them for energy production, result from combusting the residues and releasing CO_2 into the atmosphere soon after harvesting instead of letting them decompose slowly at the harvested site. As a consequence of such practice, the amount of carbon stored at the forest site decreases [20•]. These alterations have been described using terms like 'carbon debt', 'carbon deficit' or 'indirect carbon dioxide emissions' [12,13,20•,21•,22,23•].

Emissions from the production chain of forest bioenergy, that is those from machines used in biomass harvesting, processing and transport, are usually small, only a few per cent, in comparison to the changes in the carbon balance of forest [24–28].

Logging residue removal and soil carbon

Intensified harvesting output from forests by removing residues leads usually to a decrease in soil carbon [3,4]. In field studies Olsson *et al.* [29] and Thiffault *et al.* [30] found that soil C stocks under stem only harvesting were significantly higher than those under whole tree harvesting in boreal forests. Jones *et al.* [31] supported this result. Model-based calculations show clearly that intensified removal of harvest residues reduces the soil carbon stock [4,5,20,22,32,33]. Consequently, the amount of organic carbon stored in the soil decreases in the long term in comparison to a practice leaving harvest residues in forest.

Forest soil disruption associated specifically with stump harvesting may release additional CO_2 into the atmosphere. However, empirical research on the magnitude of these emissions is few [34,35]. Stump harvesting means that the tree stumps left after felling are pulled out of the ground to supply wood fuel for biomass power stations. Hope [36] found that stump removal together with forest floor scarification reduced soil carbon stocks. Generally it is known that soil disturbance can change the microclimate and stimulate the decomposition of litter [37]. In a Finnish study, the site preparation increased CO_2 efflux from the soil, but this effect leveled off rapidly [38]. However, the stump harvesting may cause deeper mixing and more extensive scarification of soil than the normal site preparation [39]. The CO_2 efflux from a stump harvest site in Sweden was observed to be slightly larger with more seasonal variation than the efflux from a clear-cut site [40]. Stump harvesting increases the temperature sensitivity of decomposition and increases CO_2 effluxes [40]. On the contrary, in the humus layer samples, taken 10 years after harvest, the rate of C mineralization was lower in whole-tree harvest than in stem-only harvest; also the rate of net N mineralization and the amounts of C and N in the microbial biomass tended to be lower, although not statistically significant [7].

Wood size and decomposition rate

When bioenergy is produced from forest harvest residues the GHG emissions depend mainly on the decomposition rate of the removed forest residues if they were left in the forest to decompose [32]. Important factors affecting the decomposition rate of forest residues are the size of the residues, climate conditions, and the chemical quality of the residues, which is associated with tree species, for example [41–43]. Thus, the GHG emissions vary remarkably between the raw material options [17].

Quite recently, there has been growing interest in the potential for utilizing stump biomass as an additional source of forest bioenergy. Stumps are the largest coarse woody debris component normally left to decompose in forest stands after clear-cutting. In mature stands, stumps account for 15–20% of the carbon and 8–15% of the nitrogen found in tree biomass [44,45]. Stumps decompose slower than roots, branches and needles [43–48] and can therefore be important C pools and long-term sources of nutrients [7]. Therefore, if decomposition occurs slowly, stumps might be more valuable as carbon storage than as an energy source.

Forest bioenergy and carbon sink

Forests of the EU have been intensively managed since many decades, yet they have formed a significant sink for carbon from the atmosphere over the past 50 years [49–52]. A carbon sink is a reservoir that accumulates and stores carbon-compounds for an indefinite period and the process by which carbon sinks remove carbon from the atmosphere is known as carbon sequestration. There are many reasons for this development, such as the European age-class structure is relatively young resulting in increased growth rates; forest area has expanded in the past 50 years; plant productivity has increased as a result of various environmental changes (including temperature change, length of growing season change, and nitrogen deposition); and most importantly the growth rates of European forest have been higher than past harvest rates [51–53].

The decreasing effect of logging residue removal on soil carbon stock has not been considered to be problematic as long as this removal practice does not jeopardize the carbon sink of soil [4,5,26,54–57]. Sievänen *et al.* [57] calculated that increasing the removals of logging residues from 4 to 15 $Mm^3\ yr^{-1}$ in Finland will not turn the Finnish forests from net carbon sinks to net sources. However, the intensified removals of the logging residues would decrease the annual carbon sink of these forest soils by 3.1 million tons of CO_2 eq.

According to field studies, logging residue extraction can also have a significant negative effect on future forest growth because of increased nutrient removal [58,59•]. This would mean a decreased carbon stock in living biomass and a further negative effect on the GHG profile of forest residue bioenergy [20•]. The reduced availability of nutrients may affect the long-term productivity of the forest ecosystem [59•]. Stumps may also play a significant role in retaining N after harvesting, and their removal for bioenergy may markedly affect the nutrient availability and nutrient cycling of boreal forests [45]. Sathre *et al.* [60] suggested that fertilization, in Norway spruce stands, can be used to compensate for the loss of soil carbon stock caused by biomass removal from the forest.

Timing of the emissions

Over time, the carbon debt could be repaid through regrowth in the harvested area and replacement of fossil fuels as an energy source (payback time). Holtsmark [61] calculated that increasing the use of wood from a boreal forest to replace coal in power plants will create a carbon debt that will only be repaid after approximately 190 years. If the wood is used to produce second-generation liquid biofuels and replaces fossil diesel, the payback time of the carbon debt was estimated to be as long as 340 years. McKechnie *et al.* [62••] studied a temperate forest in Ontario. In the case in which pellets replace coal in power plants, the payback time was somewhat shorter than in boreal forest. This was expected because the temperate forests grew more quickly [61]. This significance of the time dimension of the forest growth is also emphasized in some other studies [21•,63].

When bioenergy production from forest residues is started or the volume is increased remarkably the GHG emissions per unit of produced energy are comparable to those of fossil fuels. The latter remain constant over time but the emissions from forest residue bioenergy decrease over time because the residues decompose releasing CO_2 into the atmosphere even if left in the forest. The faster is the decay rate of the residues the faster the GHG emissions of forest bioenergy drop over time [20•,32].

Conclusions

Producing energy from biomass is meant to reduce GHG emissions. However, burning biomass causes net GHG emissions into the atmosphere just like burning fossil fuels if harvesting the biomass decreases the amount of carbon stored in plants and soils, or reduces carbon sink. Legislation that encourages substitution of fossil fuels by bioenergy, irrespective of the biomass source, may even result in increased carbon emissions. Considering bioenergy in isolation of its impact on forest carbon could inadvertently encourage the transfer of emissions from the energy sector to the forest sector rather than achieve real reductions.

In order to evaluate whether countries should use the forest bioenergy potential to contribute to reducing carbon emissions, through fossil fuel substitution, or whether they should be used as carbon sink, we need to consider the temporal perspective. In the short term, flows into the atmosphere as a result of bioenergy combustion may sometimes be slightly greater than from fossil fuel combustion because of the CO_2 emission factor for combustion of wood is higher than that of many fossil fuels [64]. It may not be possible to decrease emissions very quickly by substituting forest bioenergy for fossil fuels. Net reductions in the emissions will be achieved only in a longer term. This is relevant for the current international climate policy. Parties of the UNFCCC have set a target to limit global warming to some 2 degrees. To achieve this target, emissions of industrialized countries need to be reduced almost immediately.

The holistic ecosystem level analysis of the carbon balance should include the carbon uptake in tree growth and the emissions of decomposition of soil organic matter controlling the sink/source dynamics of the ecosystem. Furthermore, carbon is emitted in management, harvesting and transport operations. The carbon balance of any bioenergy production system must be assessed over the life cycle of the product; carbon accounting protocols for bioenergy production systems must quantify the net carbon emitted into the atmosphere and reductions in fossil fuel-derived carbon emissions achieved.

Acknowledgements

This study was funded by the Academy of Finland (Impacts of climate change on multiple ecosystem services: processes and adaptation options at landscape scales CLIMES 256231 and Soil organic carbon decomposition under a changing climate: distinguishing intrinsic properties of carbon compounds from environmental constraints on decomposition, DECORATE 138359 projects), Nessling Foundation (project ''Climate impacts of forest bioenergy'') and the Ministry of Environment (project ''Forest bioenergy and reliability of estimates for greenhouse gas emissions'').

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. EC: **The Council of European Union: the package of EU climate and energy measures approved in December 2008**. 2008.

2. Schlamadinger B, Spitzer J, Kohlmaier GH, Lüdeke M: **Carbon balance of bioenergy from logging residues**. *Biomass Bioenergy* 1995, **8**:221-234.

3. Johnson DW, Curtis PS: **Effects of forest management on soil C and N storage: meta analysis**. *Forest Ecol Manage* 2001, **140**:227-238.

4. Ågren GI, Hyvönen R: **Changes in carbon stores in Swedish forest soils due to increased biomass harvest and increased temperatures analysed with a semi-empirical model**. *Forest Ecol Manage* 2003, **174**:25-37.

5. Eriksson E, Gillespie AR, Gustavsson L, Langvall O, Olsson M, Sathre R, Stendahl J: **Integrated carbon analysis of forest management practices and wood substitution**. *Can J Forest Res* 2007, **37**:671-681.

6. IPCC: In *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Edited by Houghton YD JT, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA. Cambridge, United Kingdom/New York, NY, USA: Cambridge University Press; 2001.

7. Liski J, Lehtonen A, Palosuo T, Peltoniemi M, Eggers T, Muukkonen P, Makipaa R: **Carbon accumulation in Finland's forests 1922–2004 – an estimate obtained by combination of forest inventory data with modelling of biomass, litter and soil**. *Ann Forest Sci* 2006, **63**:687-697.

8. Obersteiner M, BÃ¶ttcher H, Yamagata Y: **Terrestrial ecosystem management for climate change mitigation**. *Curr Opin Environ Sustain* 2010, **2**:271-276.

9. Bright RM, Strømman AH: **Life cycle assessment of second generation bioethanols produced from Scandinavian Boreal forest resources**. *J Ind Ecol* 2009, **13**:514-531.

10. Zhang Y, McKechnie J, Cormier D, Lyng R, Mabee W, Ogino A, MacLean HL: **Life cycle emissions and cost of producing electricity from coal, natural gas, and wood pellets in Ontario, Canada**. *Environ Sci Technol* 2009, **44**:538-544.

11. Sjolie HK, Tromborg E, Solberg B, Bolkesjo TF: **Effects and costs of policies to increase bioenergy use and reduce GHG emissions from heating in Norway**. *Forest Policy Econ* 2010, **12**:57-66.

12. Searchinger TD, Hamburg SP, Melillo J, Chameides W, Havlik P,
•• Kammen DM, Likens GE, Lubowski RN, Obersteiner M, Oppenheimer M *et al.*: **Fixing a critical climate accounting error**. *Science* 2009, **326**:527-528.

The authors highlight that rules for applying the Kyoto Protocol and national cap-and-trade laws contain a major carbon accounting flaw in assessing bioenergy. The rules do not count CO_2 emitted from tailpipes and smokestacks when bioenergy is being used, but they also do not count changes in emissions from land use when biomass for energy is harvested or grown. This accounting erroneously treats all bioenergy as carbon neutral regardless of the source of the biomass.

13. Searchinger T, Heimlich R, Houghton RA, Dong FX, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu TH: **Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change**. *Science* 2008, **319**:1238-1240.

14. Melillo JM, Reilly JM, Kicklighter DW, Gurgel AC, Cronin TW, Paltsev S, Felzer BS, Wang XD, Sokolov AP, Schlosser CA: **Indirect emissions from biofuels: how important?** *Science* 2009, **326**:1397-1399.

15. Marland G: **Accounting for carbon dioxide emissions from bioenergy systems**. *J Ind Ecol* 2010, **14**:866-869.

16. Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P: **Land clearing and the biofuel carbon debt**. *Science* 2008, **319**:1235-1238.

17. Houghton RA, Hackler JL: **Emissions of carbon from forestry and land-use change in tropical Asia**. *Global Change Biol* 1999, **5**:481-492.

18. FAO: **What woodfuels can do to mitigate climate change**. *FAO Forestry Paper* 2010, **162**.

19. Mathews JA, Tan H: **Biofuels and indirect land use change effects: the debate continues**. *Biofuels Bioprod Biorefin* 2009, **3**:305-317.

20. Repo A, Känkänen R, Tuovinen J-P, Antikainen R, Tuomi M,
• Vanhala P, Liski J: **Forest bioenergy climate impact can be improved by allocating forest residue removal**. *GCB Bioenergy* 2012, **4**:202-212.

This study investigates the GHG emissions and consequent climate impacts of different forest-harvest-residue-based bioenergy options. It shows that the GHG emissions vary significantly between the bioenergy options depending mainly on the decomposition rate of the forest residues. It also demonstrates that increasing bioenergy production from forest residues will not result in deep GHG emission reductions in short term because of time-dependency of the emissions.

21. Zanchi G, Pena N, Bird N: *The Upfront Carbon Debt of Bioenergy*.
• Graz: Joanneum Research; 2010:. 54.

The authors underline two major gaps in the current accounting of GHG emissions in the climate change policy framework concerning the use of bioenergy, The first is a gap in spatial coverage because only a small number of countries have emission obligations, that is, through the Kyoto

Protocol (KP) and the Emission Trading Scheme (EU-ETS). The second gap is a failure to differentiate between relevance of short and long time horizons. The authors discuss the approaches to address the spatial and temporal gaps.

22. Palosuo T, Wihersaari M, Liski J: **Net greenhouse gas emissions due to energy use of forest residues – impact of soil carbon balance**. In *EFI Proceedings no. 39, Wood biomass as an energy source challange in Europe*; *European Forest Institute, Joensuu: 2001:115-130*.

23. • Melin Y, Petersson H, Egnell G: **Assessing carbon balance trade-offs between bioenergy and carbon sequestration of stumps at varying time scales and harvest intensities**. *Forest Ecol Manage* 2010, **260**:536-542.

This study examines whether, over both the short-and long-term, stumps are more important as a biomass source to replace fossil fuels, or as a carbon sink. Using historical forest inventory data, the study estimates bioenergy potential of stumps and the effects on stump-carbon sequestration in Sweden. The results show that using stumps for energy production reduces net emissions only when long time horizons are considered.

24. Forsberg G: **Biomass energy transport: analysis of bioenergy transport chains using life cycle inventory method**. *Biomass Bioenergy* 2000, **19**:17-30.

25. Wihersaari M: **Greenhouse gas emissions from final harvest fuel chip production in Finland**. *Biomass Bioenergy* 2005, **28**:435-443.

26. Eriksson LN, Gustavsson L: **Biofuels from stumps and small roundwood – costs and CO_2 benefits**. *Biomass Bioenergy* 2008, **32**:897-902.

27. Börjesson P, Gustavsson L: **Regional production and utilization of biomass in Sweden**. *Energy* 1996, **21**:747-764.

28. Routa J, KellomÄKi S, KilpelÄlnen A, Peltola H, Strandman H: **Effects of forest management on the carbon dioxide emissions of wood energy in integrated production of timber and energy biomass**. *GCB Bioenergy* 2011, **3**:483-497.

29. Olsson BA, Staaf H, Lundkvist H, Bengtsson J, Kaj R: **Carbon and nitrogen in coniferous forest soils after clear-felling and harvests of different intensity**. *Forest Ecol Manage* 1996, **82**:19-32.

30. Thiffault E, Paré D, Bélanger N, Munson AD, Marquis F: **Harvesting intensity at clear felling in the boreal forest: impact on soil and foliar nutrient status**. *Soil Sci Soc Am J* 2006, **70**:691-701.

31. Jones HS, Garrett LG, Beets PN, Kimberley MO, Oliver GR: **Impacts of harvest residue management on soil carbon stocks in a plantation forest**. *Soil Sci Soc Am J* 2008, **72**:1621-1627.

32. Repo A, Tuomi M, Liski J: **Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues**. *GCB Bioenergy* 2011, **3**:107-115.

33. Peng C, Jiang H, Apps MJ, Zhang Y: **Effects of harvesting regimes on carbon and nitrogen dynamics of boreal forests in central Canada: a process model simulation**. *Ecol Model* 2002, **155**:177-189.

34. Jandl R, Lindner M, Vesterdal L, Bauwens B, Baritz R, Hagedorn F, Johnson DW, Minkkinen K, Byrne KA: **How strongly can forest management influence soil carbon sequestration?** *Geoderma* 2007, **137**:253-268.

35. Walmsley JD, Godbold DL: **Stump harvesting for bioenergy – a review of the environmental impacts**. *Forestry* 2010, **83**:17-38.

36. Hope GD: **Changes in soil properties, tree growth, and nutrition over a period of 10 years after stump removal and scarification on moderately coarse soils in interior British Columbia**. *Forest Ecol Manage* 2007, **242**:625-635.

37. Johansson M-B: **The influence of soil scarification on the turn-over rate of slash needles and nutrient release**. *Scand J Forest Res* 1994, **9**:170-179.

38. Pumpanen J, Westman CJ, Ilvesniemi H: **Soil CO_2 efflux from a podzolic forest soil before and after forest clear-cutting and site preparation**. *Boreal Environ Res* 2004, **9**:199-212.

39. Egnell G, Hyvönen R, Högbom L, Johansson T, Lundmark T, Olsson B, Ring E, von Sydow F: **Environmental aspects on stump-harvest – compilation of knowledge and knowledge gaps Rapport ER 2007:40, juni 2007**. 2007.

40. **Stubbskörd och miljöeffekter- TEMA stubbar - Årsrapport för 2009. Swedish University of Agricultural Sciences**. 2009.

41. Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR *et al.*: **Ecology of coarse woody debris in temperate ecosystems**.**Advances in Ecological Research**. Academic Press; 1986: 133–302.

42. Harmon ME, Krankina ON, Sexton J: **Decomposition vectors: a new approach to estimating woody detritus decomposition dynamics**. *Can J Forest Res* 2000, **30**:76-84.

43. Tuomi M, Laiho R, Repo A, Liski J: **Wood decomposition model for boreal forests**. *Ecol Model* 2011, **222**:709-718.

44. Finer L, Mannerkoski H, Piirainen S, Starr M: **Carbon and nitrogen pools in an old-growth, Norway spruce mixed forest in eastern Finland and changes associated with clear-cutting**. *Forest Ecol Manage* 2003, **174**:51-63.

45. Palviainen M, Finér L, Laiho R, Shorohova E, Kapitsa E, Vanha-Majamaa I: **Carbon and nitrogen release from decomposing Scots pine, Norway spruce and silver birch stumps**. *Forest Ecol Manage* 2010, **259**:390-398.

46. Ludovici KH, Zarnoch SJ, Richter DD: **Modeling in-situ pine root decomposition using data from a 60-year chronosequence**. *Can J Forest Res* 2002, **32**:1675-1684.

47. Palviainen M, Finér L, Kurka AM, Mannerkoski H, Piirainen S, Starr M: **Decomposition and nutrient release from logging residues after clear-cutting of mixed boreal forest**. *Plant Soil* 2004, **263**:53-67.

48. Janisch JE, Harmon ME, Chen H, Fasth B, Sexton J: **Decomposition of coarse woody debris originating by clearcutting of an old-growth conifer forest**. *Ecoscience* 2005, **12**:151-160.

49. Liski J, Perruchoud D, Karjalainen T: **Increasing carbon stocks in the forest soils of western Europe**. *Forest Ecol Manage* 2002, **169**:159-175.

50. Nabuurs G-J, Schelhaas M-J, Mohren GMJ, Field CB: **Temporal evolution of the European forest sector carbon sink from 1950 to 1999**. *Global Change Biol* 2003, **9**:152-160.

51. Ciais P, Schelhaas MJ, Zaehle S, Piao SL, Cescatti A, Liski J, Luyssaert S, Le-Maire G, Schulze ED, Bouriaud O *et al.*: **Carbon accumulation in European forests**. *Nat Geosci* 2008, **1**:425-429.

52. Bellassen V, Viovy N, Luyssaert S, Le Maire G, Schelhaas M-J, Ciais P: **Reconstruction and attribution of the carbon sink of European forests between 1950 and 2000**. *Global Change Biol* 2011, **17**:3274-3292.

53. Rautiainen A, Saikku L, Kauppi PE: **Carbon gains and recovery from degradation of forest biomass in European Union during 1990–2005**. *Forest Ecol Manage* 2010, **259**:1232-1238.

54. Börjesson P: **Economic valuation of the environmental impact of logging residue recovery and nutrient compensation**. *Biomass Bioenergy* 2000, **19**:137-152.

55. Mälkki H, Virtanen Y: **Selected emissions and efficiencies of energy systems based on logging and sawmill residues**. *Biomass Bioenergy* 2003, **24**:321-327.

56. Petersen Raymer AK: **A comparison of avoided greenhouse gas emissions when using different kinds of wood energy**. *Biomass Bioenergy* 2006, **30**:605-617.

57. Sievänen R, Kareinen T, Hirvelä H, Ilvesniemi H: **Hakkuumahdollisuusarvioihin perustuvat metsien kasvihuonekaasutaseet**. *Metsätieteen aikakausikirja* 2007, **4**:329-339.

58. Egnell G: **Is the productivity decline in Norway spruce following whole-tree harvesting in the final felling in boreal Sweden permanent or temporary?** *Forest Ecol Manage* 2011, **261**:148-153.

59. Helmisaari H-S, Hanssen KH, Jacobson S, Kukkola M, Luiro J,
• Saarsalmi A, Tamminen P, Tveite B: **Logging residue removal after thinning in Nordic boreal forests: long-term impact on tree growth**. *Forest Ecol Manage* 2011, **261**:1919-1927.
This experimental study assesses the long-term impacts of logging residue removal on tree growth Nordic boreal forests. It shows that logging residue removal can decrease the growth of the next tree generation. This growth decrease is related to decline in nutrients due to logging residue removal.

60. Sathre R, Gustavsson L, Bergh J: **Primary energy and greenhouse gas implications of increasing biomass production through forest fertilization**. *Biomass Bioenergy* 2010, **34**:572-581.

61. Holtsmark B: **Harvesting in boreal forests and the biofuel carbon debt**. *Climatic Change* 2011:1-14.

62. McKechnie J, Colombo S, Chen J, Mabee W, MacLean HL: **Forest**
•• **bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels**. *Environ Sci Technol* 2010, **45**:789-795.
This study integrates life cycle assessment (LCA) and forest carbon analysis to assess total GHG emissions of forest bioenergy over time. It shows that that increasing biomass removals from the forest significantly reduces carbon stocks and delays and lessens the GHG mitigation potential of the bioenergy. Employing carbon neutrality assumption overstates the GHG mitigation potential of forest bioenergy and ignores delays in achieving overall emissions reductions.

63. Cherubini F, Peters GP, Berntsen T, Strømman AH, Hertwich E: **CO_2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming**. *GCB Bioenergy* 2011, **3**:413-426.

64. IPCC: In *Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme.* Edited by Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K. Japan: IGES; 2006.