REPORT

Climate impact of energy utilisation scenarios for forestry-drained peatlands

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1 Summary

In this study the climate impact of energy utilisation scenarios of forestry drained peatlands from a lifecycle perspective has been calculated. In the calculations the peat is utilised for energy and thereafter the cutaway peatland is used for biofuel production in the form of wood fuel or reed canary grass. The scenarios where the fuel for heat and electricity production is peat and biomass are compared to scenarios where the fuel is coal. Estimates of emissions and other conditions are chosen in order to be representative for Finnish conditions.

All peat scenarios concerns areas that initially are forestry-drained peatlands. The results show that the climate impact of scenarios where the cutaway peatland is afforested is higher than the climate impact of corresponding coal scenario. At least as long as the forest productivity of the peatland is not significantly affected by the peat cutting. Measurements of forest productivity at cut away peatlands show higher average values than productivity at forestry drained peatlands, which might indicate that the productivity in general can be increased. If the forest productivity is significantly increased after the peat cutting, the climate impact of the peat – biomass scenario is somewhat higher than that of corresponding coal scenario during the first 100-200 years and then somewhat lower. How much lower depends on how much the forest productivity is increased. An important factor for the results of the scenarios is also the initial decomposition rate of the peat layer at the forestry drained peatland. The higher the rate of decomposition of peat at the initial production reserve, the lower the climate impact of the energy utilisation scenario.

In general we see that the climate impact of energy utilisation from forestry drained peatlands is higher than in previously performed calculations for Swedish conditions. The main reason for that is probably the large difference in emission estimates of peat decomposition at these peatlands. The Swedish estimates are in general higher than the Finnish estimates. Currently there is no clear explanation to these large differences in emission estimates.

The best-best and worst-worst scenarios for the forestry drained peatlands, in which the abovementioned effects (emissions from initial peatland and increase in forest productivity) are combined, show that using peat areas with high initial greenhouse gas emissions (already drained areas) and putting effort on good productivity at the after-treated area will have significant impact on the climate impact, making it lower. At the same time using areas with low initial emissions with no increase in forest productivity after peat cutting could also have a significant impact on the climate impact, increasing it. In the best-best case the peat-afforestation scenario will have lower climate impact than coal after approximately 100 years, whereas in the worst-worst case the coal scenario still has lower climate impact after 300 years.

For scenarios where the cutaway peatland is used for reed canary grass cultivation, the potential of energy production from the land area is increased compared to the pre-peat cutting state. An important factor also in these scenarios is the initial rate of decomposition of peat at the forestry drained site. Important is also the effect on soil emissions due to the cultivation. If the soil emissions at the cut away area are increased due to the cultivation of reed canary grass, the climate impact of these scenarios will be higher than corresponding coal scenario. On the other hand if the carbon sequestration is increased by the reed canary grass cultivation the climate impact will be lower. Also the annual yield of the reed canary grass cultivation and the N_2O emissions from the cultivated area are important factors for the overall results. A higher annual yield means lower climate impact compared to scenarios with lower annual yield. In general the climate impact of the

peat- RCG cultivation scenarios are higher than the corresponding coal scenarios during a first period of at least 150 years.

The best-best and the worst-worst case scenario for the peat – reed canary grass cultivation scenarios also show that the greenhouse gas balance of the initial land area and the productivity of the after-treated are is important for the overall climate impact. In the best-best case the climate impact from the peat-RCG scenario is lower than the coal scenario already after 150 years. In the worst-worst case the peat-RCG scenario will have higher climate impact than coal curing the entire calculation period.

There is still lack of data on greenhouse gas emissions from cutaway peatlands used for reed canary grass cultivation. Input data in this study is based on preliminary research results. Final results of ongoing studies should be used to decrease the level of uncertainty of the results of this study. Other important sources of uncertainty to consider are the initial and post- forest productivity and the initial rate of peat decomposition at these peatlands.

2 Introduction

Peatlands emit and absorb greenhouse gases. Both the nutritional and hydrological status of the peatland influences the net greenhouse gas balance of the area. Natural peatlands are waterlogged areas, in which the decomposition of biomass is inhibited due to anoxic conditions. This is what has lead to the accumulation of biomass and peat formation. The anoxic conditions in natural peatlands also results in significant amounts of methane emissions. In peatlands that have been drained for some reason the decomposition rate will increase and instead of CH_4, CO_2 will be emitted. Drained peatlands used for agriculture will also emit substantial amounts of N_2O. All this indicates that peatlands both in their natural state and in man-made states have impact on the atmospheric greenhouse gas concentrations and the radiative balance.

Descriptions of the climate impact of energy peat utilisation in a lifecycle perspective have been performed by several researcher teams in both Sweden and Finland (Hillebrand 1993, Savolainen et al 1994a, Savolainen et al 1994b, Crill et al 2000, Uppenberg et al 2004[1], Nilsson & Nilsson 2004, Kirkinen et al (in press)). The results are dependent on many factors, among others the type of peatland that is used for peat cutting, i.e. its initial state and the aftertreatment of the cutaway area.

The main objective of draining peatlands, both in Sweden and Finland, has been to increase the net primary production of tree biomass (Hånell 1988, Minkkinen et al 2001, von Arnold et al 2005a), but the disturbance also affects CO_2 emissions from the soil. As the peat layer gets aerated due to the lowered water table the peat will start to decompose, resulting in CO_2 emissions. If the peat is cut and combusted these CO_2 emissions will occur all at once, but at the same time the energy within the peat can be utilised.

In previous studies of the climate impact of energy peat utilisation from a life cycle perspective, the impact on biomass production at the site has been considered in different manners in the different studies. In some of them afforestation after peat cutting is only considered in the sense that the growing forest sequesters carbon during some time, while in others the wood from the growing forest is utilised for energy production. In this study we consider the impact on the biomass productivity potential of the land area that the peat cutting might have, and include that in the

[1] Some of the results of this study have previously been published in Uppenberg, S., Zetterberg, L. & Åhman M., 2001. Climate Impact of Peat Utilisation in Sweden, IVL B-report 1423, Stockholm.

calculations of the climate impact of the peat cutting scenario. Including the energy production from peat and biomass in the same scenario means applying a land-use perspective on peatlands in contrast to just considering the impact of peat utilisation.

3 Objectives

In this study the climate impact of peat cutting and aftertreatment of forestry drained peatlands is investigated. Specifically, the study focus on using the cutaway peatlands for production of reed canary grass (RCG) or wood fuels. A comparison of the climate impact of utilisation of energy peat to the climate impact of utilisation of coal is made.

We also want to compare our results to the results by Kirkinen et al (in press) and therefore we have used as similar assumptions and input data as possible.

4 Methodology

This study includes forestry-drained peatlands and the climate impact from cutting peat at these areas and using the cutaways for biomass production by forestry or cultivation of reed canary grass. Since the scenarios include the potential for biomass production after peat cutting, it is also assumed that the forestry-drained peatlands initially were used for biomass production by forestry (see section 8.1 for a further discussion of this assumption). There are of course other areas than forestry drained peatlands and other after-treatment options that could be used but other options were not included in this study.

The calculations have been made in accordance to previous studies (Nilsson & Nilsson 2004, Kirkinen et al (in press), Uppenberg et al 2004 and Savolainen, 1994a) where the emissions in the energy peat utilisation scenario are compared to a business as usual scenario. The business as usual scenario (E_{BAU}) describes the emissions/uptake of greenhouse gases from the peatland if let be in its current state. Hence, in this study E_{BAU} includes emissions/uptake from the decomposing peat layer in the forestry-drained peatland and the production of biomass fuel from the forest growing at the area. The peat scenario, E_{peat}, includes emissions/uptake from the area caused by the extra drainage necessary for peat cutting, emissions from storage, transportation and burning of the peat-fuel as well as the emissions/uptake from the after-treated area. The emissions/uptake from the after-treated cutaway peatland also includes biomass production (reed canary grass or forest). The net emissions due to peat cutting are described by Equation 4.1.

$E_{net,\,peat} = E_{peat} - E_{BAU}$ Equation 4.1

The peat scenarios have also been compared to coal scenarios[2] and correspondingly the net emissions in the coal scenarios are calculated by Equation 4.2. The coal scenarios include emissions from coal combustion corresponding to both the peat production and to the increased biomass production at the aftertreated area (since comparable coal and peat-biomass scenarios should produce equal amounts of energy). The coal scenarios also include emissions from the peat field, which is unchanged (since in the coal scenario no peat is extracted), but these emissions are cancelled by the business as usual scenario (E_{BAU}).

$E_{net,coal} = E_{coal} - E_{BAU}$ Equation 4.2

[2] And in some cases also to natural gas.

5 System boundaries

There are different ways of considering the emissions from the after-treated cutaway peatlands. In general, previous studies have not considered the potential for biomass production at after-treated areas (Nilsson & Nilsson (2004), Kirkinen et al (in press), and Savolainen (1994a). Uppenberg et al. (2004) did consider the biomass production potential but mainly investigated the utilisation of pristine mires. None of the mentioned studies considered the initial potential of biomass production at the drained peatlands before peat cutting.

In this study the potential of biomass production at both the forestry drained peatland (wood fuel) and at the after-treated cutaway area (wood fuel or reed canary grass) is considered.

6 Scenarios

As mentioned in chapter 4 this study compares a business as usual scenario to different options. The business as usual scenario is that the forestry-drained peatland is kept in its current state, which includes forestry where biomass is used for fuel. In the business as usual scenario the peat layer is slowly decomposing, emitting CO_2 to the atmosphere. A simplified case with a constant rate of decomposition over the rotation periods was used. The reality might be different. After clear-cutting at a drained site, one might need remedial drainage to have the newly planted forest growing. Even within one rotation period one might need remedial drainage in order not to loose productivity. On the other hand if no additional drainage were to be performed, the decomposition rate of the peat layer would probably decline, since the thickness of the aerated peat layer is reduced over time.

This study applies the same method of estimating the climate impact of the energy peat production as previous studies (Uppenberg et al. 2004, Savolainen et al 1994a, Kirkinen et al (in press) and Nilsson & Nilsson 2004). This means that the emissions during the cutting and combustion of the peat as well as the emissions from the after-treated cut over peatland are considered. It also means that the emissions from the initial peatland are considered as avoided in the peat cutting scenario, i.e. in the case of a forestry drained peatland, CO_2 emissions due to the decomposition of the peat layer and carbon sequestration by uptake in tree biomass.

In the following subsections the emissions and uptake of greenhouse gases during the initial state of the drained peatlands, the peat-cutting period and the after-treated area (afforested or used for reed canary grass cultivation) are described.

6.1 Energy peat production

This study is considering peat cutting in areas of forestry-drained peatlands. Due to the drainage the peat-layer in these areas is decomposing, emitting CO_2 to the atmosphere. Cutting the peat and using it as a fuel means that these CO_2 emissions will occur sooner and at a faster rate but also that the energy trapped in this old organic material can be utilised for heat and power production.

It is assumed that a peat layer of an approximate thickness of 2-3 dm is left after peat cutting, which can be considered as a good estimate for traditional harvest methodologies (Nilsson & Nilsson 2004, Kirkinen et al. (in press). The quality of the under laying soil and its characteristics are poorly known, but according to Aro 2006 (personal communication) leaving a shallow layer of peat will improve the conditions for forest productivity. The reason is that with a shallow peat layer the trees will be able to get nutrients from the mineral soil and nitrogen from the peat layer. If the peat layer is too thick, the nutrients in the mineral soil will be to far away and if there is no peat layer left, there might be too little nitrogen available for the trees.

6.1.1 Initial land area – forestry drained peatland

The emissions assumed from this stage of the production chain are based on Kirkinen et al (in press). The net emissions of CO_2 from the soil were assumed to be 224 (± 224) g CO_2/m^2 yr. The CH_4 emissions were assumed to be 0 g CH_4/m^2 yr. and the N_2O emissions were assumed to be 0 g N_2O/m^2 yr. Unlike Kirkinen et al. (in press) we have taken into consideration that the initial forestland also is subject to conventional forestry and hence can be used for biofuel production. In this study we consider the following emissions of CO_2 from the initial land areas;

i) the soil respiration (decomposition of peat) which we assume is 224 ± 224 g CO_2/m^2yr and

ii) the uptake in the growing forest, which we assume, is –448 g CO_2/m^2yr.

It is assumed that the rotation period is 90 years and that the average productivity is 3.9 m^3 sk/ha yr[3].

6.1.2 Emissions from peat field during drainage

The forestry-drained peatland is assumed to be used for normal forestry and when mature the forest is harvested and the area is drained for peat cutting. In this study, just as Uppenberg et al (2004) and Nilsson & Nilsson (2004), it is assumed that the drainage period prior to peat cutting is approximately 5 years. During this period, the annual CO_2 emissions from the soil, due to decomposition of peat, will increase to a level of approximately 1000 g CO_2/m^2. In this study we have, like Kirkinen et al. (in press), ignored the impact of drainage on the surrounding area.

6.1.3 Emissions from peat field during peat cutting

The estimated values of emissions from this stage of the peat production chain used in this study are the average values used by Kirkinen et al (in press). During peat cutting there will be small emissions of methane, estimated to 0.0039 g CH_4/MJ, from the production field (ditches). There will also be CO_2 emissions from the production field, estimated to 6.84 g CO_2/MJ, and from the stockpiles, estimated to 1.48 g CO_2/MJ. It is also assumed that there are some emissions from working machines, estimated to 1 g CO_2/MJ. In Appendix 1 the estimated values of emissions of greenhouse gases during the different stages of the peat production chain used in this study are presented in detail.

6.1.4 Emissions during the combustion phase

The average values for the greenhouse gas emissions due to the combustion of peat from Kirkinen et al. (in press) were used in the calculations performed in this study. In Table 6.1 the reference sources of the estimated values are also given. In Appendix 1 the corresponding values for combustion of coal and natural gas are also given.

[3] The productivity corresponds to the uptake of CO_2 in the growing forest.

Table 6.1 Emissions due to combustion of peat (average values according to Kirkinen et al (in press))

Gas				Reference
Carbon dioxide	CO_2	105.9	g/MJ	Vesterinen 2003
Methane	CH_4	0.0085	g/MJ	Statistics Finland 2005
Nitrous oxide	N_2O	0.0128	g/MJ	Statistics Finland 2005

6.2 Afforestation

6.2.1 Forest productivity

In the scenarios of this study it is assumed that the entire forest production will be used for energy purposes. In modern forestry that is not the case, part of the wood biomass is used for pulp and paper industry, part of it is used for other wood industry and only 20-25% of the total production might primarily be used for energy purposes. Conventional production without utilisation of logging residues is considered. Including the potential of logging residues would increase the energy production from the forest but since the net change between the BaU scenario and the aftertreatment is what matters this will have a limited effect (see section 8.1 for a further discussion on this topic).

Based on Hånell (1997) and Kirkinen et al (in press) it is estimated that the total production of biomass in the forest during one rotation period is 350 m^3 sk/ha[4]. Hånell estimates that there is a self-thinning of approximately 50 m^3sk/ha, which reduces the available amount of wood to approximately 300 m^3sk/ha. This is the basis for the energy production and it is estimated that this corresponds to approximately 288 MJ/m^2. (This is calculated by assuming that the 300 m^3sk has an approximate water content of 50% (i.e. 0.5 ton dry matter/m^3sk. and energy content of approximately 19.2 MJ/kg (5.33 MWh/ton). That results in an energy content of 300*0.5 5.33 = 800 MWh/ha = 288 MJ/m^2). In the base scenario this is the amount of energy assumed to be harvested from the both the forestry drained and the afforested cutaway site.

In the calculations, CO_2 emissions due to the clear cut are assumed to occur all at once. Hence no consideration was made of the delay of the emissions until the fuel is combusted. Neither were thinnings or self-thinnings considered. In the scenarios there is a constant annual uptake of CO_2 in the growing forest until it is clear-cut, and then the emissions occur. In addition to the CO_2 emissions from the combustion of the biomass there is some need for fossil fuels for the clear cutting, transportation of fuel to the power plant and refining of the fuel. Those emissions were estimated to 1.5 g CO_2/MJ based on Savolainen et al (1994a) and Börjesson & Gustavsson (1996), who estimated the emissions to 1g CO_2/MJ and 3.2 g CO_2/MJ respectively. The difference between the two studies is that Börjesson & Gustavsson (1996) are looking at forest residues whereas Savolainen et al. (1994a) are looking at wood fuel. The energy content of logging residues is less dense which means a larger input of machinery and transportation per MJ of harvested fuel. Since this study does not consider the potential of logging residues a lower value than the estimate by Börjesson & Gustavsson (1996) has been used.

In order to investigate the impact of the forest productivity a few different scenarios (described in section 6.2.4) were considered. In the base scenario it is assumed that the productivity of the forest is not affected by the peat cutting, i.e. the productivity is the same before the peat cutting as after. The assumption of the forest productivity, 3.9 m^3 sk/ha yr., is based on Kirkinen et al (in press).

[4] Annual productivity estimated to 3.9 m^3sk/ha, rotation period 90 years.

6.2.2 Accumulation in above-ground litter

Just as in Kirkinen et al (in press) and in Nilsson & Nilsson (2004) we have assumed that there will be accumulation of aboveground litter at the afforested site. We have assumed the same accumulation rate as in Kirkinen et al -147 g CO_2/m^2yr until the average value 1.8 kg C/m^2 is reached.

6.2.3 Decomposition of residual peat

Using conventional methods for peat cutting will leave a residual layer of peat, approximately 2-3 dm thick. If the area is left in a drained state the residual peat will decompose. Kirkinen et al. (in press) have assumed that the carbon pool in the residual peat would decrease exponentially from 15 000 g C/ m^2. The decomposition is assumed to continue until the amount of carbon in the soil is the same as what is expected to accumulate in below-ground forest litter within 300 years (at an average accumulation rate of -4 g C/m^2yr.). Hence, after 300 years, the amount of carbon in the soil is 1200 g C/m^2. In this study the same assumptions were made for the emissions from the decomposition of the residual peat layer.

6.2.4 Peat scenarios with afforestation as aftertreatment

There are reasons to assume that the productivity of the forest can be increased by the peat cutting (see section 8.1), and therefore we have made two scenarios where this is the case. One scenario where the forest productivity increases modestly by 1 m^3sk/ha yr. (to 4.9) after peat cutting and one scenario where the productivity is substantially increased by 7 m^3sk/ha yr. (to 10.9).

According to Aro, L., 2006 (personal communication) there are studies showing that cutaway afforested peatlands could have very high productivity (probably as high as 15-16 m^3sk/ha yr.). However these studies do not say anything about the productivity at these sites before peat cutting. The productivity of the forest is also very site dependent so these values should probably not be used as average values. However, it also indicates that also the highest increase in productivity used in this study might be a realistic case for some areas.

The reference scenario, i.e. the estimated emissions and uptake of greenhouse gases at the initial forestry drained site has great impact on the resulting climate impact for all scenarios. In order to reflect this importance there are two scenarios with altered rate of decomposition of the peat in the forestry drained peatland made for afforestation scenarios. However, this effect has great importance also for the scenarios with reed canary grass cultivation as aftertreatment.

The scenarios with afforestation as aftertreatment investigated in this study are;

1. Scenario with same forest productivity pre- and post peat cutting, no increase in productivity
2. Scenario with moderately increased forest productivity post peat cutting compared to initial state, +1 m^3sk/ha yr.
3. Scenario with substantially increased forest productivity post peat cutting compared to initial state +7 m^3sk/ha yr.

4,5 Scenarios with increased and decreased rate of decomposition of peat in the initial forestry drained peatland.

6, Scenario with combined effects. Scenario 6 has high decomposition rate (448 g CO_2/m^2yr) in initial stage and substantially increased forest productivity compared to initial state (+7

m^3sk/ha yr.). Also scenario 6 can be considered as a combined scenario with low decomposition rate in initial stage (0 g CO_2/m^2yr.) and no increase in forest productivity.

The scenarios are presented with names and data in Table 6.2.

Table 6.2 Scenarios where cutaway area is used for forestry.

Scenario name	**Forest productivity**		**Initial rate of CO_2 loss**
	Pre peat cutting [m^3sk/ha yr.]	**Post peat cutting [m^3sk/ha yr.]**	**[g CO_2/m^2yr.]**
1. Peat – afforestation no prod. increase	3.9	3.9	224
2. Peat – afforestation, prod. incr. 1 m^3sk/ha	3.9	4.9	224
3. Peat – afforestation, prod. incr. 7 m^3sk/ha	3.9	10.9	224
4. Peat – afforestation, no prod increase, decomposition rate 224	3.9	3.9	224
5. Peat – afforestation, no prod increase, decomposition rate 0	3.9	3.9	0
6. Peat – afforestation, no prod increase, decomposition rate 448	3.9	3.9	448

6.3 Production of Reed Canary Grass

Reed canary grass, RCG, is a cool season, sod forming and perennial wetland grass. It is native to the temperate regions of Europe, Asia and North America. RCG has historically been used for fodder and also for erosion control. Today the main interest for RCG is for material and energy purposes. During the 1980s several projects were initiated in Sweden to evaluate different crops and their biomass potential. RCG was identified as one of the most interesting crops (Thériault et al 2003).

6.3.1 Fuel properties and yields

The most important difference between RCG and wood fuels, from a fuel quality perspective, is the higher ash content and fluffiness of the ashes from RCG. The ash content varies with the soil characteristics. The highest ash contents are found on clay soils whereas organic soils will give the lowest ash contents (Burvall (1997), Glommers Miljöenergi (2002)).

Reed Canary Grass harvested during springtime has due to losses of nutrients and chloride during wintertime much better fuel properties than grasses harvested during summer or fall (Burvall, 1997).

According to Bullard & Metcalfe (2001) and Burvall (1997), the yield from RCG cultivation will be somewhat lower during the first year compared to following years when the crop has been established. The assumption used in this study is that during the first (of ten) years the yield is 2/3 of the average yield during the coming years. According to Nyrönen (personal communication

2006) and Burvall (1997), the average annual yield of dry weight of reed canary grass to be expected in Nordic conditions is 6 t dry matter/ha, which corresponds to an energy yield of 10.7 MJ/m^2yr.

The emission factors for combustion of RCG are presented in Table 6.3 below. The CO_2 emission factor has been determined by using data on chemical composition, moisture content and calorific values and corresponds to the uptake in the growing biomass. In the calculations it is assumed that the same amount of CO_2 is emitted during combustion as is sequestered during growth. The emission factors for methane, CH_4, and nitrous oxide, N_2O, are based on data given by the Swedish EPA (2006) and Uppenberg et al (2001). The values for CH_4 and N_2O also include the emissions for collecting and transporting the biomass.

Table 6.3 Combustion emission factors for Reed Canary Grass

Gas	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
	103	0.0056	0.005

6.3.2 Establishment of plantation

Since the RCG is a perennial grass, re-sowing is not necessary every year. Bullard & Metcalfe (2001) assumed that there is a need of re-sowing every five years. According both to VTT & Vapo (2005) and Burvall (1997) re-sowing is only needed every ten years. However, by then the whole plantation has to be renewed. In this study it is assumed that RCG is grown at the cutaway area for the next three hundred years (with renewing of the plantation every 10 years). That is a theoretical scenario but has been made in order to compare it to other after-treatment options.

6.3.3 CO_2 emissions due to energy input in RCG production

Bullard & Metcalfe (2001) and Börjesson (1996) have made extensive analyses of the energy input of biomass production and transportation. Bullard & Metcalfe (2001) mainly concentrates on perennial grasses and also evaluates the corresponding CO_2 emissions whereas Börjesson 1996 looks at biofuels in a broader perspective and estimates the energy input in the production and transportation for these fuels in 1996 and predicts the same energy input in 2015. Bullard & Metcalfe (2001) base their calculations on cultivation in the United Kingdom whereas Börjesson (1996) base the calculations on Swedish conditions. In this study it is assumed that the Swedish conditions are more similar to Finnish conditions. However, since 2006 is halfway from 1996 to 2015 (1996 & 2015 are the years for which Börjesson (1996) has made estimates) the data from Bullard & Metcalfe (2001) have been used to adjust these estimates. Compared to the Bullard & Metcalfe (2001) study, the yield is assumed to be lower in Finland and the transportation distance to the power plants longer. On the other hand, renewal of the field has been assumed to be needed only once every ten years instead of every five years.

Table 6.4 summarises the CO_2 emissions due to energy input in the production and transportation of the RCG. Note that the inputs vary over the ten-year cycle. Input for seeds is only required once, fertilisation is applied every year but not in equal amounts, pesticides are only used at the renewal stage. The estimated CO_2 emissions due to inputs in the production per MJ of produced RCG over a ten-year period were 3.8 g CO_2/MJ.

Table 6.4 Estimate of energy input and related CO_2 emissions in production and transportation of RCG

	Establishment (year 1) MJ/ha	Establishment (year 1) kg C/ha	Year 2 MJ/ha	Year 2 kg C/ha	Year 10 MJ/ha	Year 10 kg C/ha
Seed	120	2				
N	5892	118	337	6.75	337	6.75
P2O5	1416	25	136	2.35	136	2.35
K2O	1260	20	200	3.18	200	3.18
Mn/Lime	5500	111				
Pesticide	1953	16			1816	15
Cultivation	3054	96				
Drill	621	12				
Fertiliser application	6108	119	461	9	461	9
Chemical application	545	8				
Harvest	453	6	679	9	679	9
Storage	95	3	143	5	143	5
Transport	640	9	960	14	960	14
Handler	356	6	534	9	534	9
TOTAL	**28013**	**550**	**3450**	**57**	**5266**	**72**

6.3.4 Below-ground uptake and soil and root respiration

It is known that the soil respiration is higher on peatlands used for agriculture due to the increased aeration and working of the ground. It is also known that perennial crops such as RCG might increase the below-ground uptake of carbon. However, at this point there is no good estimate of the NEE (Net Ecosystem Exchange) of reed canary grass production on cutaway peatlands. There are currently ongoing studies where CO_2 fluxes are measured by micrometeorological methods (eddy covariance) at cutaway peatlands used for bioenergy production in the form of reed canary grass cultivation (Hyppönen et al (in prep), Shurpali et al (in prep)). Results from these studies in the form of data on CO_2-balance will decrease the uncertainty of whether reed canary grass cultivation at cutaway peatlands actually increases the carbon loss of the soil or if it can lead to carbon sequestration.

The estimate of uptake and losses of carbon used in this study is based on preliminary results from Huttunen et al (2004). A fixed value on the average loss from the residual peat-layer is used, the same as for the afforestation scenario (see section 6.2.2). Whether the below-ground uptake of biomass and soil respiration at the RCG cultivation will increase the carbon loss or increase the carbon sequestration is uncertain (Huttunen et al (2004)) and we have made calculations for both cases.

In this study we make three different scenarios in order to reflect the possible effects;

i) the below-ground uptake and root respiration at the RCG field result in a zero net loss/accumulation,

ii) the below-ground uptake and root respiration at the RCG field results in a net accumulation of 105 g C/m^2 (lowest estimated based on Huttunen et al (2004) and

iii) the below-ground uptake and root respiration at the RCG field results in an additional net loss of the corresponding amount 105 g C/m^2.

6.3.5 Soil emissions of N_2O

Cultivated drained peatlands are known to be large sources of N_2O emissions (Maljanen et al (2003), Regina et al (2004) and Kasimir-Klemedtsson (1997)). This study considers cut-away peatlands previously not used for agriculture and the initial level of N_2O emissions can therefore be assumed to be modest. This is based on the fact that, forestry drained peatlands are smaller sources of N_2O then cultivated peatlands (von Arnold (2005a) & (2005b), Maljanen et al (2003), Regina et al (2004) and Kasimir-Klemedtsson (1997)). However, the cultivation and fertilisation of the field might increase the N_2O emissions.

In this study three scenarios with different levels of N_2O emissions are calculated. Based on Ulff (2005), there is a low scenario with 0.3 g N_2O/m^2yr. There is also one scenario with emissions of 1.0 g N_2O/m^2 yr. based on estimates of N_2O emissions from drained peatlands used as grasslands (Nilsson & Nilsson 2004). Finally there is also one intermediate scenario with emissions of 0.5 g N_2O/m^2yr.

6.3.6 Peat scenarios with reed canary grass cultivation as aftertreatment

Scenarios investigated for the reed canary grass production are:

1 base scenario with a yield of 6t dry matter/ha yr. No net effect on soil respiration due to cultivation, low emissions of N_2O (0.3 g N_2O/m^2yr.).

2,3 scenarios with higher levels of N_2O emissions (0.5 g N_2O/m^2yr. and 1.0 g N_2O/m^2yr. respectively).

4,5 scenarios with affected level of soil respiration due to RCG cultivation (+105 g C/m^2yr and – 105g C/m^2yr respectively).

6,7 scenarios with other levels of RCG productivity (5 t dry matter/ha and 7 t dry matter/ha respectively).

8, 9 scenarios showing combined effects of RCG productivity (5 t dry matter/ha and 7 t dry matter/ha respectively) and decomposition rate at initial stage (0, and 448 g CO_2/m^2yr. respectively)

Table 6.5 summarises input data for the peat cutting scenarios with reed canary grass cultivation as aftertreatment method. In scenarios 1-7 the initial decomposition rate at the forestry drained peatland is assumed to be 224 g CO_2/m^2yr.

Table 6.5 Scenarios where cutaway area is used for reed canary grass cultivation

Scenario name	Productivity [t dry weight /ha yr.]	Soil respiration (Net emissions of below-ground uptake and soil respiration[5])	N_2O emissions
1. Peat RCG 6t, nba 0, N2O 0.3	6	0 g C/m²yr	0.3 g N_2O/m^2yr.
2. Peat RCG 6t, nba 0, N2O 0.5	6	0 g C/m²yr	0.5 g N_2O/m^2yr.
3. Peat RCG 6t, nba 0, N2O 1.0	6	0 g C/m²yr	1.0 g N_2O/m^2yr.
4. Peat RCG 6t, nba +105, N2O 0.3	6	+105 g C/m²yr.	0.3 g N_2O/m^2yr.
5. Peat RCG 6t, nba -105, N2O 0.3	6	-105 g C/m²yr.	0.3 g N_2O/m^2yr.
6. Peat RCG 5t, nba 0, N2O 0.3	5	0 g C/m²yr.	0.3 g N_2O/m^2yr.
7. Peat RCG 7t, nba 0, N2O 0.3	7	0 g C/m²yr.	0.3 g N_2O/m^2yr.
8. Peat RCG, 5t, nba 0, N2O 0.3 decomp 0	5	0 g C/m²yr.	0.3 g N_2O/m^2yr.
9. Peat RCG, 7t, nba 0, N2O 0.3 decomp 448	7	0 g C/m²yr.	0.3 g N_2O/m^2yr.

6.4 Comparative fossil fuel scenarios

The climate impact of using alternative fuels (coal and in some cases also natural gas) is calculated as comparison to the peat – biomass scenarios. Since the different peat –biomass scenarios due to differences of biomass productivity at after-treated areas, results in different amounts of energy produced, it is necessary to make scenarios with corresponding energy production also for the alternative fuels.

Analogous to the calculations for the peat scenarios, the alternative fuel scenarios are compared to a business as usual scenario (E_{BAU}). In the business as usual scenario the forestry-drained peatland is left in its current state and the biomass production continued. In the coal scenario, energy corresponding to the amount produced by the peat in the peat scenarios is produced by burning coal. If extra energy is produced at the after-treated area (in case of increased forest productivity in the afforestation scenarios and in the RCG scenarios), the extra energy production is also replaced by coal. Table 6.6 describes the energy production in the different peat scenarios and the corresponding coal/natural gas scenarios.

In our business as usual scenario the forestry-drained peatland is used for normal forestry and all wood is used for heat and power production. The biomass produced is used for energy production. Cutting the peat means a time lag in the normal biomass production by 25 years (5 years of drainage before peat cutting and 20 years of peat cutting). The time lag also has an impact on the radiative balance. The effect of time lag is further explained in Appendix 2. Since the time lag is only 25 years, and the emissions delayed are limited, it has not a significant impact on the overall results. For this reason and in order to simplify for the reader, we have not included the time lag in the calculation of the scenarios presented in section 7.2.

[5] We named this factor nba = net below-ground accumulation and is used in the scenario name.

Table 6.6 Description of energy production in different scenarios

Scenario name	Energy production	Scenario description
-	288 MJ every 90 years	Business as usual, E_{BAU}
-	169 MJ /yr. during 20 years of peat cutting + 288 MJ every 90 years (3.9 m3sk/ha yr.)	Peat, E_{peat}
Peat - afforestation no prod. increase	169 MJ/yr. during 20 years of peat cutting	Peat, net emissions, $E_{net,\ peat}$
Coal (Afforestation, no prod increase)	169 MJ/yr. during 20 years	Coal, net emissions, $E_{net,\ coal}$
Peat – (Afforestation, prod incr. 1 m^3sk/ha)	169 MJ/yr. during 20 years of peat cutting + 86 MJ every 90 years (1 m^3sk/ha)	Peat, net emissions, $E_{net,\ peat}$
Coal (Afforestation, prod incr. 1 m^3sk/ha)	169 MJ/yr. during 20 years of peat cutting + 86 MJ every 90 years (1 m^3sk/ha)	Coal, net emissions, $E_{coal,\ net}$
Coal (Afforestation, prod incr. 7 m^3sk/ha)	169 MJ/yr. during 20 years of peat cutting + 603 MJ every 90 years (7 m^3sk/ha)	Coal, net emissions, $E_{coal,\ net}$
Peat RCG 6t, nba 0, N2O 0.3	169 MJ/yr. during 20 years of peat cutting +10.74 MJ/yr. (RCG prod.) – 288 MJ every 90 years	Peat, net emissions, $E_{peat,\ net}$
Peat RCG 5t, nba 0, N2O 0.3	169 MJ/yr. during 20 years of peat cutting + 8.95 MJ/yr. (RCG prod.) – 288 MJ every 90 years	Peat, net emissions, $E_{net,\ peat}$
Peat RCG 7t, nba 0, N2O 0.3	169 MJ/yr. during 20 years of peat cutting +12.53 MJ/yr. (RCG prod.) – 288 MJ every 90 years	Peat, net emissions, $E_{peat,\ net}$
Coal RCG 6t	169 MJ/yr. during 20 years of peat cutting + 10.74 MJ/yr. (RCG prod.) – 288 MJ every 90 years	Coal, net emissions, $E_{net,\ coal}$
Coal RCG 5t	169 MJ/yr. during 20 years of peat cutting + 8.95 MJ/yr. (RCG prod.) – 288 MJ every 90 years	Coal, net emissions, $E_{net,\ coal}$
Coal RCG 7t	169 MJ/yr. during 20 years of peat cutting + 12.53 MJ/yr. (RCG prod.) – 288 MJ every 90 years	Coal, net emissions, $E_{net,\ coal}$
Natural gas RCG 6t	169 MJ/yr. during 20 years of peat cutting + 10.74 MJ/yr. (RCG prod.) – 288 MJ every 90 years	Natural gas, net emissions, $E_{net,\ natural\ gas}$

7 Results

7.1 Emissions of CO_2 from the different scenarios

In order to explain the different climate impacts of the different scenarios the accumulated CO_2 emissions (which is the most important of the three greenhouse gases in these scenarios) are presented. Figure 7.1 show the total CO_2 emissions from the different scenarios during the 300 year period divided by sources. Four scenarios are shown in the figure, Peat – afforestation scenario, a peat – reed canary grass cultivation scenario and two coal scenarios. Also shown in the figure are the net CO_2 emissions in the different scenarios (the black staples to the right of each scenario). Note that the CO_2 emissions from the reference scenario are shown as negative emissions (avoided emissions) in the peat scenarios.

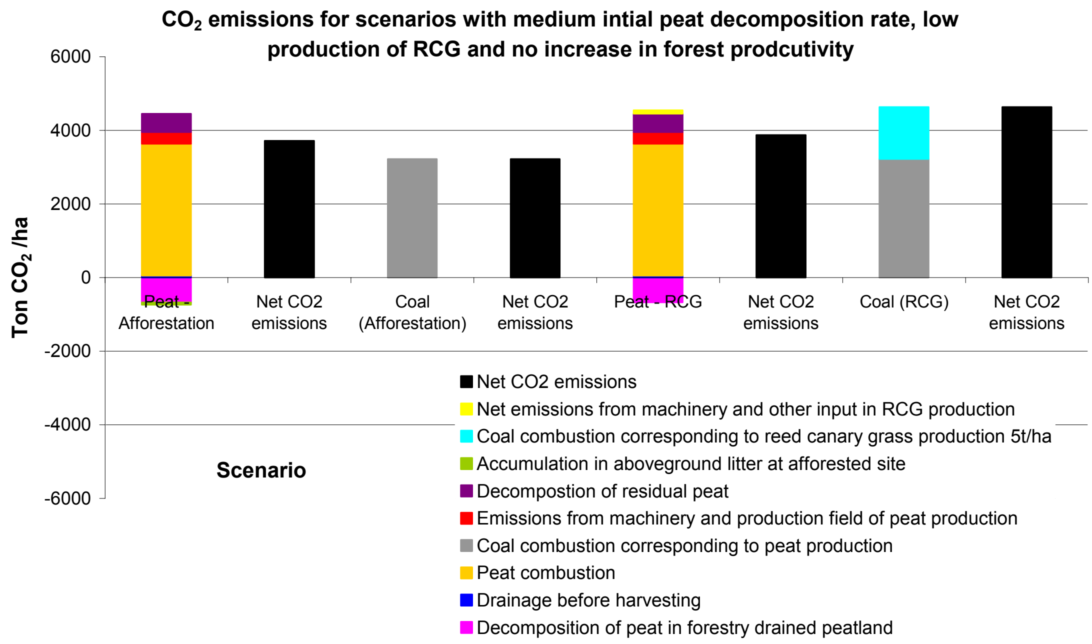

Figure 7.1 CO_2 emissions due to energy peat utilisation and aftertreatment from 1ha forestry drained peatland. Peat is extracted during 20 years but period considered for emissions is 300 years (including 280 years after peat cutting) Note that there will be some emissions of methane and nitrous oxide that also will affect the results to a small extent, which are not included in the figure. Each black staple shows the net emissions of the staple to the left.

Figure 7.1 and Figure 7.2 show different cases. In Figure 7.1 we have average rate of peat decomposition (224 g $CO_2/m^2yr.$) in the forestry drained peatland, no increase in the forest productivity and a productivity of RCG of 5 ton dm[6]/ha. In Figure 7.2 we have maximum rate of peat oxidation (according to the estimates in Kirkinen et al (in press)), an increase in forest productivity of 7 m^3sk/ha and a productivity of RCG of 7 ton dm/ha. Looking at these figures it seems like in most of the cases the peat scenarios result in less emissions than the corresponding coal scenarios since the total net CO_2 emissions are lower. However, what Figure 7.1 does not show, is the distribution in time of the emissions.

Figure 7.3 shows the accumulated CO_2 emissions over time for the different scenarios (corresponding to the scenarios in Figure 7.1 (with average peat decomposition rate, 224 g CO_2/m^2), the coal (afforestation) scenario with a productivity increase of 7 m^3sk/ha is from Figure 7.2). First after 200 years are the emissions in the peat – afforestation scenario (with high production increase) similar to the emissions in the coal scenarios. In the scenario of peat - reed canary grass production this happens much earlier due to the larger biomass fuel production. When in time emissions occur is an important factor for the climate impact and is the main reason why calculations of radiative forcing are made. The results of the radiative forcing scenarios are presented in the sections below.

[6] Dm = dry matter.

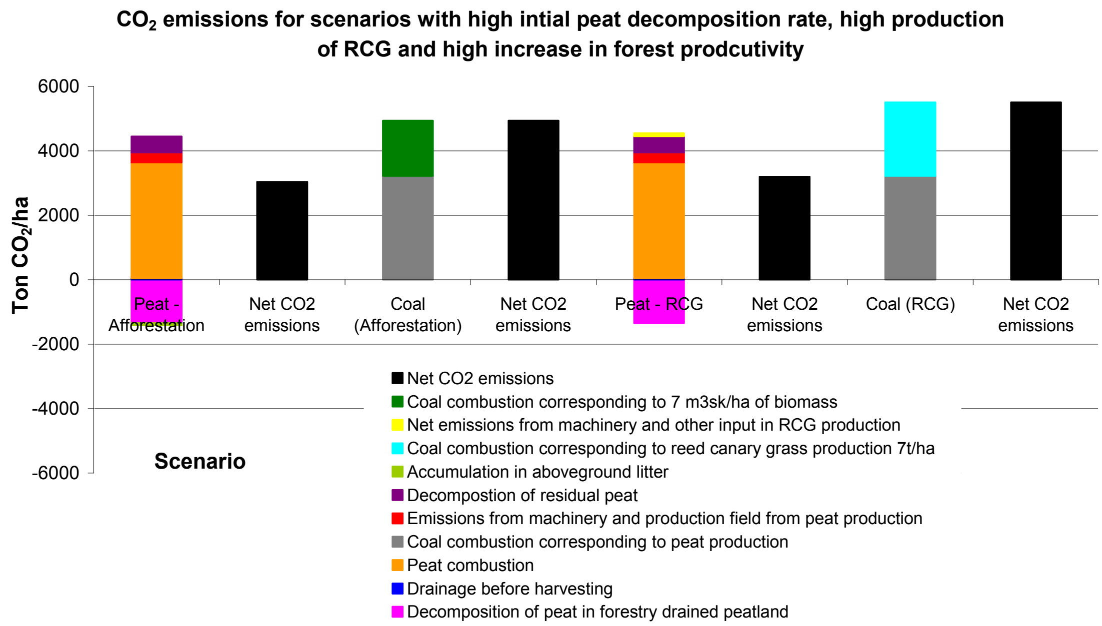

Figure 7.2 CO_2 emissions due to energy peat utilisation and aftertreatment from 1ha of forestry drained peatland. Peat is extracted during 20 years but period considered for emissions is 300 years (including 280 years after peat cutting). Note that there will be some emissions of methane and nitrous oxide that also will affect to a small extent, which are not included in the figure. Each black staple shows the net emissions of the staple to the left.

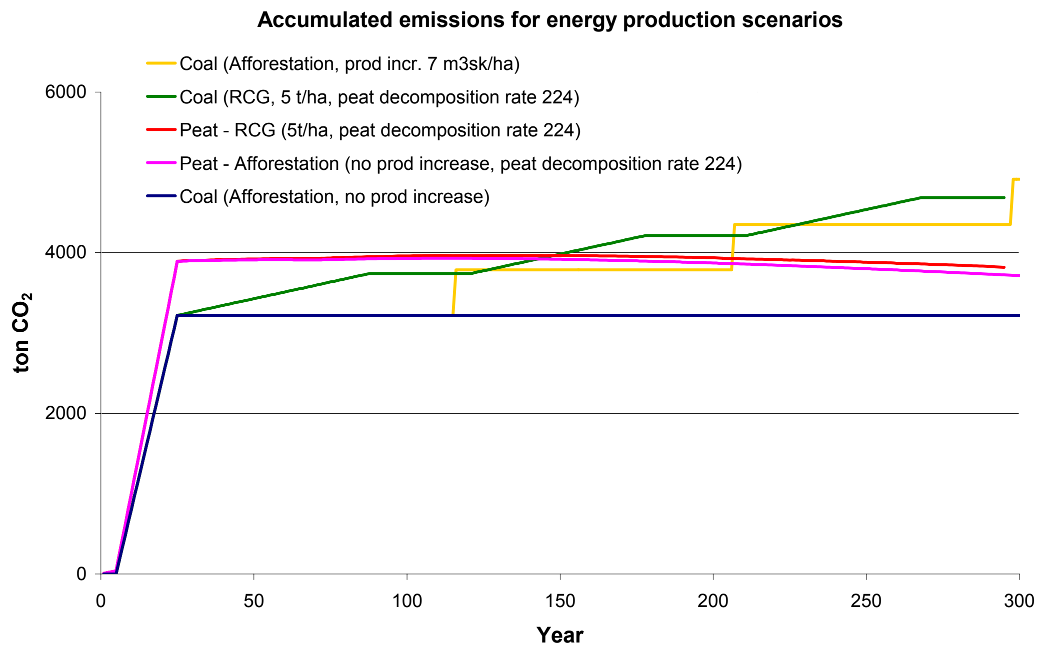

Figure 7.3 Accumulated CO_2 as distributed over time for a selection of scenarios from Figure 7.1 and Figure 7.2.

7.2 Peat – afforestation scenarios

7.2.1 The effect of forest growth

The results for the peat-biomass scenarios where the cutaway area is afforested show that initially the radiative forcing (RF), both instantaneous and accumulated, is higher than the corresponding coal scenarios (Figure 7.4 and Figure 7.5). According to Figure 7.4 it takes the entire calculation period until the instantaneous radiative forcing of the peat- biomass scenarios with a modest increase in forest productivity get to the same level as in the coal scenario. This is due to the emissions from the decomposing peat in the residual peat layer which, at least initially, are in the same range as the emissions from decomposing peat in the business as usual scenario. The period until which the climate impact is similar for the coal and the peat – biomass scenarios is the time it takes until the reduced soil emissions compensate for the higher emission factor of peat and the increased emissions during peat cutting. For instance that period is approximately 200 years for the peat – afforestation scenario with significant increase of forest productivity showed in Figure 7.5.

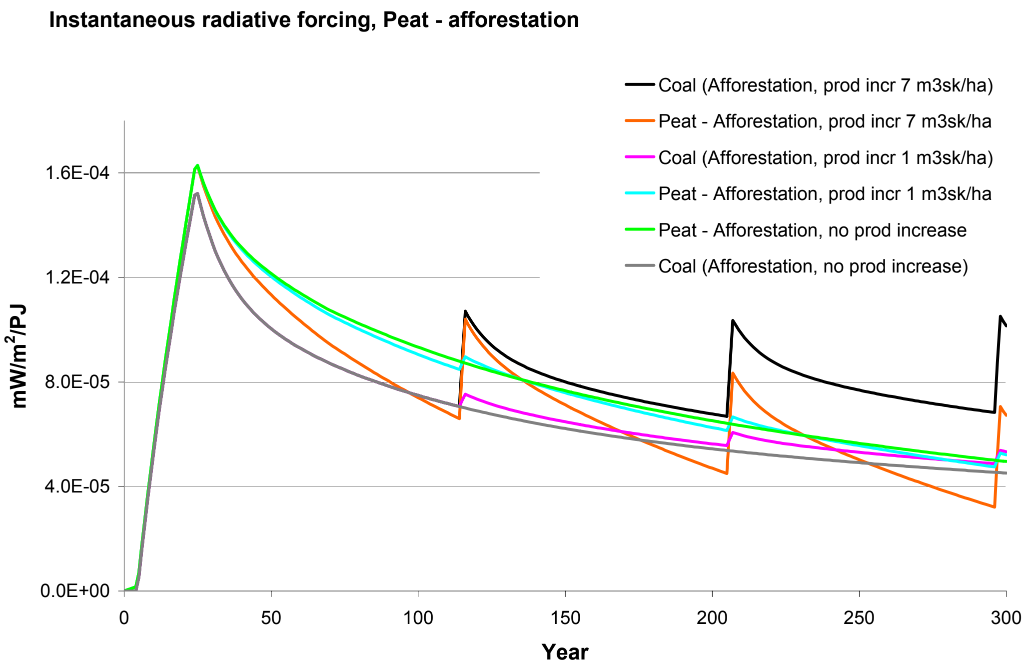

Figure 7.4 The effect of forest productivity. Instantaneous radiative forcing for scenarios with different post peat cutting forest productivity. Scenario names are explained in Table 6.2 & Table 6.6.

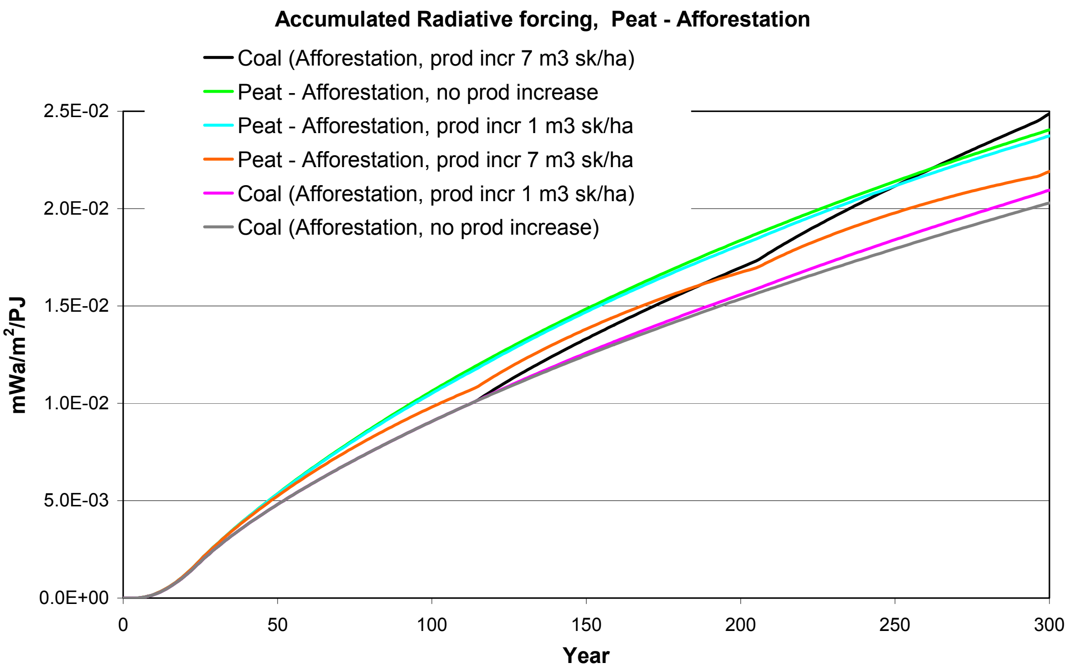

Figure 7.5 The effect of forest productivity. Accumulated radiative forcing for scenarios with different post peat cutting forest productivity. Scenario names are explained in Table 6.2 & Table 6.6.

7.2.2 The effect of peat decomposition rate

In order to also illustrate the impact of the reference scenario, a few scenarios with different initial rate of decomposition of peat at the forestry drained peatland have been calculated. The results are shown in Figure 7.6 and Figure 7.7. As can be seen in these figures, the decomposition rate has a significant impact on the climate impact of the peat scenarios. Decomposition rate 224 means emissions of 224 g CO_2/m^2yr due to peat decomposition. The values for the other two scenarios are as indicated by the names 0 g CO_2/m^2yr. and 448 g CO_2/m^2yr. respectively. The upper and lower limits of the decomposition rate are based on estimates given in Kirkinen et al (in press).

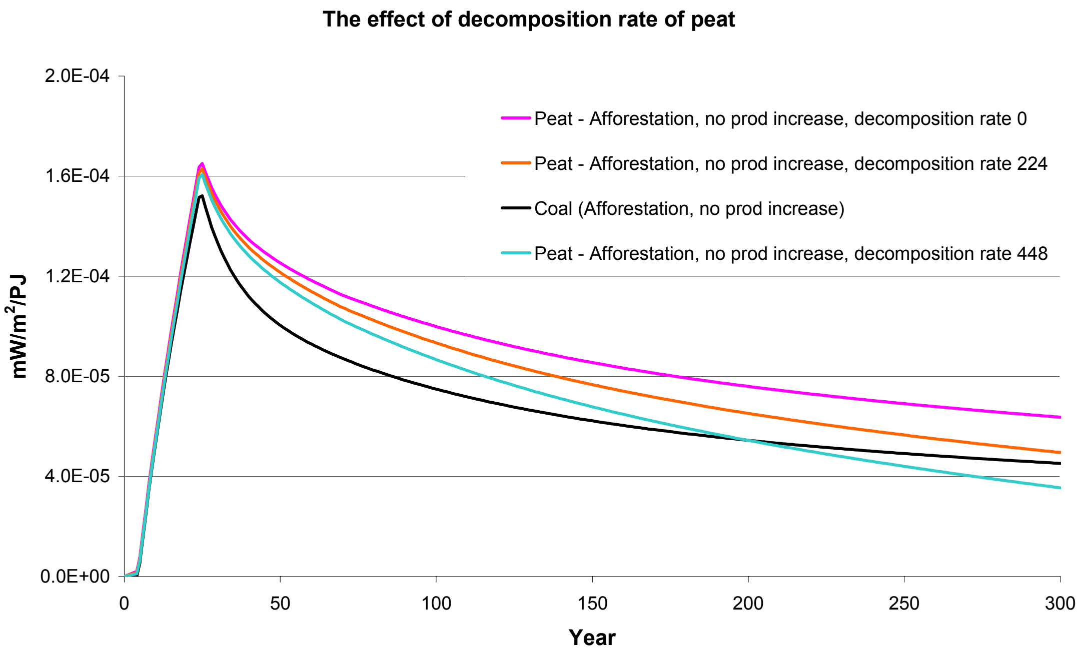

Figure 7.6 Instantaneous radiative forcing for scenarios with different initial decomposition rate of peat. For an explanation of the scenario names see Table 6.2.

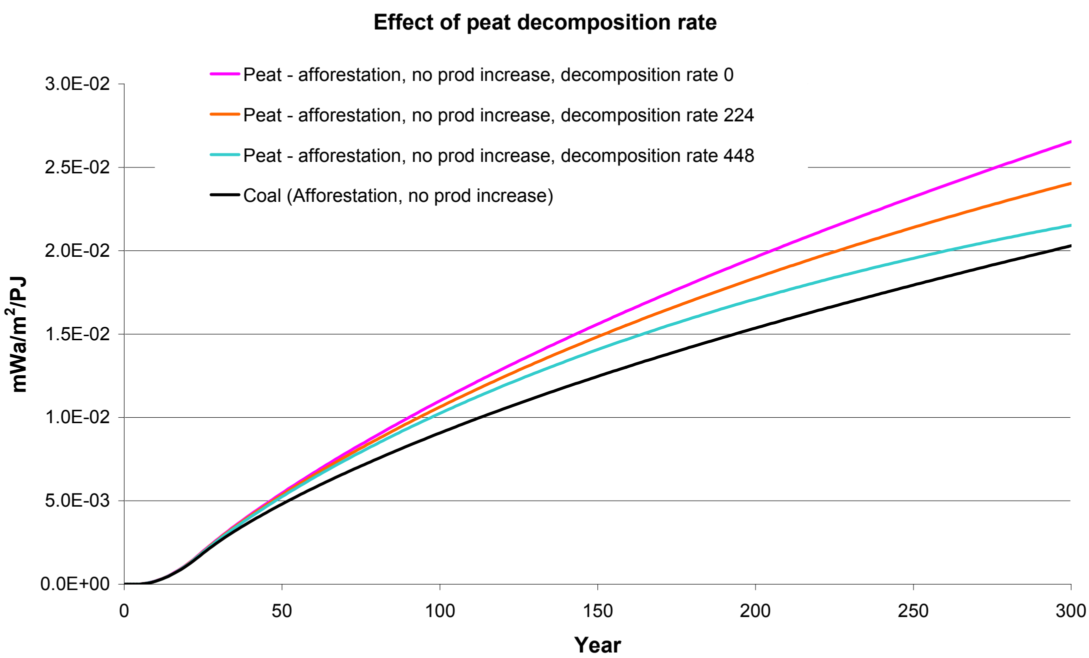

Figure 7.7 Accumulated radiative forcing for scenarios with different initial rate of peat decomposition. For an explanation of the scenario names see Table 6.2.

7.2.3 Combined effects

In order to illustrate the possible outcome of combined effects, calculations of a best-best and a worst-worst scenario for the peat – afforestation scenarios were made. In the best-best scenario (peat – afforestation 2 in Figure 7.8 and Figure 7.9) the initial forestry drained peatland has a high decomposition rate of peat (448 g CO_2/m^2yr) and the forest productivity is increased significantly after peat cutting (+7 m^3sk/ha yr.). In the worst-worst scenario (peat – afforestation 1 in Figure 7.8 and Figure 7.9) the initial forestry drained peatland has very low decomposition rate of peat (0) and the forest productivity is not changed due to the peat extraction. As can be seen in Figure 7.9 the accumulated radiative forcing in the worst-worst case is higher than the corresponding coal scenario (coal 1) whereas the best-best case energy peat scenario is lower than the corresponding coal scenario (coal 2) approximately 100 years after peat cutting.

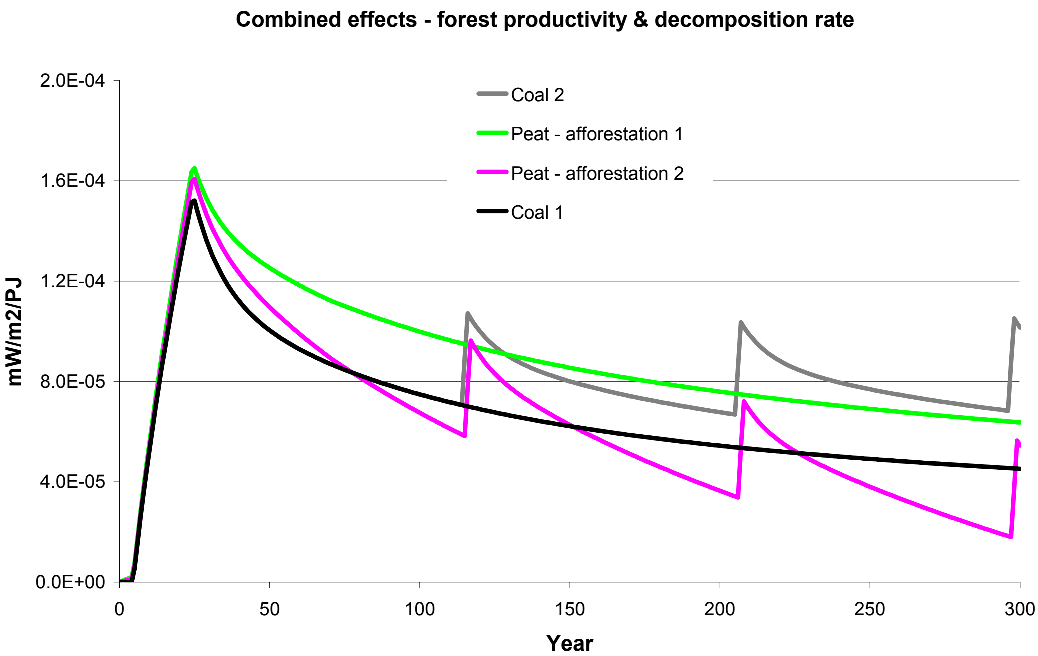

Figure 7.8 Combined effects. Worst-worst and best-best case scenarios. Compare the peat and coal scenarios with similar energy production, hence "Coal 1" with "Peat – afforestation 1" and "Coal 2" with "Peat – afforestation 2".

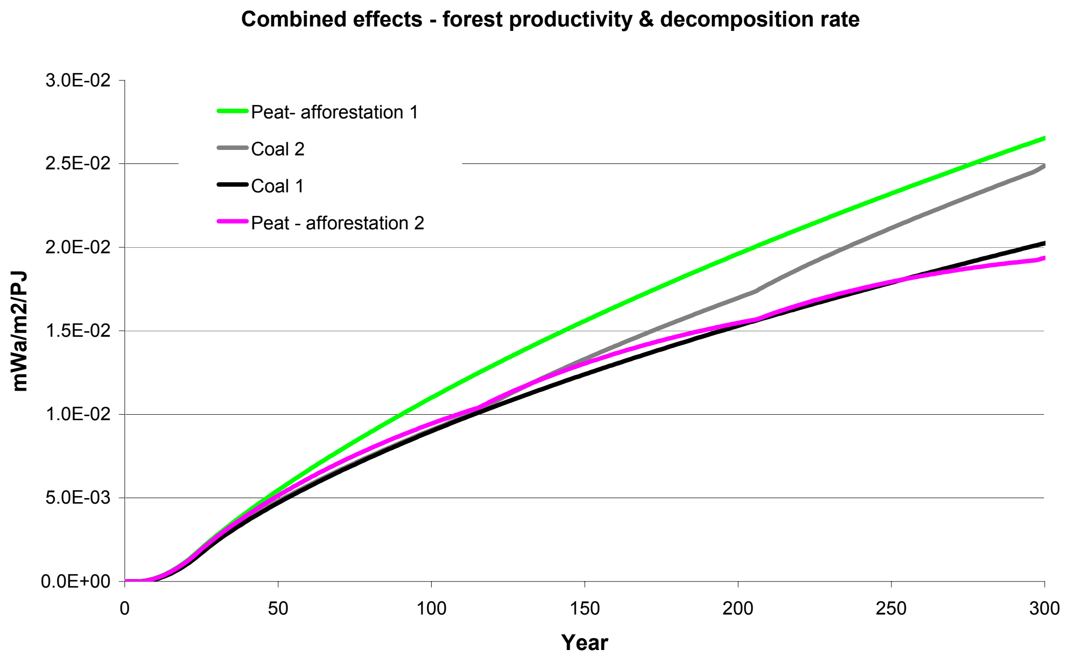

Figure 7.9 Combined effects. Worst-worst and best-best case scenarios. Compare the peat and coal scenarios with similar energy production, hence "Coal 1" with "Peat – afforestation 1" and "Coal 2" with "Peat – afforestation 2".

7.3 Peat - Reed Canary Grass cultivation scenarios

7.3.1 The effect of N_2O soil emissions

Figure 7.10 and Figure 7.11 show the scenarios with different levels of N_2O emissions from the reed canary grass cultivation. (The three levels are 0.3, 0.5 and 1.0 g N_2O/m^2 yr. respectively). If cultivation of the cut-away area leads to significantly increased N_2O emissions from the soil, this will have some impact on the overall climate impact of the peat-biomass scenarios.

As can be seen in Figure 7.10, approximately 125 years after peat cutting (year 140) the instantaneous radiative forcing of the peat – biomass scenarios is lower than the corresponding coal scenarios. The reason is that the reed canary grass scenario has a higher yield of energy than the reference scenario. In the utilisation of reed canary grass, CO_2 emissions caused by combustion is compensated (every year) by the uptake in the growing field. Since the coal scenario produces the same amount of energy as the peat- biomass scenario, additional production leads to higher climate impact. Figure 7.11 shows that it takes approximately 250 years after peat cutting until also the accumulated radiative forcing of the peat- biomass scenarios is in the same ranges as the coal scenarios. This shows that it is of importance when in time emissions are made since the gas remains in the atmosphere for a long time.

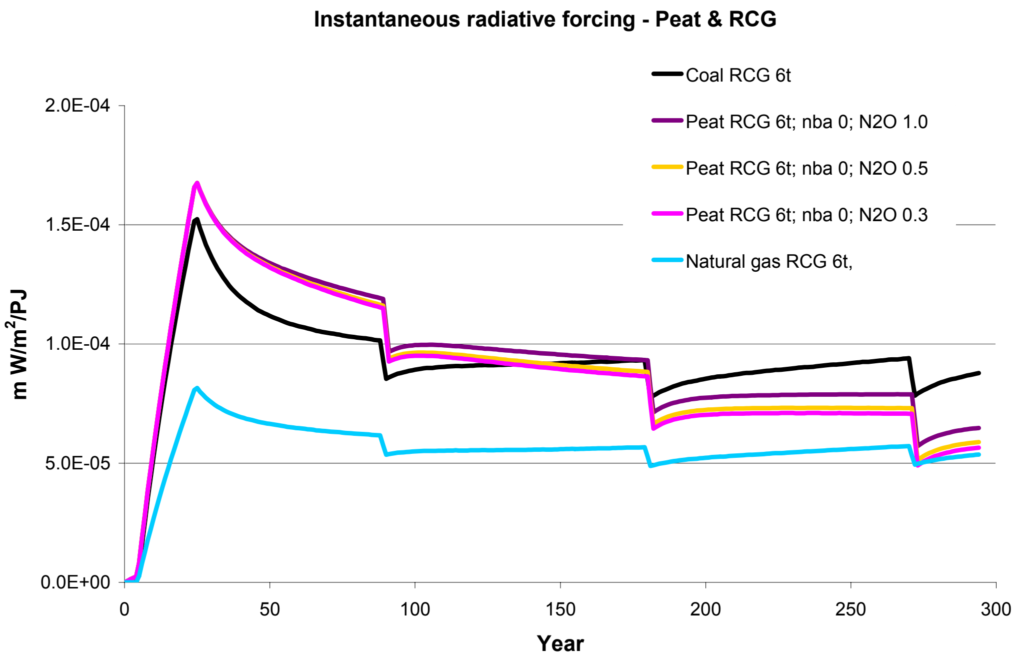

Figure 7.10 Three peat-cutting scenarios with different levels of N_2O emissions from the reed canary grass field. As comparison the corresponding energy producing scenarios by coal and natural gas are shown. Scenario names are explained in Table 6.5.

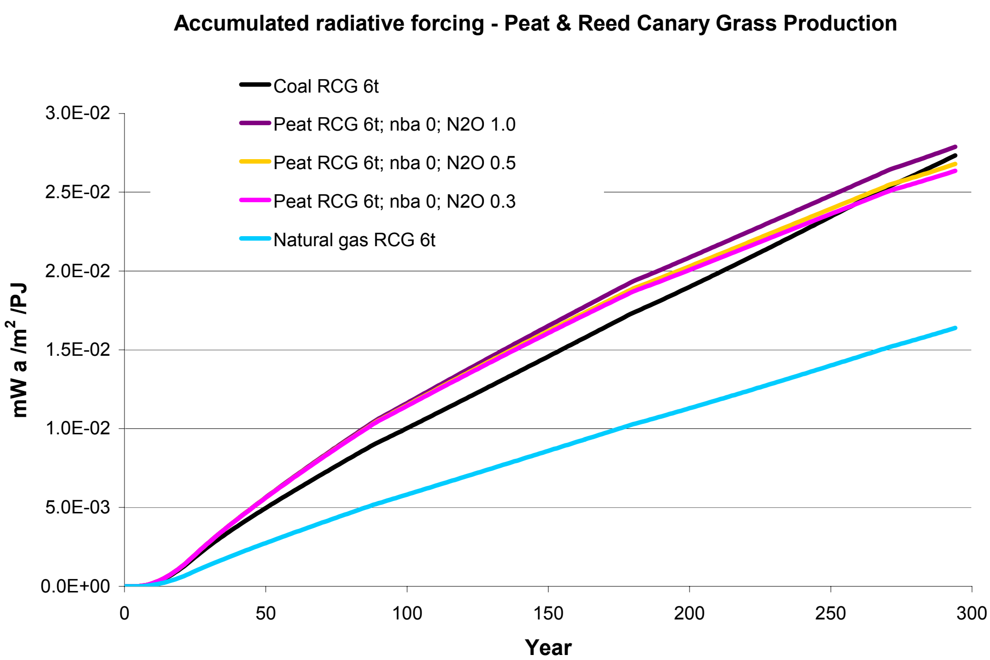

Figure 7.11. Accumulated radiative forcing for three peat-cutting scenarios with different levels of N_2O emissions from the reed canary grass field. As comparison the corresponding energy producing scenarios by coal and natural gas are shown. Scenario names are explained in Table 6.5.

7.3.2 The effects of below ground biomass accumulation and increased soil respiration

Figure 7.12 and Figure 7.13 show the effect of different assumed impact of the RCG cultivation on the carbon sequestration in the soil (the combined effect of below-ground biomass accumulation and the increased soil respiration). In the "nba 0" scenario it is assumed that the cultivation of RCG does not affect the decomposition of the residual peat and no extra carbon is sequestered in the below-ground biomass[7]. In the scenario with "nba –105" the RCG cultivation is assumed to result in a net accumulation of 105 g C/m^2 yr. in below-ground biomass. In the scenario with "nba +105" the RCG cultivation is assumed to result in an increased soil respiration of 105 g C/m^2yr.

The instantaneous RF of the peat – biomass scenarios in Figure 7.12 is initially higher than the coal scenario, but approximately 75-150 years after peat cutting they are in the same range or lower. The accumulated radiative forcing of these scenarios (presented in Figure 7.13) is lower than the coal scenarios after long time (300 years). However the scenario where the cutaway field will have a higher soil respiration rate the climate impact will be higher than the corresponding scenario for coal. For the scenario where the cutaway field will be sequestering carbon the climate impact will already after 150 years have lower climate impact (accumulated RF) than the corresponding coal scenario. The level of N_2O emissions in these scenarios were chosen to 0.3 g /m^2a since the only reference on emissions from reed canary grass cultivation gave this value (Ulff, 2005). Since the scenarios were calculated in order to show the effect of carbon sequestration, choosing a higher level of N_2O emissions would only have resulted in higher climate impact for all peat scenarios, still showing the same relative effect due to differences in the carbon sequestration rate.

Figure 7.12 and Figure 7.13 show that a changed net below-ground accumulation of carbon has a significant effect on the resulting climate impact. An increase results in lower climate impact whereas a decrease (net loss of soil carbon) results in higher climate impact.

[7] We called this impact net below-ground accumulation = nba.

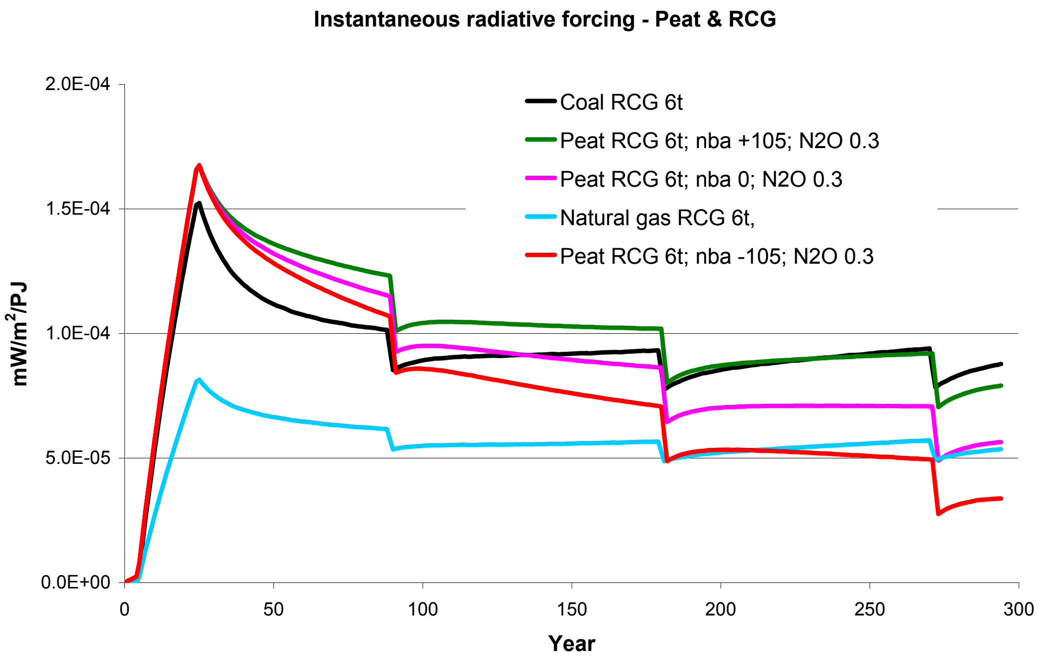

Figure 7.12 The effect of below-ground biomass accumulation. Instantaneous radiative forcing for scenarios where RCG cultivation has different impact on below-ground carbon sequestration. For an explanation of scenario names see Table 6.5.

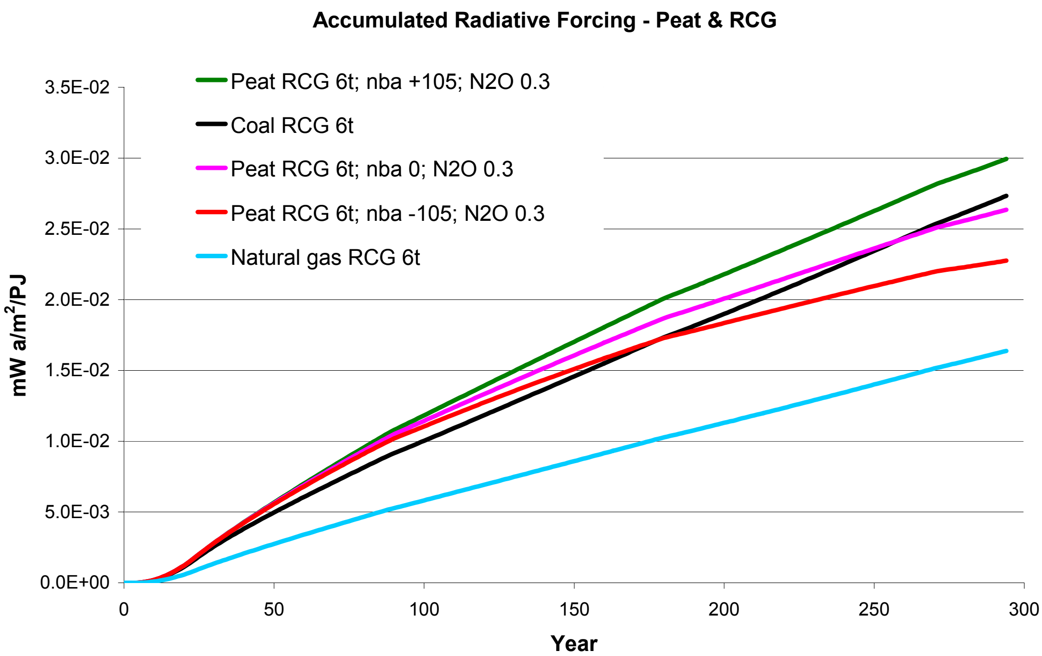

Figure 7.13 The effect of below-ground biomass accumulation. Accumulated radiative forcing for scenarios where RCG cultivation has different impact on below-ground carbon sequestration. Scenario names are explained in Table 6.5.

7.3.3 The effect of annual yield in RCG production

Figure 7.14 and Figure 7.15 show that the amount of energy produced by the reed canary grass cultivation has a significant impact on the comparative fossil fuel scenarios.

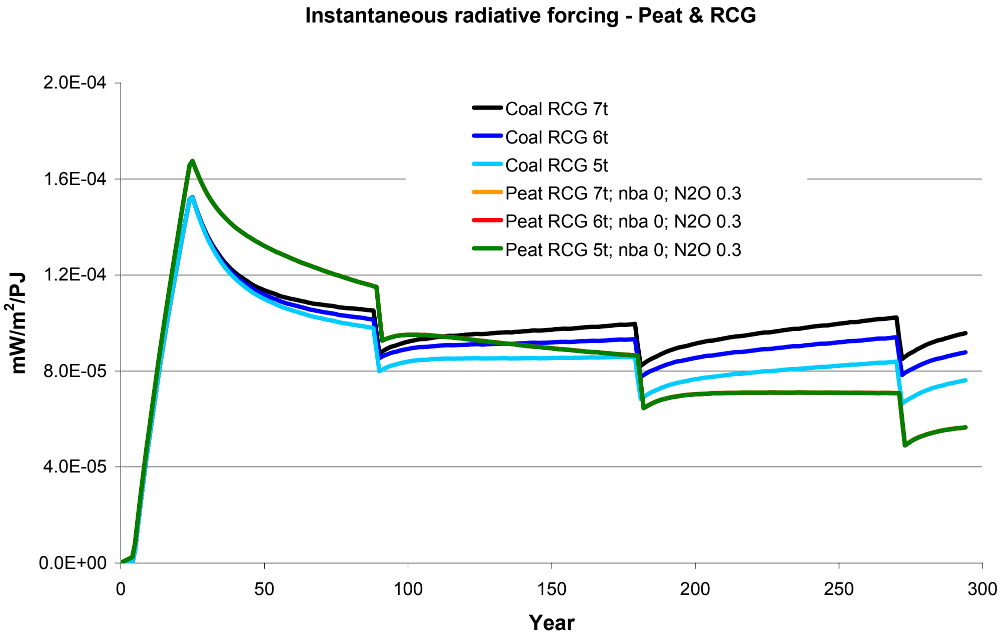

Figure 7.14 The effect of RCG yield. Instantaneous radiative forcing for scenarios with different yield of RCG. Scenario names are explained in Table 6.5. All peat scenarios have similar values of radiative forcing and hence the green scenario is covering the red and the orange scenarios respectively.

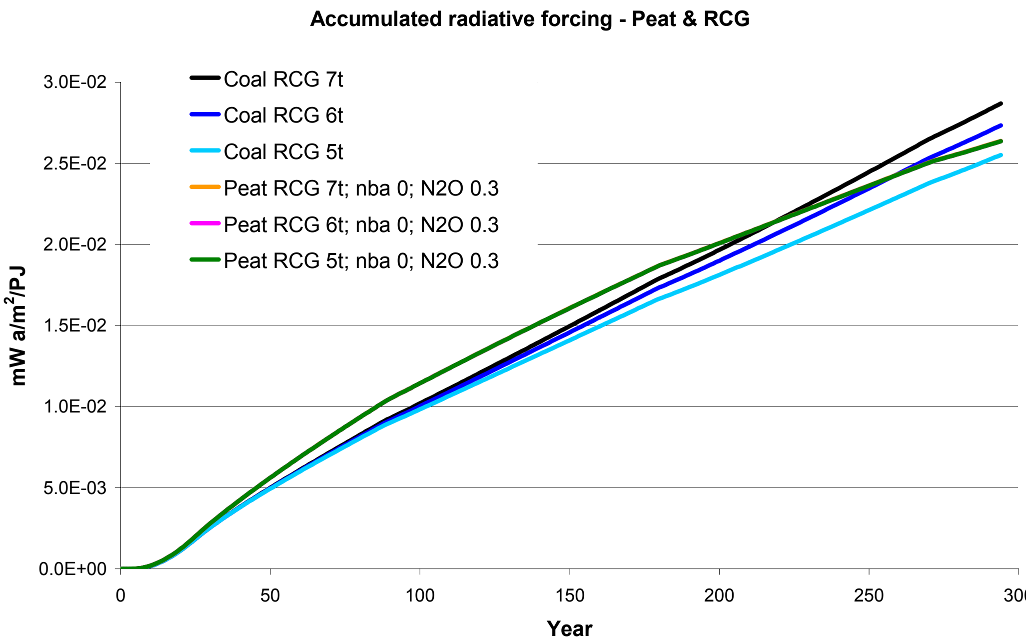

Figure 7.15 The effect of RCG yield. Accumulated radiative forcing for scenarios with different yield of RCG. Scenario names are explained in Table 6.5. All peat scenarios have similar values of radiative forcing and hence the green scenario is covering the red and the orange scenarios respectively.

The instantaneous radiative forcing of the peat – biomass scenarios in Figure 7.14 will be lower than the coal scenario approximately 100-150 years after peat cutting. Figure 7.15 shows that it will take long time (almost the entire calculation period) until also the accumulated RF of the peat – biomass scenarios will be similar or lower than the coal scenarios.

7.3.4 Combined effects

In order to illustrate the possible outcome of combined effects, calculations of a best-best and a worst-worst scenario for the peat – RCG utilisation chain was made. In the best-best scenario ("Peat – RCG 4", in Figure 7.16 and Figure 7.17) the initial forestry drained peatland has a high decomposition rate of peat (448 g CO_2/m^{2}yr) and the yield of the RCG will be high (7t dry matter/ha). In the worst-worst scenario ("Peat – RCG 3" in Figure 7.16 and Figure 7.17) the initial forestry drained peatland has very low decomposition rate of peat (0) and the RCG yield is low (5t dry matter/ha). As can be seen in Figure 7.16 the radiative forcing in the worst-worst case is higher than the corresponding coal scenario ("coal 3") during almost the entire calculation period whereas the best-best case energy peat scenario (pink) is lower than the corresponding coal scenario ("coal 4") already 50 years after peat-cutting. According to Figure 7.17 the accumulated radiative forcing in the worst-worst case will be higher than the coal scenario throughout the calculation period. For the best-best scenario the accumulated radiative forcing will be lower than the coal scenario approximately 150 years after peat cutting.

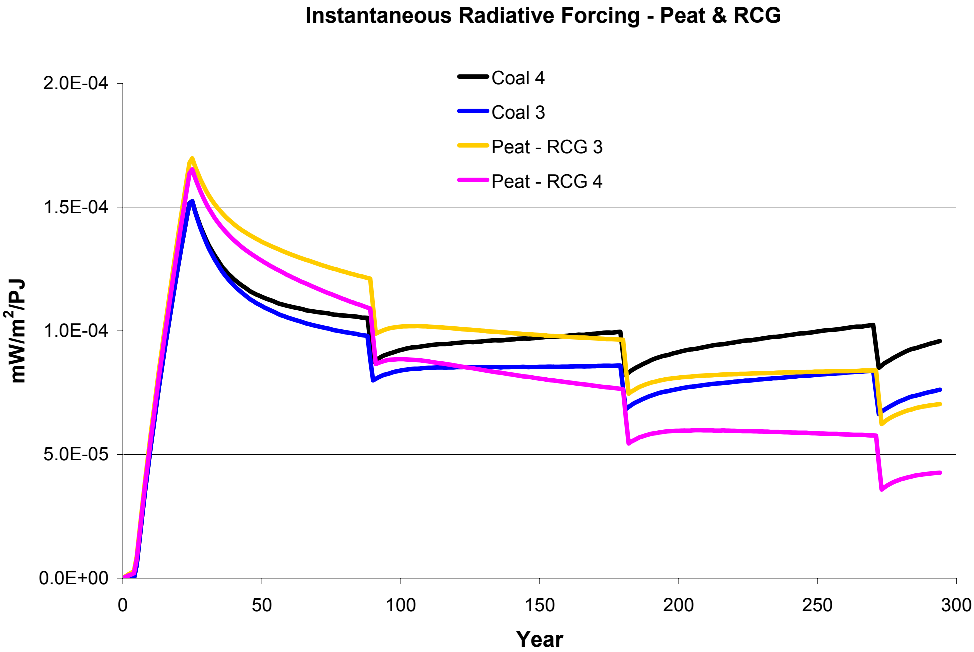

Figure 7.16 Combined effects. Worst-worst and best-best case scenarios. Compare the peat and coal scenarios with similar energy production, hence "Coal 3" with "Peat – RCG 3" and "Coal 4" with "Peat – RCG 4".

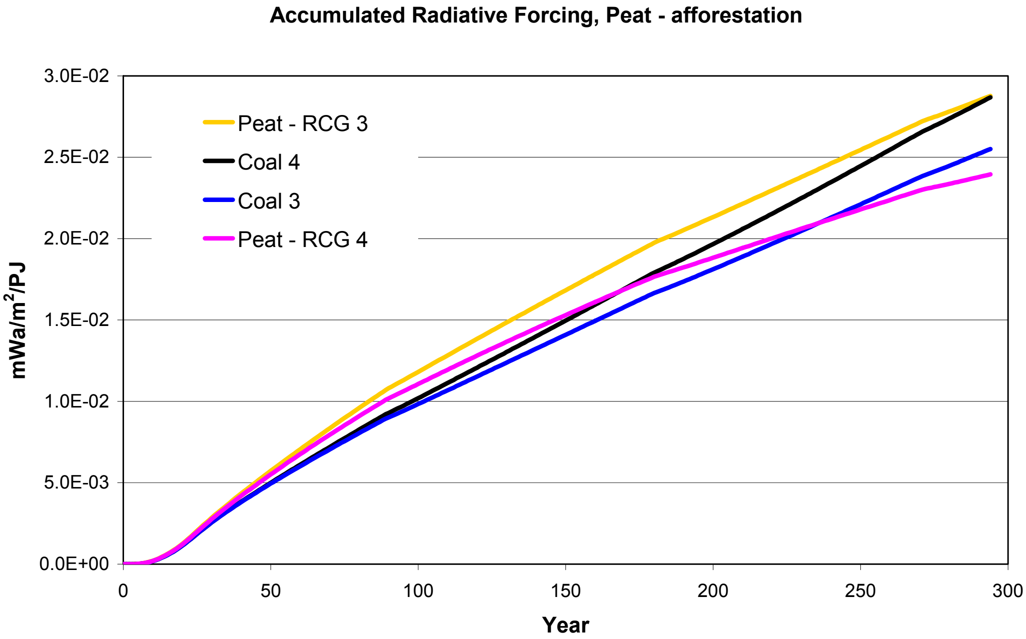

Figure 7.17 Combined effects. Worst-worst and best-best case scenarios. Compare the peat and coal scenarios with similar energy production, hence "Coal 3" with "Peat – RCG 3" and "Coal 4" with "Peat – RCG 4".

8 Discussion

8.1 Forest scenarios

Our results show that the peat cutting scenarios where the cutaway peatland can be used for producing substantial amounts of biomass fuel, are more favourable (from a climate impact point of view) then scenarios where the potential for biomass fuel production is lower. In the scenarios where afforestation is the aftertreatment method only those with substantially increased forest productivity after peat cutting will result in more favourable scenarios than coal scenarios and first after long time the climate impact of them will be lower.

Our results also show that the higher the emissions from the initial forestry drained peatland, the lower the climate impact of the peat- biomass scenario. We have used the estimates of CO_2 emissions from forestry drained peatlands due to decomposition of peat as made by Finnish researchers for Finnish conditions. However, estimates for Swedish conditions used in Nilsson & Nilsson (2004) were significantly higher, resulting in lower climate impacts of the peat scenarios. There is still some uncertainty of the reason for this great difference. Explanations mentioned are different management methods (ditching techniques) and differences in how to estimate the litter production. Since the peat decomposition is not measured directly but indirectly by measuring soil emissions, other inputs and outputs have to be estimated. This is mainly made by models.

The forest productivity of both the forestry-drained peatlands and the cut-away peatlands can be discussed. According to Hillebrand (1993) the Finnish forests produce on average of 3.4 m^3 sk/ha of stem wood annually (includes both forestry-drained peatlands and mineral soil forest). In this average the total forested area in Finland is included; also the northern parts with low-productivity sites. This value is close to the value we have used in this study (3.9 m^3 sk/ha). One can argue that the forest productivity of forestry drained peatlands in southern Finland actually might be higher due to better climate conditions. On the other hand the average is based on both forestry drained peatlands and mineral soil forests so it might still be a good estimate.

Concerning the forest productivity we have not considered the possibility to also use logging residues from the afforested area for biofuels due to a couple of reasons;

i) if we would consider the energy content in the forest residues that should be done both for the pre peat cutting forest and the post peat cutting forest. If there is no increase in productivity there will be no difference to current scenarios. If there is an increase in productivity the amount of forest residues will most likely also increase, resulting in a somewhat larger difference in energy production between pre peat cutting and post peat cutting. This effect will probably be small and our general conclusions concerning the effect of increased productivity will still be valid.

ii) If logging residues are removed from an area it is important to secure the nutrient supply of the site, so that it is not depleted. If logging residues are used, fertilisation or recycling of ashes could be used in order to avoid soil depletion. If either of these options is used we also need to consider the energy input for spreading fertilisers/ashes. We have not taken these options directly into consideration in our scenarios but the main results of increased forest productivity have been shown.

Figure 7.4 and Figure 7.5 show the effect of increased forest productivity at the cutaway area. An instant reflection could be to ask: Why does the bio-fuel production have such a low impact on the climate impact of the peat –biomass scenarios? First of all we have to remember that it is only the increase in forest productivity that is taken into account since we have assumed that there is some forest productivity also in the business as usual scenario. The CO_2 emission factor for peat is 105.9 g CO_2/MJ, whereas the emission factor for coal is 95.18 g CO_2/MJ, an approximate difference of 10%. In the scenarios where the biofuel production is increased by 1 m^3sk/ha, an extra amount of 78 MJ/m^2 is produced every 90 years. During the peat producing period 3400 MJ is produced. 10% of 3400 is 340 MJ, which means that more than 4 forest rotations is needed before the extra production of biomass can compensate for the higher emission factor of peat. If the increase in forest productivity is 2 m^3sk/ha this means that just over two rotation periods are required in order to compensate for the higher emission factor.

Another positive effect of the peat - biomass scenario is that the leakage of CO_2 from the forestry-drained area is disrupted. The significance of this effect on the overall climate impact can be explained by the following. The annual leakage of CO_2 from the forestry-drained area is approximately 224 g CO_2/m^2. During 100 years this leakage results in 22 kg CO_2/m^2. Burning of peat from one 1 m^2 during 20 years results in 358 kg CO_2. Burning the corresponding amount of coal results in 322 kg CO_2 Removing the peat by harvesting will indeed increase the rate of decomposition during harvesting but after harvesting the emissions will decrease. During the first 100 years after peat cutting the emissions from decomposition from residual peat is estimated to 32.7 kg CO_2/m^2a. This means that cutting the peat will initially not reduce the soil emissions but rather increase them by 10 kg CO_2/m^2 during the first 100 years[8]. This also indicates that removing as much as possible of the peat layer, leaving as little as possible will reduce the climate impact. However, it is important to leave enough peat for sustaining high potential of forest productivity. Kirkinen et al (in press) has showed the impact on the climate impact of minimising the amount of residual peat.

The calculations of the climate impact of peat cutting at forestry drained peatlands made by Kirkinen et al (in press) showed that these scenarios had a larger climate impact than coal. Hence for our scenarios where the productivity of the cutaway area is limited compared to the initial area the results are similar.

In this study we have considered both the peat cutting and the biomass production in the same scenario. But what would be the effect if the peat was not cut and the biomass production could be increased anyway? For example it might be possible to increase the forest productivity of a forestry-drained site with peat qualities not suited for energy production and hence have a scenario where the peat is left. This could (theoretically) be done by remedial drainage, cleaning of ditches, fertilisation, re-circulation of wood ashes etc.

In this study we have only made calculations for cases of after-treatment where the forest production could be increased. Of course this demands some properties of the soil and the area. It is important that enough peat is left so that the need for nitrogen of the new forest is covered. On the other hand the peat layer should be shallow enough so that the trees could reach the mineral soil in order to cover the supply of other important nutrients. Of course also the hydrology of the after treated area is very important. If it will not stay naturally drained, one might have to consider other emissions in the stage of after-treatment (i.e. if pumping or other artificial strategies would be needed). Neither have we included any possible need for fertilisation not at the initial area nor at the after-treated area (in case of afforestation). To include the emissions connected to utilisation of fertilisers would not have a significant impact on the overall result. Of course going from a state where fertilisation is required to a state where it is not, is an improvement whereas the opposite situation is a worsening from at climate point of view. Measurements of forest productivity at cut away peatlands show higher average values than productivity at forestry drained peatlands (Leiviskä, 2004), which might indicate that the productivity in general can be increased. According to Hånell (1997), it is reasonable to assume that the forest productivity at low productive forestry drained peatlands can be increased after peat cutting. However measurements of forest productivity should be done both before and after peat cutting at the same site in order to determine the average increase of forest productivity.

8.2 Reed Canary Grass scenarios

As mentioned we have assumed that reed canary grass will be cultivated continuously during the entire study period (300 years). Although we consider that the field will have to be renewed every 10 years, the assumption of such a long crop rotation is very theoretical. The reason for using the assumption was mainly to show the effect of a fast growing energy crop that would give higher yield than forestry.

Our results show that the peat cutting scenarios where we can use the cutaway land to produce substantial amounts of biomass fuel, are more favourable (from a climate impact point of view)

[8] Note that if the initial decomposition rate of the peat is higher, e.g. 448 g CO_2/m^2yr there will be a reduction of the soil emissions already during the first 100 years.

compared to scenarios where no or just limited amounts of biomass fuels can be produced. The uncertain factors such as the impact on N_2O emissions due to cultivation of the cutaway and the impact on soil sequestration of carbon have significant impact on the results. Both these factors need further investigation. There is ongoing research in this area and first results will soon be available.

It is important to remember that it might be possible to change the land-use of forestry drained peatland without cutting the peat. The effect compared to the reference scenario will be similar as in the peat-biomass scenarios. The difference between a scenario where the land-use of the forestry drained peatland is changed and a scenario where the peat is cut is that the peat can replace coal in the peat-cutting scenario. In the land-use change scenario, there will be emissions due to the decomposition of the peat but no energy produced.

8.3 General

We have in this study, like Kirkinen et al (in press) not considered the effect of N_2O emissions from forestry drained peatlands. According to von Arnold (2005a) & (2005b), the N_2O emissions from forestry drained peatlands, especially at rich sites can be substantial. We know that removing the peat will also diminish the CO_2 emissions from these sites but we know little about the N_2O balances of afforested cutaway peatlands. This is something that should be investigated further.

9 Conclusions

9.1 Forest scenarios

If there is no increase in forest productivity due to peat cutting, the climate impact of the peat-afforestation scenarios will be higher than the coal scenario during the whole study period (300 years). If the forest productivity is significantly increased after the peat cutting, the climate impact of the peat – biomass scenario is somewhat higher than that of corresponding coal scenario during the first 100-200 years and then somewhat lower, how much lower depends on how much the forest productivity is increased. How long time it will take until the climate impact of the peat - afforestation scenario is lower than the coal scenario depends on the size of the productivity increase. However, even if the increase of the productivity is large, it will still take at least one rotation period (~90-100 years after peat cutting) for the instantaneous radiative forcing to be lower. If the productivity is decreased due to the peat cutting the conditions will be reversed. It can also be concluded that peat reserves with high initial CO_2 losses (high decomposition rate) will result in lower climate impact compared to peatlands with small initial CO_2 losses.

9.2 Reed Canary Grass Scenarios

Cultivating reed canary grass at the after-treated area results in a potentially higher energy production than the reference case. In the long run this means a lower climate impact compared to coal than the peat – afforestation scenarios, if not soil emissions are increased due to the cultivation.

If the N_2O emissions are increased significantly due to the cultivation this will increase the climate impact of the peat- RCG scenario. What the N_2O emissions will be on this type of land is not very well known, however in general there is a risk for increased N_2O soil emissions due to fertilisation and working of the ground.

The effect on below-ground litter accumulation and increased soil respiration in RCG cultivation at cut away peatland is very important and is poorly known. The results of this study show that whether the RCG cultivation will lead to increased carbon sequestration or increased rate of soil respiration will have a significant impact on the climate impact of the peat – RCG scenarios. If RCG cultivation will lead to increased carbon sequestration the climate impact will be reduced.

The effect of yield has not a substantial impact on the climate impact from the peat - RCG scenario, but it has impact to the relative difference of the fossil scenarios (since less energy is produced if there is a lower annual yield of RCG). Hence a higher yield results in relatively lower climate impact compared to the coal scenario.

In general the climate impact of the peat – RCG cultivation scenarios have somewhat higher climate impact than the corresponding coal scenario during at least the first 150 years after peat cutting (depending on yield, impact on soil carbon sequestration and N_2O emissions due to the cultivation). In the best-best case scenario where the initial forestry drained area has high emissions of CO_2 and the yield of RCG is high, the climate impact of the peat – RCG scenario gets lower than the corresponding coal scenario after approximately 150 years.

10 Further research

There are important factors with direct impact on our results that we recommend are investigated further. These further investigations include measurements to determine greenhouse gas balances in the following areas:

1. There seem to be some uncertainty in determining the CO_2 emissions from forestry drained peatlands. Especially in the estimates of litter production and decomposition. This is an important factor and has to be investigated further.

2. N_2O emissions at afforested cutaway peatlands. We know today that forestry drained peatland with low CN-ratio (rich sites) emit large amounts of N_2O (von Arnold 2005a & 2005b). What happens to those emissions after the peat is cut away? Will the N_2O emissions still stay at high levels or will they be reduced substantially?

3. N_2O emissions at cutaway peatlands used for biofuel cultivation (reed canary grass, or other energy crops with short rotation period). It is known that drained peatlands used for agriculture are large sources of N_2O emissions. What will happen with the emissions of N_2O at cutaway sites that are used for energy crop cultivation?

4. Below-ground litter accumulation and soil respiration in RCG cultivation at cutaway peatlands is poorly known. Research results is underway but research probably need to be carried on for longer time periods.

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Appendix 1

Input data used in this study

Forestry-drained peatland

Emissions from oxidation of peat due to drainage:

Carbon dioxide	CO_2	224 g/m²yr-	based on Kirkinen et al 2006
(variation)	CO_2	448 g/m²yr.	
(variation)	CO_2	0 g/m²yr.	

Uptake of carbon in growing forest:

Carbon dioxide	CO_2	-448 g/m²a	based on Kirkinen et al (in press)

Total emissions

Carbon dioxide	CO_2	-224	g/m²a
(variation)	CO_2	0	g/m²a
(variation)	CO_2	-448	g/m²a
Methane	CH_4	0	g/m²a
Nitrous oxide	N_2O	0	g/m²a

Peat Utilisation

Emissions of peat production field

Emissions during drainage period (5 years prior to peat cutting)

Carbon dioxide	CO_2	1000 g/m²	Uppenberg et al 2004.

Emissions during cutting	Average	Unit	Corresponding	Source
Carbon dioxide, CO_2	6.84	g/MJ	(1157.3 g/m²yr)	Kirkinen et al (in press)
Methane, CH_4	0.0039	g/MJ		Kirkinen et al (in press)

Emissions of peat stockpile

Carbon dioxide	CO_2	1.48	g/MJ	(250.4 g/m²yr)	Kirkinen et al (in press)

Working machines

Carbon dioxide	CO_2	1	g/MJ	(169.2 g/m²yr)	Uppenberg et al.2001

Total CO_2 emissions during production phase (20 years)

Carbon dioxide, CO_2 1576.94 g/m²yr

Emissions of combustion of peat

Carbon dioxide	CO_2	105.9	g/MJ	Vesterinen 2003
Methane	CH_4	0.0085	g/MJ	Kirkinen et al (in press)
Nitrous oxide	N_2O	0.0128	g/MJ	Kirkinen et al (in press)

Final Phase

Afforestation

Sequestration of carbon to growing forest

Carbon dioxide	CO_2	-448	g/m^2a	Kirkinen et al (in press)
(variation)		-564 g CO_2/m^2a		
(variation)		-679 g CO_2/m^2a		
(variation)		-1257 g CO_2/m^2a		

Decomposition of residual peat

Amount of C is decreasing exponentially from 15 0000 g C/m^2			Kirkinen et al (in press)
Amount of residual peat	15 000	g/m^2	Kirkinen et al (in press)

Accumulation of above-ground forest litter[9]

CO_2 -147 g CO_2/m^2a (until the value 1.8 kg C/m^2 is reached) Kirkinen et al (in press)

Accumulation of below-ground forest litter

CO_2 -4 g CO_2/m^2a Kirkinen et al (in press)

Production of wood fuel (average productivity 3.9 m^3 sk/ha, rotation period 90 years).

1 620 000 MJ/ha (162 $MJ/m^2/90yr$) Olsson, R. 2006 (personal communication)

Emissions from combustion and production of coal

Carbon dioxide	CO_2	95.18	g/MJ	Kirkinen et al 2006 (in press)
Methane	CH_4	0.34	g/MJ	Kirkinen et al 2006 (in press)
Nitrous oxide	N_2O	0.002	g/MJ	Kirkinen et al 2006 (in press)

Emissions of combustion of natural gas

Carbon dioxide	CO_2	59	g/MJ	Nilsson & Nilsson 2004
Methane	CH_4	0.0028	g/MJ	Nilsson & Nilsson 2004
Nitrous oxide	N_2O	0.00056	g/MJ	Nilsson & Nilsson 2004

Reed Canary Grass Production

Sequestration of carbon
to growing biomass Since this crop is harvested annually we assume the net sequestration is 0.

Decomposition of residual peat C Amount of C is decreasing exponentially from 15 000 g C/m^2 Based on Kirkinen et al (in press)

Amount of residual peat	Average	Low	High		
	15 000	0	22500	g/m^2	Kirkinen et al (in press)

Accumulation of aboveground litter (yield)

We assume that there is no net accumulation of aboveground litter.

Base scenario 6 t dry matter/ha yr. (4 t during establishing year)

Lower scenario 5t dry matter /ha yr. (3.3 t during establishing year)

[9] Forest litter sequesters carbon until the value 1,8 kg C/m^2 is reached.

Higher scenarios 7t dry matter/ha yr. (4.7 t during establishing year)

***Accumulation of below-ground forest litter*.**	Medium	Low	High	Unit	Source
Carbon dioxide	0	105	-105	g C/m²	Huttunen et al 2004

Energy input in RCG cultivation

Carbon dioxide 3.8 g CO_2/MJ (see Table 6.4) Bullard & Metcalfe 2001 and Börjesson 1996.

Appendix 2

Time lag effect

Afforestation scenarios

The effect of time lag is shown in these diagrams, i.e. the delay of the biomass production (forest growth) due to peat cutting.

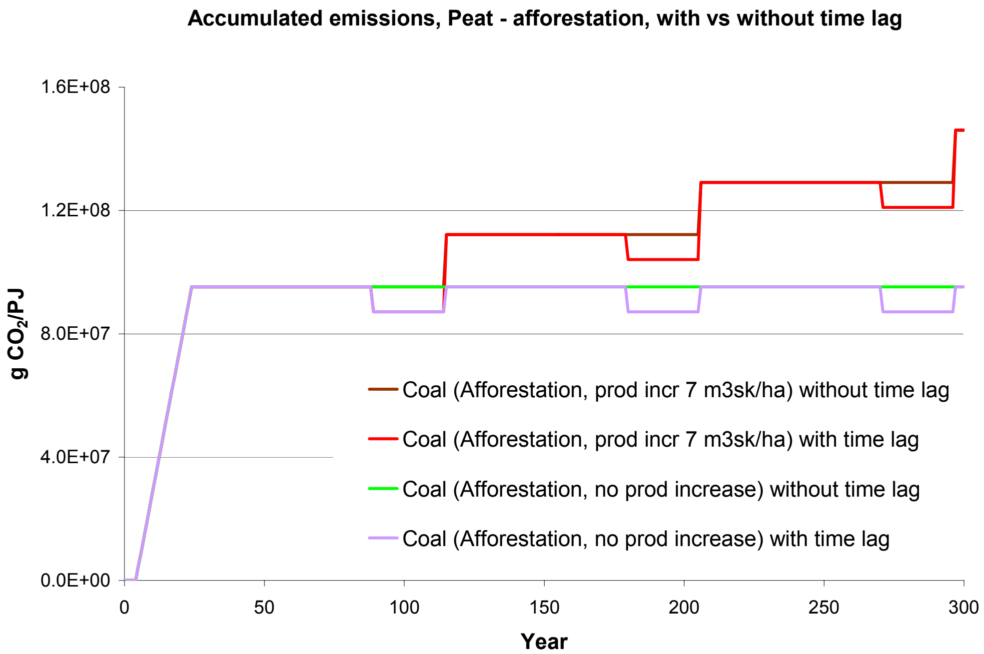

Figure 1. Accumulated emissions for coal scenarios either considering or not considering the time lag. The same amounts of emissions are emitted but the emissions are distributed differently in time.

Figure 1 shows how the CO_2 emissions are distributed in time in the different scenarios. Note that the same amount of emissions is emitted in two comparable scenarios, only the distribution in time is different. This is due to the timing of the energy production from the forest, which is delayed due to peat cutting. How this different distribution in time affects the radiative forcing (both instantaneous and accumulated) is shown in the two figures below. The table in this section shows the energy production distributed in time for the different scenarios.

Table 1 Energy production in coal scenarios

Scenario	Year	Energy production [MJ/m^2 yr.]
Coal (Afforestation, no prod. increase)	0-5	0
. with time lag	6-25	169.2
.	26-89	0
.	90	-288
.	91-115	0
	116	288
Coal (Afforestation, no prod. increase)	0-5	0
. without time lag	6-25	169.2
.	26-115	0
.	116	0 (=-288+288)
Coal (Afforestation prod. incr. 7 m3sk/ha)	0-5	0
. with time lag	6-25	169.2
.	26-89	0
.	90	-288
.	91-115	0
.	116	891
Coal (Afforestation prod incr. 7 m3sk/ha)	0-5	0
.without time lag	6-25	169.2
.	26-115	0
.	116	603 (=891-288)

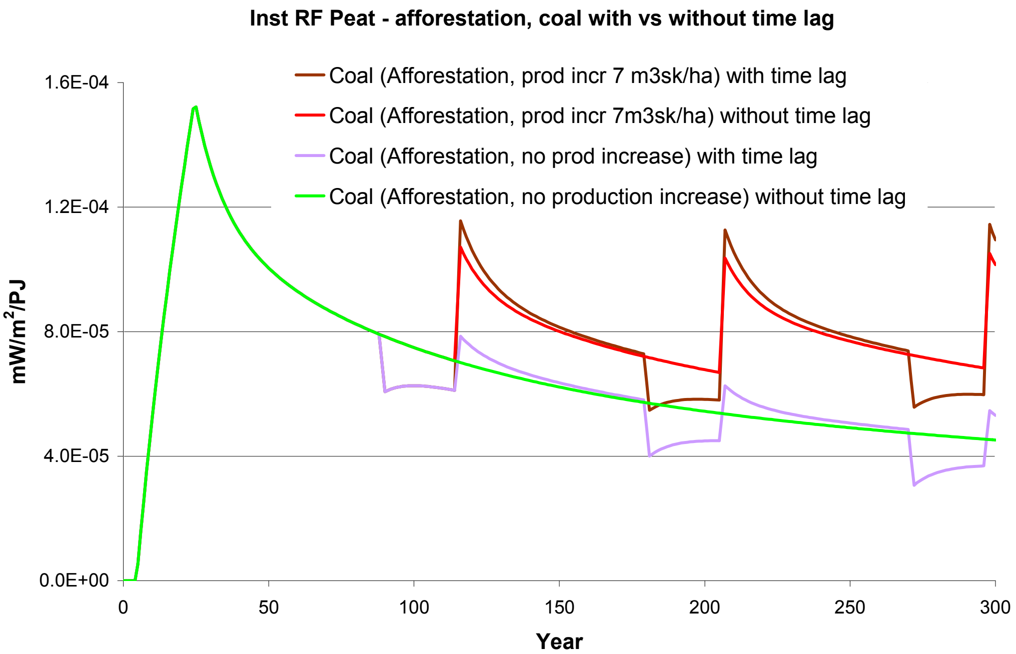

Figure 2. Instantaneous radiative forcing for the coal scenarios being substitute to peat cutting scenarios followed by afforestation.

In Figure 2 the two sets of peat- afforestation scenarios where coal is used instead of peat cutting is presented. The only difference between the scenarios is that in the ones where indicated the time lag in forest growth caused by the time needed for the peat cutting is considered. This result in the energy being produced at different times. Figure 3 shows the accumulated radiative forcing for the same scenarios and hence the accumulated effect.

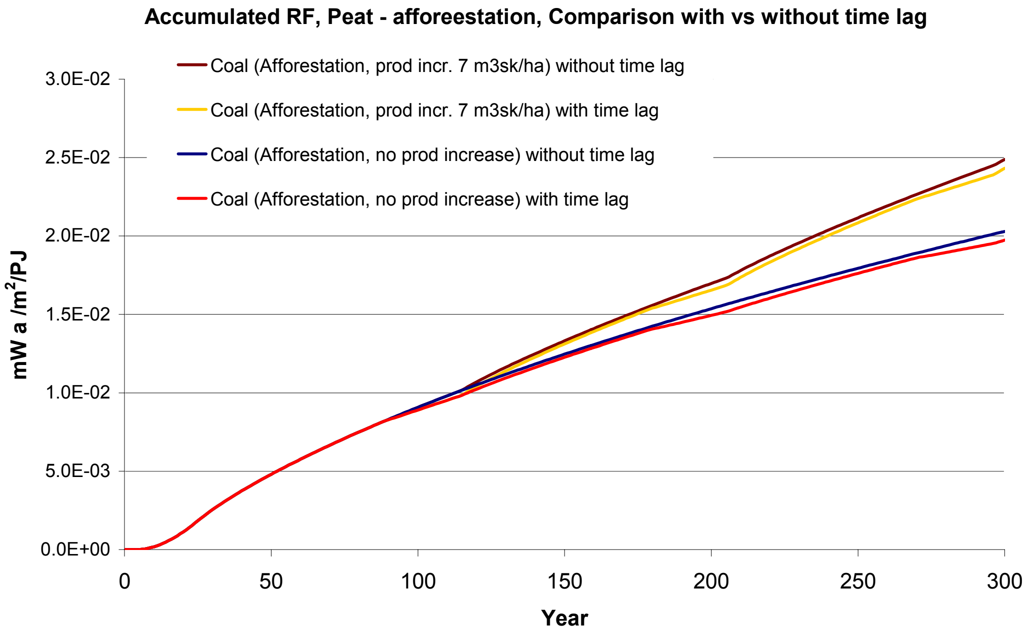

Figure 3. The effect of time lag. Accumulated radiative forcing either considering or not considering the time lag of the energy production.

The impact is getting larger and larger for each rotation. The relative difference is also larger where the lagged production relatively larger compared to total production. The climate impact is lower in the scenarios where the time lag is considered.

Reed Canary Grass Scenarios

The effect of time lag of emissions is shown in Figure 4 and Figure 5, i.e. the effect of the delay of the biomass production due to the peat cutting.

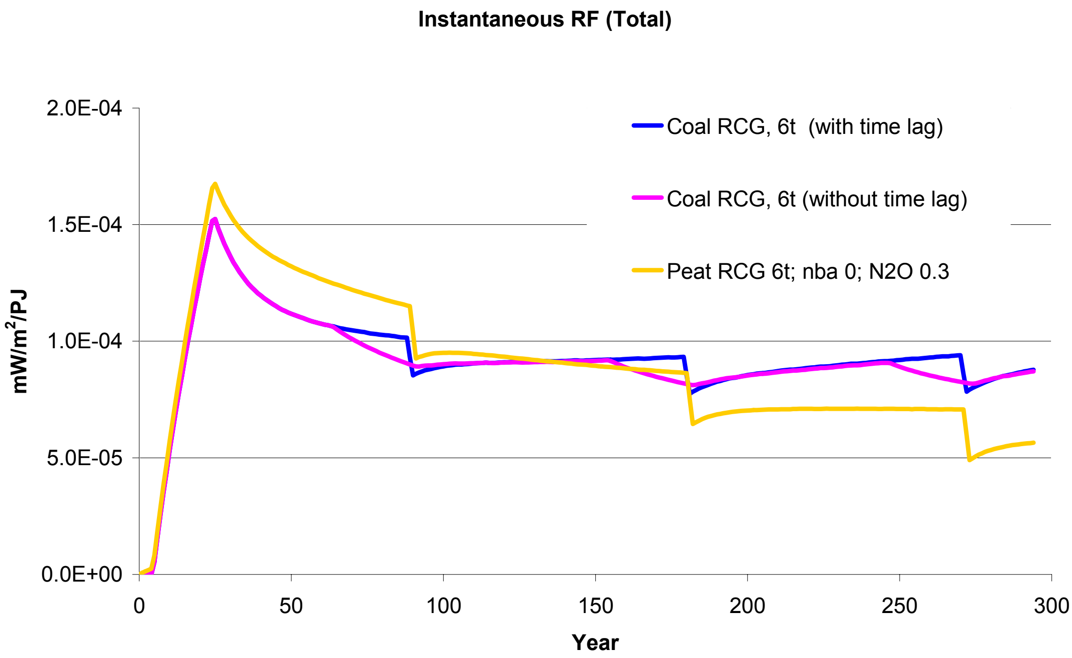

Figure 4. The two coal scenarios produce the same amount of energy only at different points in time

According to figure 4 there is some difference in radiative forcing between scenarios where the time lag of the energy production is considered. Figure 5 shows the accumulated radiative forcing and hence the accumulated effect over time. As can be seen the accumulated effect is very small (difference between uppermost curves in Figure 5).

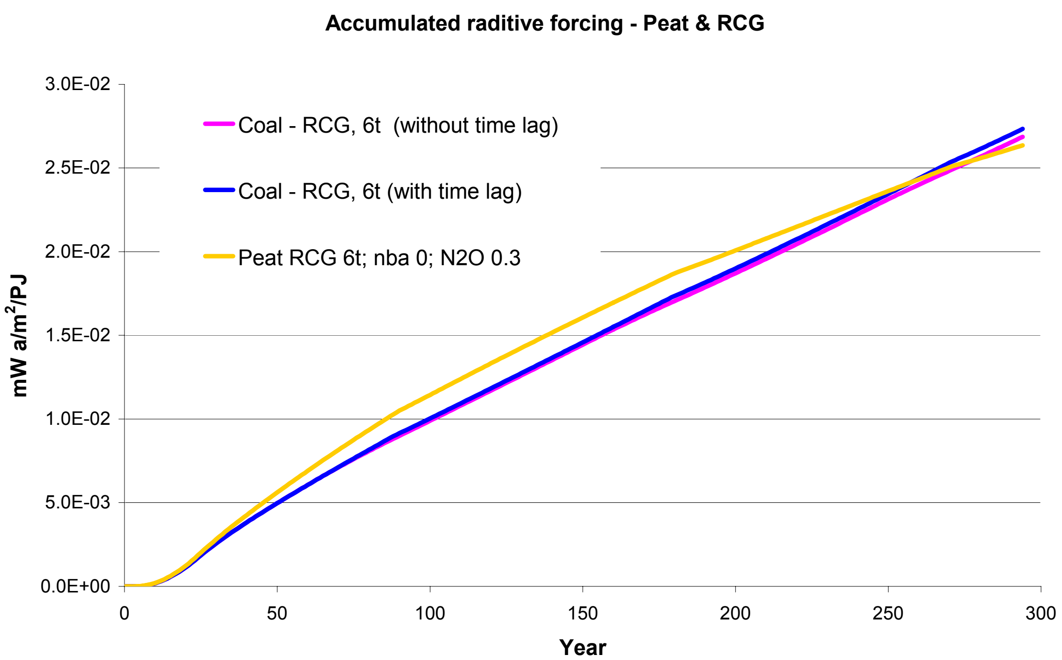

Figure 5.The two coal scenarios produce the same amount of energy only at different points in time.