Time-dependent climate benefits of using forest residues to substitute fossil fuels

Leif Gustavsson and Roger Sathre
Linnéuniversitet, Växjö, Sweden

IEA Bioenergy Task 38/40/43 Workshop
19-21 September 2011, Campinas, Brazil
Session topic 3a: Quantifying land use effects of bioenergy– continuation

Global primary energy use in 2007 (≈500 Exajoule)

- Oil 34%
- Coal 26%
- Gas 21%
- **Total fossil 81%**
- Bioenergy 10%
- Nuclear 6%
- Other 3%

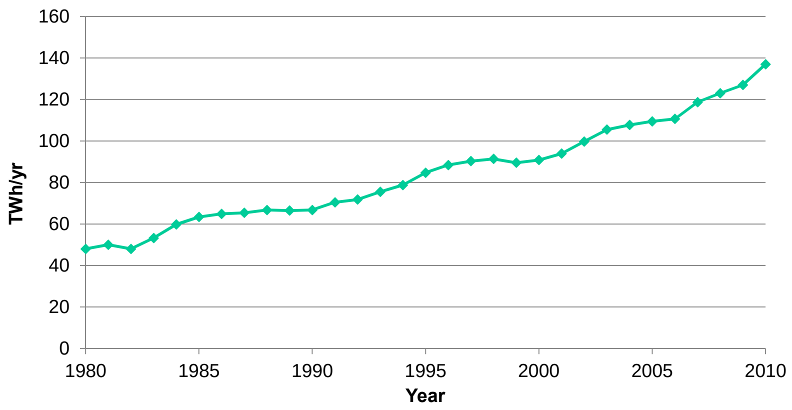
Increased use of bioenergy reduces fossil fuel use – Substitution effects

Exa = 10^{18}
Source: International Energy Agency, 2009. *Key World Energy Statistics*

Greenhouse gas balance of bioenergy systems - Complex analyses

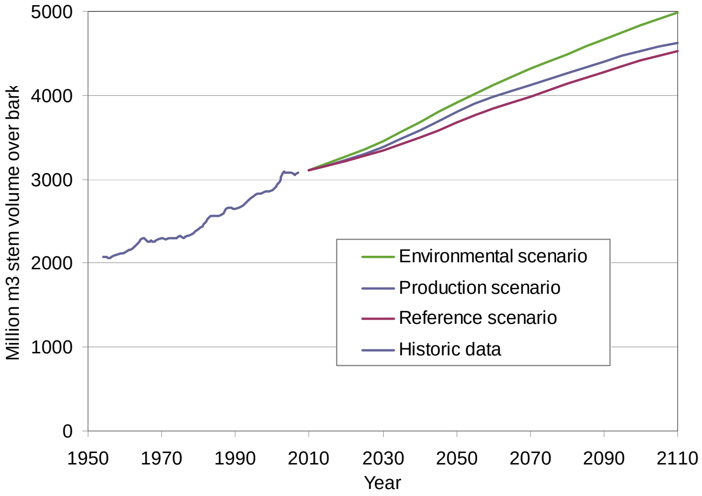
- **Consider the full chain of a bioenergy system, from the natural resources to the delivered services**
  - Biomass production
  - Biomass processing and distribution
  - Final conversion of (refined) biomass
  - Final energy use
- **Consider the full chain of the replaced fossil system**
- **Use a suitable functional unit** (the same service out of the systems)

Annual Swedish bioenergy use



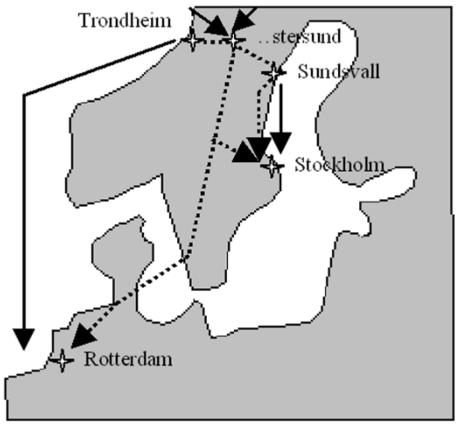
Source: Swedish Energy Agency: Energy in Sweden 2009, and Kortsiktsprognos 2010

Standing stem volume on Swedish productive forest land and scenarious for 2010 - 2110



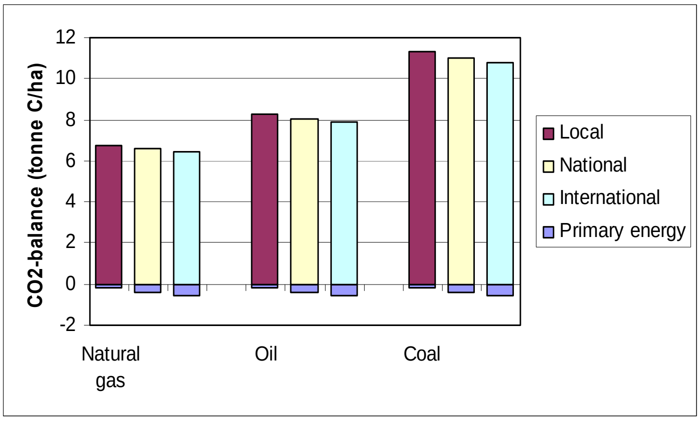
Source: Skogsstyrelsen, Skogliga konsekvensanalyser och virkesbalanser 2008

Example: Solid biomass (logging residues) replace fossil fuels in non-mobile plants



- A system analysis from **forest area** to **local** (80km), **national** (600km) and **international** (1100km) **end-users**
- Functional unit is 1 MWh of delivered wood chips at the local, national and international end-users
- Data for forest residues based on experience in central Sweden

Fossil CO_2 balance when solid biomass replaces different fossil fuels in non-mobile plants



Source: Gustavsson, Eriksson and Sathre, 2011

Cumulative radiative forcing effects of using forest residues to substitute fossil fuels

Forest residues: Energy substitution to replace fossil fuels

- Slash from final harvest: 75% of branches and 25% of needles
- Stumps: 50% of recoverable stumps and coarse roots
- This biomass substitutes either coal, oil, or fossil gas in stationary plants, taking into account relative conversion efficiencies and full fuel-cycle emissions (Gustavsson et al. 2006)
- Combustion emissions return to the atmosphere as CO_2

Fossil energy used to recover and transport the biofuel

Case	Fossil energy input (MJ per dry ton of delivered biomass)	
	Branches and tops	Stumps
Base case (medium energy input)	500	700
Sensitivity analysis (low energy input)	300	500
Sensitivity analysis (high energy input)	700	900

Decay of biomass left in forest

- **Instantaneous oxidation at Year 0**

or

- **Negative exponential decay**

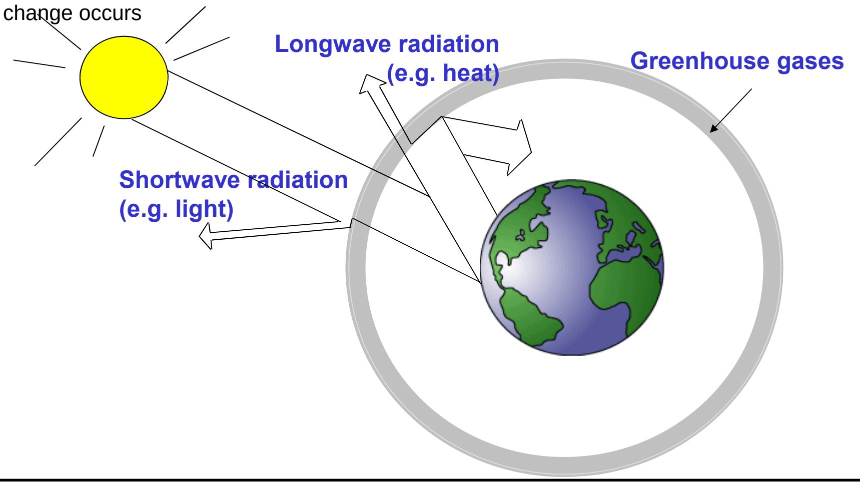
Decay constants:

-0.046 for stumps and coarse roots	(Melin et al. 2009)
-0.074 for branches and tops	(Palviainen et al. 2004)
-0.170 for needles	(Palviainen et al. 2004)

We also analyze 50% faster and 50% slower decay in a sensitivity analysis

GHGs cause an imbalance between incoming and outgoing radiation - "radiative forcing"

- Instantaneous radiative forcing is in units of W/m^2, i.e. power per area
- Integrated over time, **cumulative radiative forcing is** W-s/m^2, i.e. energy per area – **a proxy for temperature increase**
- The longer a GHG is in the atmosphere the more energy is trapped and the more climate change occurs

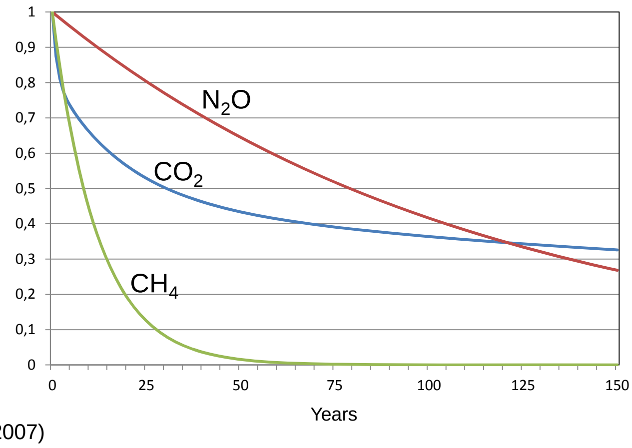


Atmospheric decay of unit pulses of GHGs

$$(CO_2)_t = 0.217 + 0.259e^{\frac{-t}{172.9}} + 0.338e^{\frac{-t}{18.51}} + 0.186e^{\frac{-t}{1.186}}$$

$$(N_2O)_t = e^{\frac{-t}{114}}$$

$$(CH_4)_t = e^{\frac{-t}{12}}$$



(IPCC 1997, 2001, 2007)

Radiative forcing (W/m²) due to GHG concentration change

$$F_{CO_2} = \frac{3.7}{\ln(2)} \times \ln\left\{1 + \frac{\Delta CO_2}{CO_{2ref}}\right\}$$

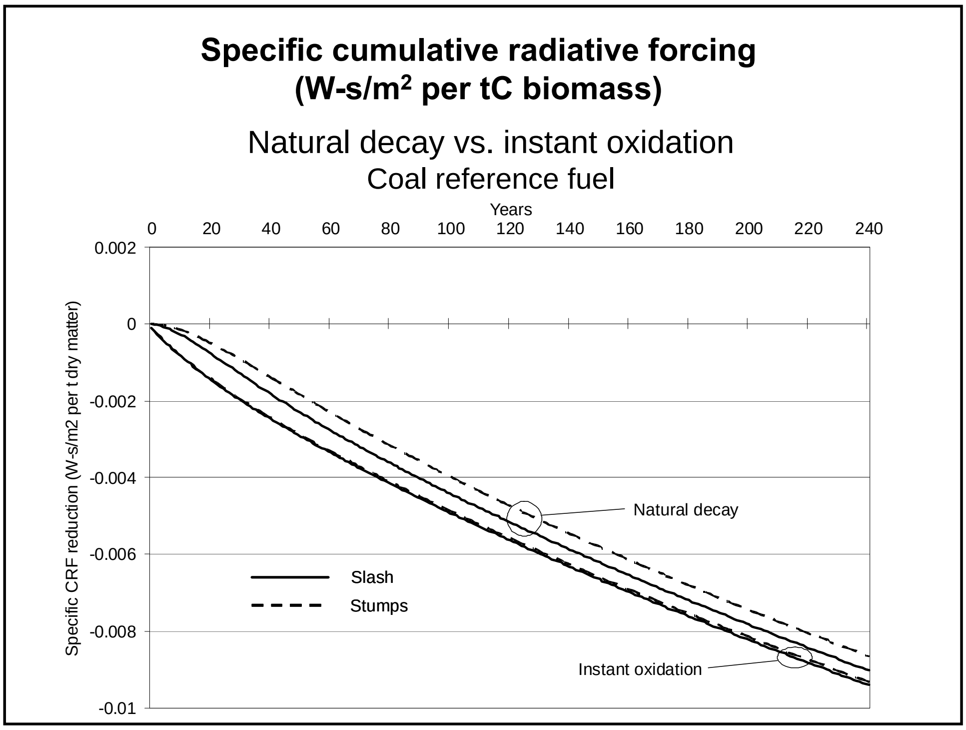
$$F_{N_2O} = 0.12 \times \left(\sqrt{\Delta N_2O + N_2O_{ref}} - \sqrt{N_2O_{ref}}\right) - f(M,N)$$

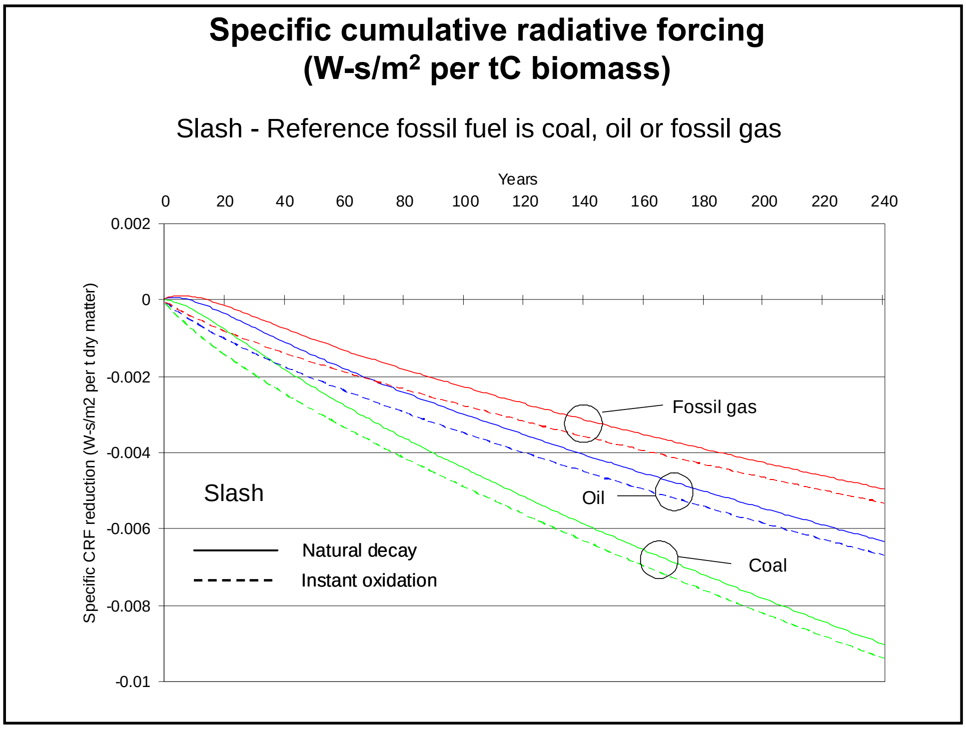
$$F_{CH_4} = 0.036 \times \left(\sqrt{\Delta CH_4 + CH_{4ref}} - \sqrt{CH_{4ref}}\right) - f(M,N)$$

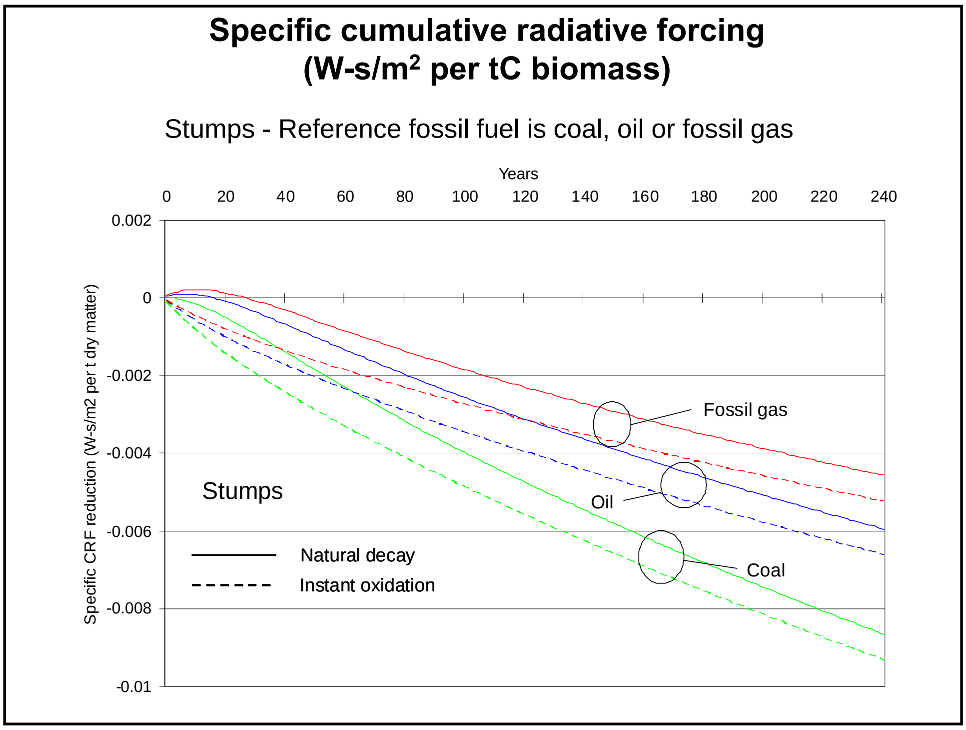
where CO_{2ref} = 383ppmv, N_2O_{ref} = 319ppbv, CH_{4ref} = 1774ppbv

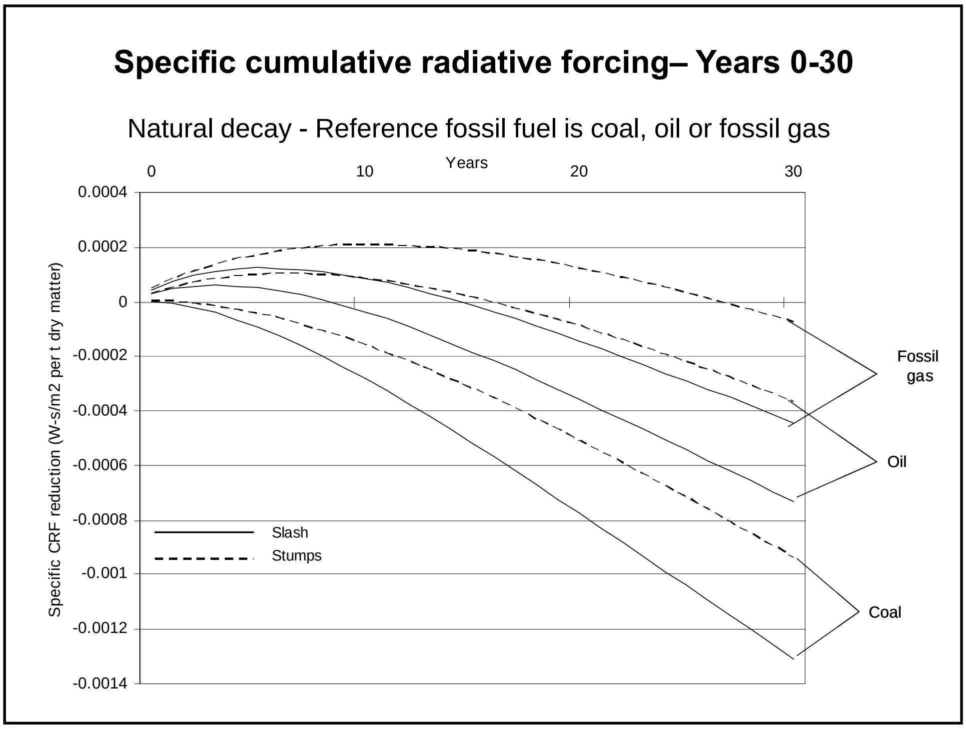
- Assumes relatively minor marginal changes in GHG concentrations
- Spectral overlap between N_2O and CH_4 is accounted for
- Radiative forcing not related to GHGs (e.g. albedo change) is not considered

(IPCC 1997, 2001, 2007)


Specific cumulative radiative forcing
(W-s/m2 per tC biomass)
Natural decay vs. instant oxidation
Coal reference fuel
Years
0 20 40 60 80 100 120 140 160 180 200 220 240
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
Specific CRF reduction (W-s/m2 per t dry matter)
Natural decay
Slash
Stumps
Instant oxidation

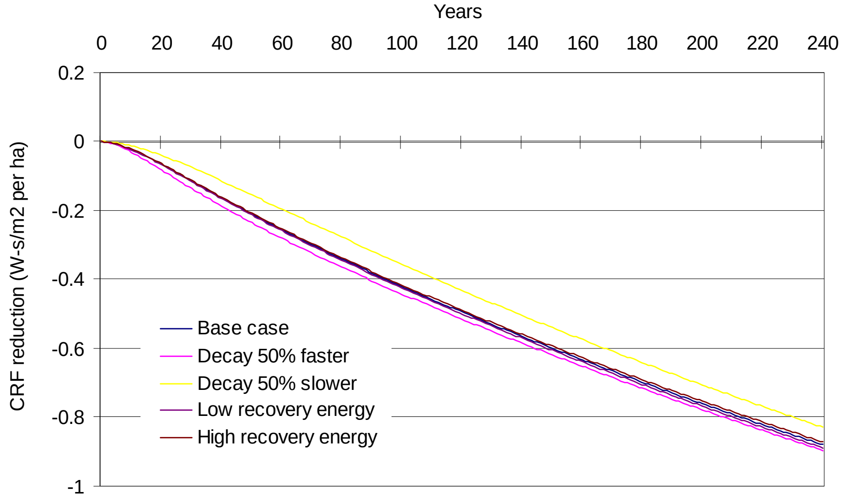

Specific cumulative radiative forcing
(W-s/m2 per tC biomass)
Slash - Reference fossil fuel is coal, oil or fossil gas
Years
0 20 40 60 80 100 120 140 160 180 200 220 240
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
Specific CRF reduction (W-s/m2 per t dry matter)
Fossil gas
Slash
Oil
Natural decay
Instant oxidation
Coal


Specific cumulative radiative forcing
(W-s/m2 per tC biomass)
Stumps - Reference fossil fuel is coal, oil or fossil gas
Years
0 20 40 60 80 100 120 140 160 180 200 220 240
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
Specific CRF reduction (W-s/m2 per t dry matter)
Stumps
Natural decay
Instant oxidation
Fossil gas
Oil
Coal


Specific cumulative radiative forcing– Years 0-30
Natural decay - Reference fossil fuel is coal, oil or fossil gas
Years
0 10 20 30
0.0004
0.0002
0
-0.0002
-0.0004
-0.0006
-0.0008
-0.001
-0.0012
-0.0014
Specific CRF reduction (W-s/m2 per t dry matter)
Slash
Stumps
Fossil gas
Oil
Coal

Sensitivity analysis

Faster and slower natural decay rates of slash
Higher and lower fossil energy use for biomass recovery and transport
Reference fossil fuel is coal



Conclusions

- Over a 240-year period, cumulative radiative forcing (CRF) is significantly reduced when forest residues are used instead of fossil fuels
- The type of fossil fuel replaced is important, with coal replacement giving the greatest CRF reduction
- Replacing oil and fossil gas also gives long-term CRF reduction, although CRF is positive during the first 10-25 years when these fuels are replaced
- Biomass natural decay rates have minor significance
- Fossil energy inputs for biomass recovery and transport has very little impact

References

Berg S and Lindholm EL. 2005. Energy use and environmental impacts of forest operations in Sweden. *Journal of Cleaner Production* 13: 33-42.

Gustavsson L., Eriksson L. and Sathre R. (2011) Costs and CO2 benefits of recovering, refining and transporting logging residues for fossil fuel replacement. *Applied Energy* 88: 192-197.

IPCC.1997. *An Introduction to Simple Climate Models Used in the IPCC Second Assessment Report.* IPCC Technical Paper II.

IPCC. 2001. *Climate Change 2001: The Scientific Basis.* Contribution of Working Group I to the Third Assessment Report.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report.

Lindholm, E.L., Berg, S. and Hansson, P.A. 2010. Energy efficiency and the environmental impact of harvesting stumps and logging residues. *European Journal of Forest Research* 129: 1223-1235.

Mead DJ and Pimentel D. 2006. Use of energy analysis in silvicultural decision-making. *Biomass and Bioenergy* 30: 357-362.

Melin Y, Petersson H and Nordfjell T. 2009. Decomposition of stump and root systems of Norway spruce in Sweden: a modelling approach. *Forest Ecology and Management* 257:1445-1451.

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

Sathre R. and Gustavsson L. 2011. Time-dependent climate benefits of using forest residues to substitute fossil fuels. *Biomass and Bioenergy* 35: 2506-2516 .

Thank you

leif.gustavsson@lnu.se