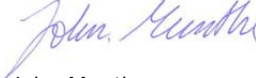# The time aspect of bioenergy - climate impacts of bioenergy due to differences in carbon uptake rates

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## Summary

This paper investigates the climate impacts from bioenergy due to how they influence carbon stocks over time and more specifically how fast combustion related carbon emissions are compensated by uptake of atmospheric carbon. A set of fuel types representing different uptake rates are investigated, namely willow, branches and tops, stumps and coal. Net emissions are defined as emissions from utilizing the fuel minus emissions from a reference case of no utilisation. In the case of forest residues, the compensating "uptake" is avoided emissions from the reference case of leaving the residues to decompose on the ground. Climate impacts are estimated using the measures *radiative forcing* and *global average surface temperature*, which have been calculated by an energy balance climate model. We conclude that there is a climate impact from using bioenergy due to how fast the emission pulse is compensated by uptake of atmospheric carbon (or avoided emissions). Biofuels with slower uptake rates have a stronger climate impact than fuels with a faster uptake rate, assuming all other parameters equal. The time perspective over which the analysis is done is crucial for the climate impact of biofuels. If only biogenic fluxes are considered, our results show that over a 100 year perspective branches and tops are better for climate mitigation than stumps which in turn are better than coal. Over a 20 year time perspective this conclusion holds, but the differences between these fuels are relatively smaller. Establishing willow on earlier crop land may reduce atmospheric carbon, provided new land is available. However, these results are inconclusive since we haven't considered the effects, if needed, of producing the traditional agricultural crops elsewhere. The analysis is not a life cycle assessment of different fuels and does therefore not consider the use of fossil fuels for logging, transportation and refining, other greenhouse gases than carbon or energy conversion losses.

# Sammanfattning

Föreliggande rapport undersöker klimatpåverkan från användningen av biobränslen med avseende på hur snabbt de förbränningsrelaterade utsläppen kompenseras av upptag av koldioxid från atmosfären. Ett urval av biobränslen som representerar olika upptagshastigheter har undersökts, nämligen salix, grenar och toppar (GROT), stubbar samt kol. Nettoemissioner definieras som emissioner från bränsleanvändningen minus emissioner från ett referensfall där biomassan inte används som bränsle. I fallet med GROT och stubbar utgörs "upptaget" av undvikta utsläpp från referensfallet där hyggesresterna får ligga kvar i skogen och brytas ner. Klimatpåverkan har uppskattats med måtten radiative forcing och genomsnittlig global yttemperatur, vilket beräknats med hjälp av en atmosfärisk energibalansmodell. Vi finner att det finns en klimatpåverkan från användningen av biobränslen som beror på hur snabbt de förbränningsrelaterade utsläppen kompenseras av upptag av koldioxid (eller undvikta emissioner). Biobränslen som tar upp koldioxid långsamt har en större klimatpåverkan än biobränslen som tar upp koldioxid snabbt, under förutsättning att alla andra parametrar är lika. Tidsperspektivet har stor betydelse. Om endast de biogena flödena av koldioxid beaktas, kan vi konstatera att över ett 100-årsperspektiv leder användningen av GROT till en lägre klimatpåverkan än stubbar som i sin tur har en lägre klimatpåverkan än kol. Denna slutsats gäller även ur ett 20-årsperspektiv, men skillnaden mellan bränsletyperna är mindre. Salix som etableras på tidigare jordbruksmark kan leda till ett nettoupptag av koldioxid från atmosfären. Det är dock svårt att dra slutsatser från detta eftersom vi inte har beaktat konsekvenserna av att odla jordbruksgrödorna någon annanstans. Den gjorda studien är inte en livscykelanalys av olika bränslen och innefattar till exempel inte förbrukningen av insatsbränslen för avverkning, insamling, transport och förädling. Studien innefattar inte heller andra växthusgaser än koldioxid eller omvandlingsförluster.

# Contents

# 1. Introduction

## 1.1 Does bioenergy have a climate impact?

When biomass is combusted the carbon that once was bound in the growing forest is released, thus closing the biogenic carbon cycle. For this reason bioenergy has often been considered carbon neutral[1]. For instance, carbon emissions from biofuels are not included in the EU emission trading system (European Commission, 2003). However, Eriksson and Hallsby (1992) showed that using logging residues for energy, instead of leaving them on the ground, could lead to lower carbon storage in litter and soils. Melin et al (2010) and Walmsley and Godbold (2011) pointed out that the use of stumps would result in a reduction in the carbon stored in dead organic matter. But this effect is of transient character. If forest residues or stumps are left on/in the ground, they would decompose and release carbon to the atmosphere. Using forest residues and stumps for energy can be seen as shifting the emissions earlier in time compared to leaving them on the ground to decompose (Lindholm, 2010, Zetterberg and Hansén, 1998). The time for forest residues to decompose to 50 % if the original content is approximately 6-9 years for branches and tops (Ågren et al 2010, Repo et al 2010) and approximately 15- 30 years for stumps (Melin et al 2010, Ågren et al 2010, Repo et al 2010). One may argue that the longer it takes for emissions to be compensated, the greater could the climate impacts be. Therefore, it may be important to consider how fast combustion related carbon emissions are compensated when assessing the climate impacts and benefits of different types of bioenergy.

## 1.2 Current understandning

Several studies have investigated carbon emissions and expected climate impacts[2] from biofuels due to how their usage influences the biogenic carbon stocks in the forest ecosystem (Table 1). Schlamadinger et al (1995) estimated remaining carbon from branches and tops to be 10 %-28 % after 100 years, depending on decomposition rate. Wihersaari (2005) estimated the soil carbon related emissions from branches and tops to be 11-12 g $CO_2$-eq/MJ fuel over a 100 year perspective[3]. Based on a dynamic ecosystem carbon model, Lindholm et al (2010) estimated the reduced soil carbon build up due to using branches and tops in Southern Sweden to be approximately 20 g $CO_2$/MJ as an average

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[1] In this paper, we define a system to be carbon neutral if the cumulative fluxes of carbon to and from a system over a given time period are zero. The concept of carbon (climate) neutrality and how it's used is discussed in for instance Holmgren et al (2007).

[2] Different metrics have been used to describe expected climate impacts from biofuel usage. Carbon stock changes are usually expressed in $CO_2$-emissions per energy unit of extracted fuel or per area unit. Estimates of expected climate impacts are usually expressed in radiative forcing or derivatives thereof. These metrics include instantaneous radiative forcing, absolute global warming potential (AGWP) – also called accumulated radiative forcing and relative radiative forcing commitment, RRFC. These metrics are defined and explained under the methodology chapter.

[3] This can be compared to the carbon content in forest residues which is approximately 94 g $CO_2$/MJ (value used in this paper).

over one rotation period (100 years).  For stumps in Southern Sweden, the carbon stock reduction was approximately 37 g $CO_2$-equiv/MJ as an average over one rotation period. Repo et al (2010) have used a dynamic soil carbon model to estimate emissions from using logging residues for energy instead of leaving them on the ground to decompose. After 100 years, remaining amount of carbon was estimated to be 2 %-16 % for branches and 19 % - 28 % for stumps.  This corresponds to 2-16 g $CO_2$/MJ for branches and 17-27 g $CO_2$/MJ for stumps. Kujanpää et al (2010) estimated the soil carbon related emissions from use of branches and tops to be 94, 27 and 17 g $CO_2$/MJ over 5, 50 and 100 years respectively. Several studies have investigated the climate impacts from using forest residues and express these impacts in terms of radiative forcing[4]. Holmgren et al (2007) have compiled emissions data for forest residues and estimated the climate impact expressed as instantaneous radiative forcing.  The authors concluded that using of 1 PJ forest residues per year will have an instantaneous radiative forcing of 1.8 $\mu W/m^2$ after 20 years and 2.4-2.6 µW/m2 after 100 years. Zetterberg et al (2004) found that using 1 PJ forest residues per year will result in an instantaneous radiative forcing of 1.7 $\mu W/m^2$ after 20 years and 1.6 $\mu W/m^2$ after 100 years. Kirkinen el al (2008) estimated the climate impact for different fuel chains, expressed as Relative Radiative Forcing Commitment, RRFC. Over 100 years, the RRFC for forest residues was estimated to be 20-40, which corresponds to an *accumulated radiative forcing* of approximately 40-80 nJ/m$^2$/MJ fuel (author's estimate).

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[4] The following example may facilitate the translation between emissions and radiative forcing. If coal with an emission factor of 93 g $CO_2$/MJ is combusted at a rate of 1PJ/year, the corresponding instantaneous radiative forcing will be 4.1 $\mu W/m^2$ after 20 years and 14.2 $\mu W/m^2$ after 100 years (values derived in this paper).

**Table 1**. Summary of studies that have estimated carbon emissions and radiative forcing from biofuels due to how their usage influences the biogenic carbon stocks in the forest ecosystem. The term "Soil carbon" includes litter and forest residues on the ground, but not growing trees.

| Reference | Biofuel | Measure | Value | System boundaries |
|---|---|---|---|---|
| Schlamadinger et al (1995) | Branches and tops | Emissions | 10 %-28 % of original carbon, corresponding to 9-26 g $CO_2$/MJ (after 100 years) | Soil carbon |
| Wihersaari (2005) | Branches and tops | Emissions | 11-12 g $CO_2$/MJ (100 year) | Soil carbon |
| Lindholm et al (2010) | Branches and tops | Emissions | 20 g $CO_2$/MJ (average over 100 year) | Soil carbon |
| | Stumps | Emissions | 37 g $CO_2$/MJ (average over 100 year) | Soil carbon |
| Kujanpää et al (2010) | Branches and tops | Emissions | 94 g $CO_2$/MJ (after 5 years) 27 g $CO_2$MJ (after 50 years) 17 g $CO_2$/MJ (after 100 years) | Soil carbon |
| Repo et al (2010) | Branches and tops | Emissions | 2-16 g $CO_2$/MJ (after 100 years) | Soil carbon |
| | Stumps | Emissions | 18-27 g $CO_2$/MJ (after 100 years) | Soil carbon |
| Zetterberg et al (2004) | Branches and tops | Inst. Radiative Forcing for 1PJ/year | 1.7 $\mu W/m^2$ (20 years) 1.6 $\mu W/m^2$ (100 years) | Soil carbon |
| Holmgren et al (2007) | Branches and tops | Inst. Radiative Forcing for 1PJ/year | 1.8 $\mu W/m^2$ (20 years) 2.4-2.6 $\mu W/m^2$ (100 years) | Soil carbon |
| | Coal | Inst. Radiative Forcing for 1PJ/year | 3.8 $\mu W/m^2$ (20 years) 11.3 $\mu W/m^2$ (100 years) | |
| Kirkinen el al (2008) | Branches and tops | RRFC (Relative radiative forcing commitment) | 20-40 (100 years) | Full production chain. $CO_2$, $CH_4$ and $N_2O$ included |
| | Coal | RRFC | 160-180 (100 years) | |

## 1.3  Objectives and contribution of this paper

The objective of this paper is to investigate the climate impacts from biofuels due to how fast the combustion related emissions are compensated by uptake of atmospheric carbon or avoided emissions. A set of biofuels representing a wide range of carbon uptake rates[5] has been analysed, namely willow; forest residues in the form of branches, tops and stumps; and coal. In the case of forest residues, the compensating "uptake" is rather avoided emissions from the reference case of leaving the residues to decompose on the ground. The focus has been on the importance of carbon uptake rates rather than the climate impacts of individual fuels. Most studies investigating the climate impacts from biofuels use radiative forcing or derivatives thereof as a measure. This study goes one step further to introduce the measure *global average surface temperature* as a complementary measure for assessing the dynamic climate effects of emission scenarios. The impacts of biofuel scenarios on global climate have mainly been analysed using a simple energy balance climate model developed for this study. In addition, the climate response from two schematic biofuel emission scenarios, has been analysed using a 3D general circulation model which offers much more detail in describing climate processes and results.

## 2.  Methods and definitions

The climate impacts from different biofuels have been calculated in four steps:

  i)    Emissions have been calculated based on data on biogenic carbon stock changes

  ii)   Atmospheric concentration changes have been calculated based on emissions

  iii)  Radiative forcing has been calculated based on atmospheric concentration changes

  iv)   Global surface temperature has been calculated based on radiative forcing or concentrations (depending on climate model used)

The first three steps follow the same methodology as for instance Kirkinen (2010), Zetterberg et al (2004) and Holmgren et al (2007), while the fourth step, global average surface temperature, is estimated using two different climate models. These methods and models are described below.

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[5] The carbon uptake rate is defined as the rate, expressed in carbon units per year that an emission pulse is compensated by uptake of atmospheric carbon or avoided emissions.

## 2.1  Emissions

In this paper, the *net* emissions, $E_{net}$, from a biofuel are defined as the emissions, $E$, from the case of utilisation minus the emissions from a reference case:

$$E_{net} = E_U \text{-} E_{Ref} \tag{1}$$

The subscript $U$ refers to the utilisation case and *Ref* to the reference case.

Expression (1) follows recommendations by Schlamadinger et al (1997) and is applied by for instance Zetterberg and Hansén (1998), Lindholm et al (2010), Kirkinen et al (2008) and Hagberg and Holmgren (2008).

Emissions of carbon to the atmosphere, $E(t)$ expressed in kg $CO_2$/year, are calculated based on how the use of bioenergy affects the carbon stock of the ecosystem, $S(t)$. $S(t)$ is expressed in kg $CO_2$.  Assuming that a reduction of the ecosystem's carbon stock results in an immediate emission to the atmosphere, the emissions can be calculated as the time derivate of the carbon stock, with opposite sign:

$$E(t) = -S'(t) \tag{2}$$

Using (2) into (1) the net emissions, $E_{net}$ can be expressed in carbon stock terms:

$$E_{net}(t) = S_{Ref}{}'(t) - S_U{}'(t) \tag{3}$$

It's sometimes useful to present emissions as accumulated net emissions $AE_{net}(t)$ which is calculated by integration of expression (3):

$$AE_{net}(t) = S_{Ref}(t) - S_U(t) \tag{4}$$

The accumulated emissions are equal to the net carbon stock change with opposite sign. We have here assumed that at t=0, the carbon stock in the reference case is equal to the carbon stock in the utilisation case, $S_{Ref}(0) = S_U(0)$.

Finally, the carbon uptake rate, $U(t)$, expressed in kg $CO_2$/year, is defined as the annual emissions with opposite sign:

$$U(t) = -E(t) \tag{5}$$

## 2.2   Atmospheric concentrations

A pulse emission of $CO_2$ results in an increase of atmospheric $CO_2$. However, the remaining mass in the atmosphere from this emission pulse decreases over time. This is due to a number of processes that transports carbon from the atmosphere to other carbon pools, including uptake in mixed layer of ocean, transport from surface water to deeper ocean and uptake in biota (IPCC, 2007).

The Intergovernmental Panel on Climate Change, IPCC (2007) has presented a carbon response function as a combination of several exponential decay functions:

$$f(t) = 0.217 + 0.259 * e^{-t/172.9} + 0.338 * e^{-t/18.51} + 0.186 * e^{-t/1.186} \qquad (6)$$

The remaining mass of carbon dioxide $M_{CO2}(t)$ due to emissions $E(t)$ at time $t$ can then be calculated as:

$$M_{CO2}(t) = \int_0^t E_{net}(\tau) f(t - \tau) d\tau \qquad (7)$$

Based on t $M_{CO2}(t)$, the change in carbon dioxide concentration $C_{CO2}(t)$ at the time $t$ can be calculated as:

$$C_{CO2}(t) = \frac{M_{CO2}(t) \cdot MV_{Atm}}{M_{Atm} \cdot MV_{CO2}} \qquad (8)$$

Where $M_{ATM}$ is the mass of the atmosphere, $MV_{Atm}$ is the molecular weight of the atmosphere and $MV_{CO2}$ is the molecular weight of $CO_2$.
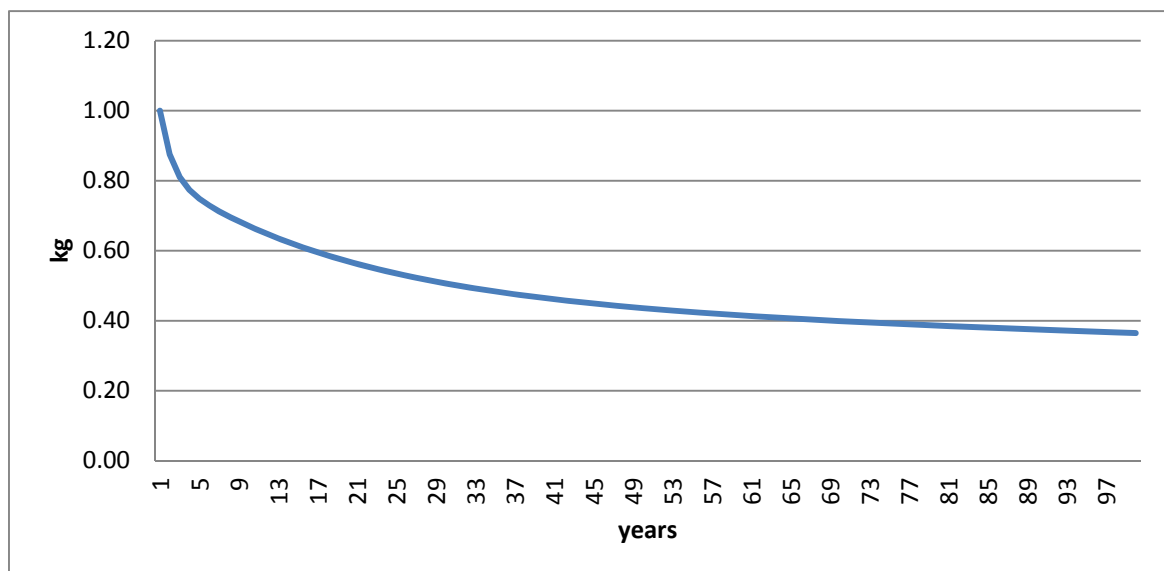


**Figure 1**. Remaining amount of $CO_2$ after a 1 kg pulse emission at t=0. Data from IPCC (2007), page 213.

## 2.3  Radiative Forcing

Radiative forcing is commonly used for assessing the expected climate impacts from global emission scenarios. The measure has also been used to assess the expected climate impacts from different energy sources ( see for instance Savolainen et al (1994), Zetterberg et al (2004), Holmgren et al (2006), Holmgren et al (2007), Kirkinen et al (2007) and Kirkinen et al (2010)). Radiative forcing, expressed in $W/m^2$, is described as a change in average net radiation at the top of the troposphere, due to a change in either solar or infrared radiation (IPCC, 1994). This can for instance be caused by changes in greenhouse gas concentrations, particles from volcanic eruptions or changes in solar intensity. A radiative forcing perturbs the balance between incoming and outgoing radiation of the climate system. A positive radiative forcing tends to warm the surface; a negative radiative forcing tends to cool the surface. Increased concentrations of $CO_2$ lead to a positive radiative forcing. The IPCC (1992) has described the relation between increased concentrations of greenhouse gases and radiative forcing in simple functions, which are parametrisations of more complex radiative models. The radiative forcing, $\Delta Q$ due to increased concentration $C$ is described as:

$$\Delta Q(CO_2) = 6.3 * \ln(CO_2 / CO_{2,0}) \tag{9}$$

where $CO_{2,0}$ is the reference atmospheric $CO_2$ concentration, which we assume to be 360 ppmv.

Often, derivatives of radiative forcing are used, such as:

*AGWP, Absolute global warming potential* was described by the IPCC (1996) as the time integration of radiative forcing from when the emission occurs to a prescribed time perspective, usually 20, 50 or 100 years.

$$AGWP(t) = \int_0^t RF(\tau)d\tau \tag{10}$$

*AGWP* is expressed in $J/m^2$. *Accumulated radiative forcing* is an alternative name for AGWP. The term *Instantaneous radiative forcing*, expressed in $W/m^2$, is sometimes used to distinguish radiative forcing from *accumulated radiative forcing* expressed in $J/m^2$. The Relative Radiative Forcing Commitment, *RRFC(t)* is described by Kirkinen et al (2007) as a ratio that accounts for the energy absorbed in the earth system due to changes in greenhouse gas concentrations compared to the energy released at the combustion of the fuel. It is calculated as:

$$RRFC(t) = \frac{AGWP(t) \cdot A}{E_{fu}} \tag{11}$$

Where A is the surface of the earth and $E_{fu}$ is the energy of the fuel used.

## 2.4  Global Average Surface Temperature

Global Average Surface Temperature change is calculated using two different models:

- The *Planet simulator*, a 3-dimensional General Circulation model (GCM)

- *IMAGES*, a simpler energy balance model developed for this study (see Appendix 1)

### 2.4.1  The Planet Simulator

The *Planet Simulator* (Planet Simulator, 2011) has been used to investigate a simplified emission scenario that has the main features of a biofuel scenario. The model was run with 10 pressure levels, and T21-resolution[6]. Sea and Ice modules are included. Input data are time dependent $CO_2$-concentrations, while other trace gases are kept constant at default values. The Planet Simulator produces a wide range of output data, out of which only the global surface temperature, averaged annually was used. A control run was executed in order to determine a temperature baseline with which the $CO_2$ emission pulse runs were compared to. In this control run the $CO_2$-concentration was held constant at 360 ppmv.

### 2.4.2  IMAGES - Impact Model for Assessing Greenhouse gas Emission Scenarios

The Planet simulator is an assessment tool providing great detail in describing climate processes and output, but has disadvantages. Executing a 100 year simulation requires significant amount of computer time. For each biofuel scenario, multiple simulations using different starting conditions need to be executed and the results averaged. Moreover, the emission scenario needs to be of considerable magnitude in order to produce a signal that can be separated from the noise. Therefore, a simpler energy balance model, called IMAGES (Impact Model for Assessing Greenhouse Gas Emission Scenarios), has been developed in order to investigate a wider range of biofuel emission scenarios. The IMAGES model calculates emissions, concentrations and radiative forcing using the functions in sections 2.1-2.3. In addition, IMAGES calculates global average surface temperature using analytical functions described in Appendix 1.

Figure 2 shows the calculated average surface temperature change due to a pulse emission of 1 kg $CO_2$ at t=0.

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[6] T21 resolution corresponds to approximately 5.6 degree (600 km) grid size in the global model.
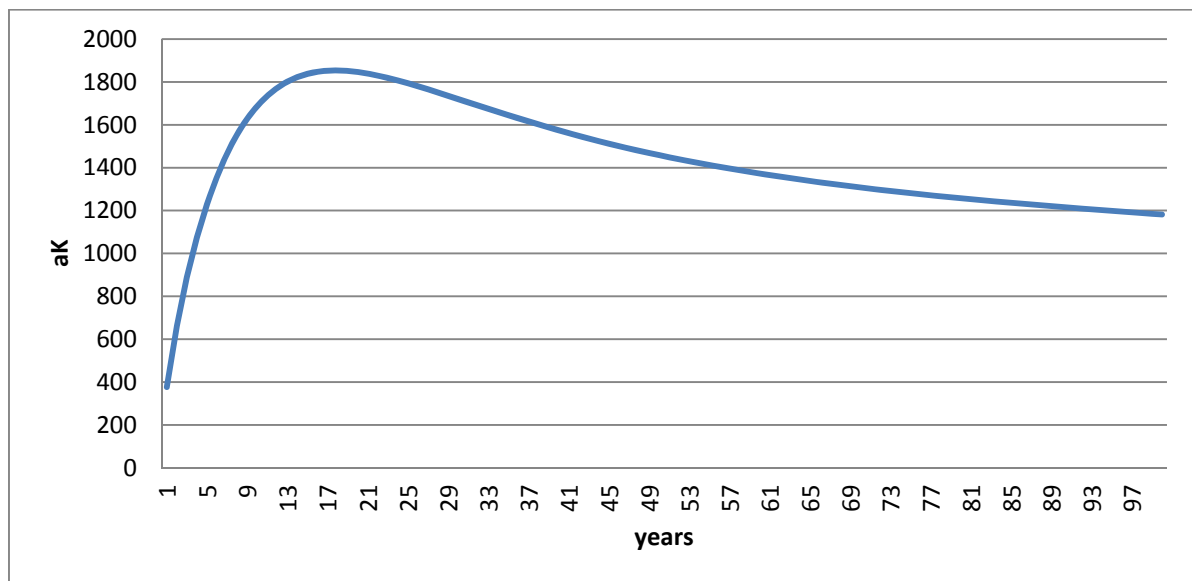
**Figure 2.** Global average surface temperature change due to 1 kg $CO_2$ pulse emission at t=0. The pulse emission leads to an instant increase in radiative forcing and a consequent increase in temperature. The temperature responds slowly to the radiative forcing due to the inertia of the climate system. When the atmospheric concentration of carbon decays (see Figure 1), the radiative forcing is reduced. The temperature responds to this decreased forcing, but again slowly due to the inertia of the climate system. The temperature response will culminate after a certain time and thereafter decrease.

# 3.  Investigated biofuels and system boundaries

The investigated fuels are listed in Table 2.

**Table 2**. Fuels investigated in this paper

| Investigated fuel | Reference case |
| --- | --- |
| 1. **Branches and tops (Q-model)**. Branches and tops from a spruce forest in southern Sweden are extracted for energy. 80 % of the branches and tops are extracted. Estimates are based on the dynamic soil carbon Q-model (Ågren et al, 2010). Also called "GROT" from the Swedish "GRenar Och Toppar". | Decomposition of residues |
| 2. **Branches (Yasso)**. Forest residues in the form of branches from southern Finland are extracted for energy. Estimates are based on the dynamic soil carbon model Yasso07 (Repo et al, 2010) | Decomposition of residues |
| 3. **Stumps (Q-model)**. Stumps from a spruce forest in southern Sweden are extracted for energy. 50 % of the stumps are extracted. Estimates are based on the Q-model (Ågren et al, 2010) | Decomposition of residues |

| | |
|---|---|
| 4. **Stumps (Yasso)**. Stumps from southern Finland are extracted for energy. Estimates are based on the Yasso07-model (Repo et al, 2010). | Decomposition of residues |
| 5. **Willow (Q-model)**.  Willow is assumed to be produced on land previously used for crop production. Estimates are based on the Q-model (Ågren et al, 2010). | Continued crop production with no net soil carbon changes |
| 6. **Coal**, used as a benchmark for comparison | - |

The analysis focuses on climate impacts due to how use of bioenergy influences biogenic carbon stocks and fluxes over time. The investigated system includes uptake of atmospheric carbon due to growth in the forest ecosystem and emissions of biogenic carbon (carbon originating from the forest ecosystem) either due to decomposition or combustion. In the case of calculated radiative forcing and global average temperature change, the global carbon sink processes that transports carbon to other pools are included. The system and system boundaries is described in Figure 3.

Emissions from (fossil) fuel used in equipment for logging, collection, transportation, refining and storage of the fuels are not included. Nor are energy conversion losses, for instance in the production of electricity considered. Substitution effects, such as the avoided emissions when biofuels replace fossil fuels are not considered. Other greenhouse gases than $CO_2$ are not included in the analysis.
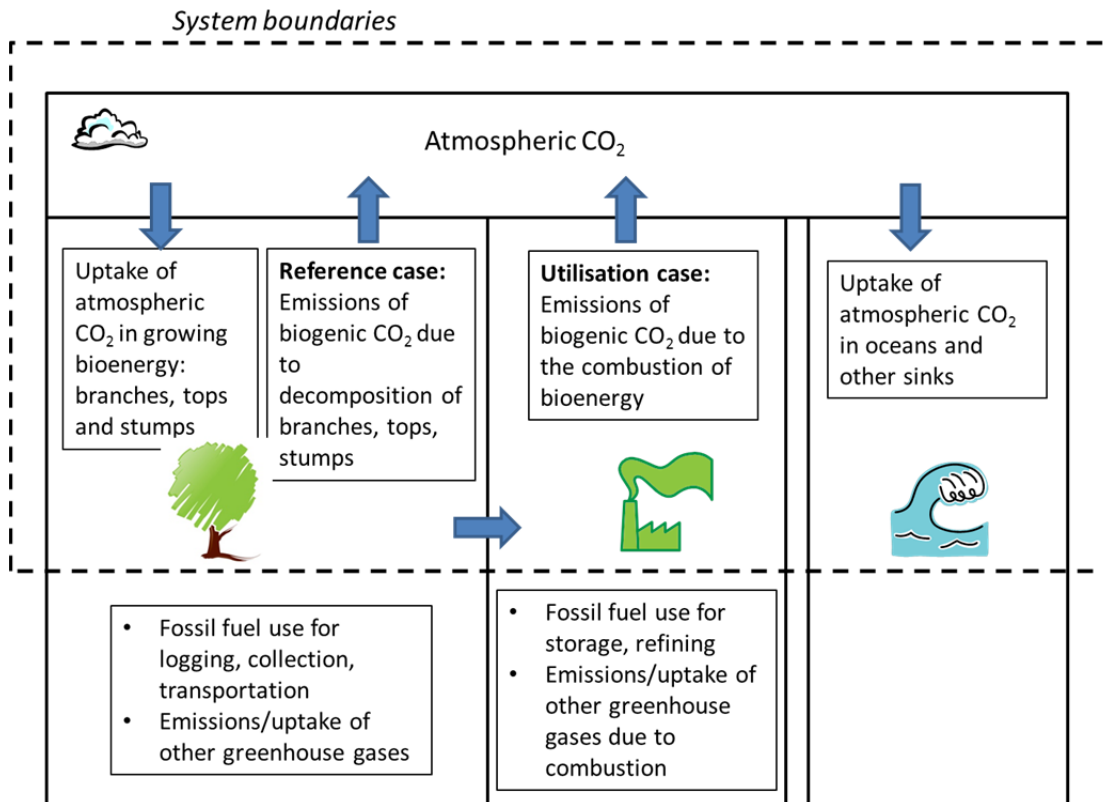
**Figure 3**. System boundaries for the investigated bioenergy.

# 4. Input data

## 4.1 Branches and tops and stumps estimated by the Q-model

Emissions data for the use of branches, tops and stumps in Sweden is based on Ågren (2011) who has used the Q-model to simulate the development of carbon stocks (soil and trees) for a spruce forest at Växjö, assuming three different management regimes:

- A *reference case* with no extraction of branches, tops or stumps;

- *Branches and tops*: 80 % of branches and tops are removed at each harvest,

- *Branches, tops and stumps*: 80 % branches and tops are removed at each harvest and 50 % of the stump-coarse root system at final harvest.
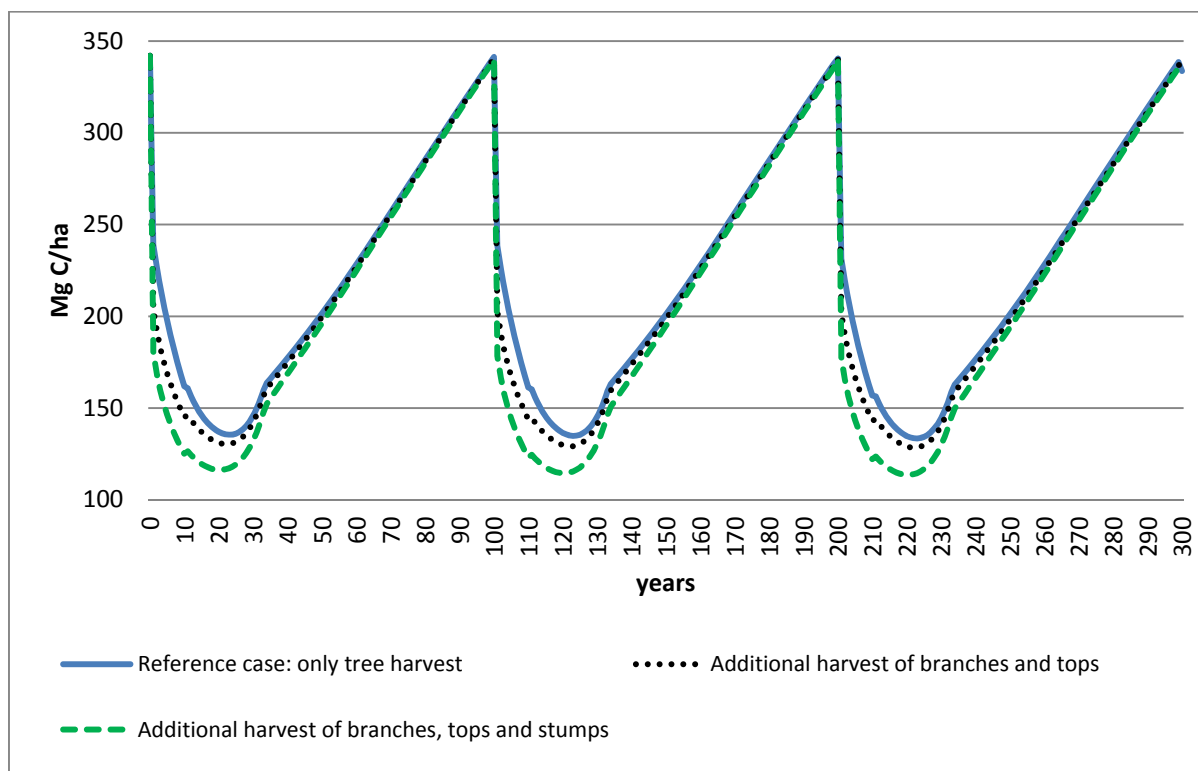
**Figure 4.** Development of carbon stocks (soil and trees) simulated by the Q-model for a spruce forest at Växjö for three different management regimes and during 300 years (Ågren, 2011). The sudden reduction in carbon t=0, 100 and 200 years is due to harvest and extraction of logs and forest residues. The characteristics of is figure is discussed in chapter 7.

At each harvest event, there are three types of biomass fractions available. The largest fraction consists of logged trees and corresponds to approximately 103 MgC/ha. If branches and tops are extracted, this fraction corresponds to approximately 35 MgC/ha and if, in addition, stumps are extracted these correspond to an additional 24 MgC/ha. In this paper, the climate impacts from using branches, tops and stumps for energy has been analysed. However, the potential use of logged wood for energy has not been analysed.

## 4.2 Branches and stumps, Finland

Emissions data for branches and stumps in Finland are based on carbon stock changes estimated by the "Yasso-model" (Repo et al, 2010). Figure 5 shows net emissions as a function of time for branches (d=2 cm) and stumps (d= 26 cm).
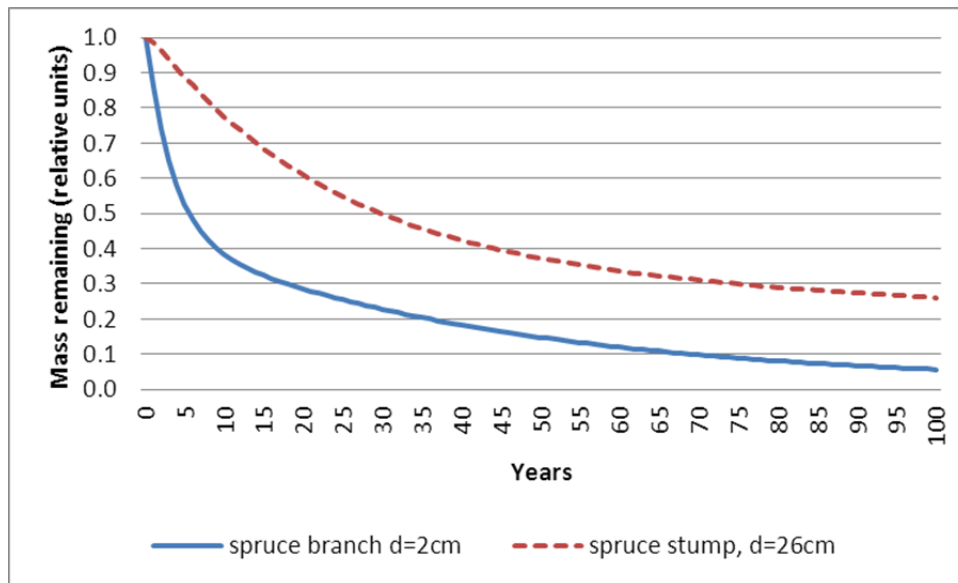
**Figure 5.** Mass remaining of decomposing Norway spruce branches (diameter 2 cm) and stumps (diameter 26 cm) over a 100 year period after the start of decomposition in southern boreal conditions as simulated by the Yasso07 model (Repo et al 2010).

## 4.3 Willow, Sweden

Data on willow (*Salix*) and the reference case of crops are based on carbon stock changes simulated by the Q-model (Ågren, 2010) and presented in Figure 6.
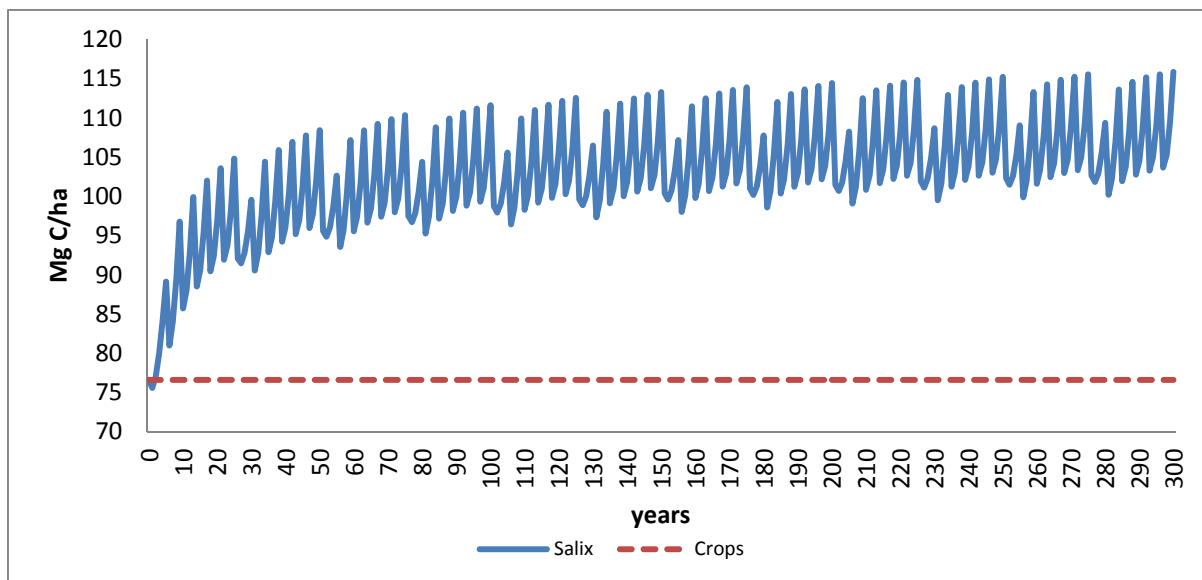


**Figure 6.** Carbon stock changes for willow planted on earlier crop land. Data from Ågren et al (2010).

## 4.4 Combustion related emission factors of investigated biofuels

Emission factors for the combustion of biofuels from different references are presented in Table 3.

**Table 3**. Carbon dioxide emission factors for the combustion of forest residues.

| Reference | Biofuel | Emission factor | Comment |
|---|---|---|---|
| Zetterberg and Hansén (1998) | Branches and tops | 95-115 g $CO_2/MJ_{fuel}$ | Compilation of several references |
| Kirkinen et al (2008) | Branches and tops | 109.6 g $CO_2/MJ_{fuel}$ | |
| Holmgren et al (2007) | Branches and tops | 100-110 $CO_2/MJ_{fuel}$ | Based on Kirkinen et al (2008) and Zetterberg and Hansén (1998) |
| Repo et al (2010) | Branches | 94.4 g $CO_2/MJ_{fuel}$ | Calorific heating value: 19.30 MJ/kg; dry wood carbon content 50 % |
| Repo et al (2010) | Stumps | 95.0 g $CO_2/MJ_{fuel}$ | Calorific heating value: 19.18 MJ/kg; dry wood carbon content 50 % |
| Melin et al (2010) | Stumps | 95.4 g $CO_2/MJ_{fuel}$ | Calorific heating value: 19.2 MJ/kg; dry wood carbon content 50 % |

In this paper, an emission factor of 94.4 g $CO_2/MJ_{fuel}$ has been applied for tops and branches and 95.0 g $CO_2/MJ_{fuel}$ for stumps. For a discussion on the choice of emission factors, see chapter 7. For coal, an emission factor of 93.0 g $CO_2/MJ$ is applied, which is also used in the Swedish national communication to the UNFCCC (Naturvårdsverket, 2011).

# 5.  Results

## 5.1  Illustration of how net emissions are calculated from carbon stock changes

For illustration Figure 7 shows how net emissions are calculated from carbon stock changes and the role of the reference case. Tops and branches from spruce forest in southern Sweden have been used as an example. The reference case is when the forest residues are left in the soil to decay naturally (top curve). The utilisation case is when the residues are harvested (second curve from the top). The net emissions (bottom curve) have been calculated as the difference between the reference case and the utilisation case. The graph shows that the net emissions are reduced over time approaching zero and carbon neutrality.
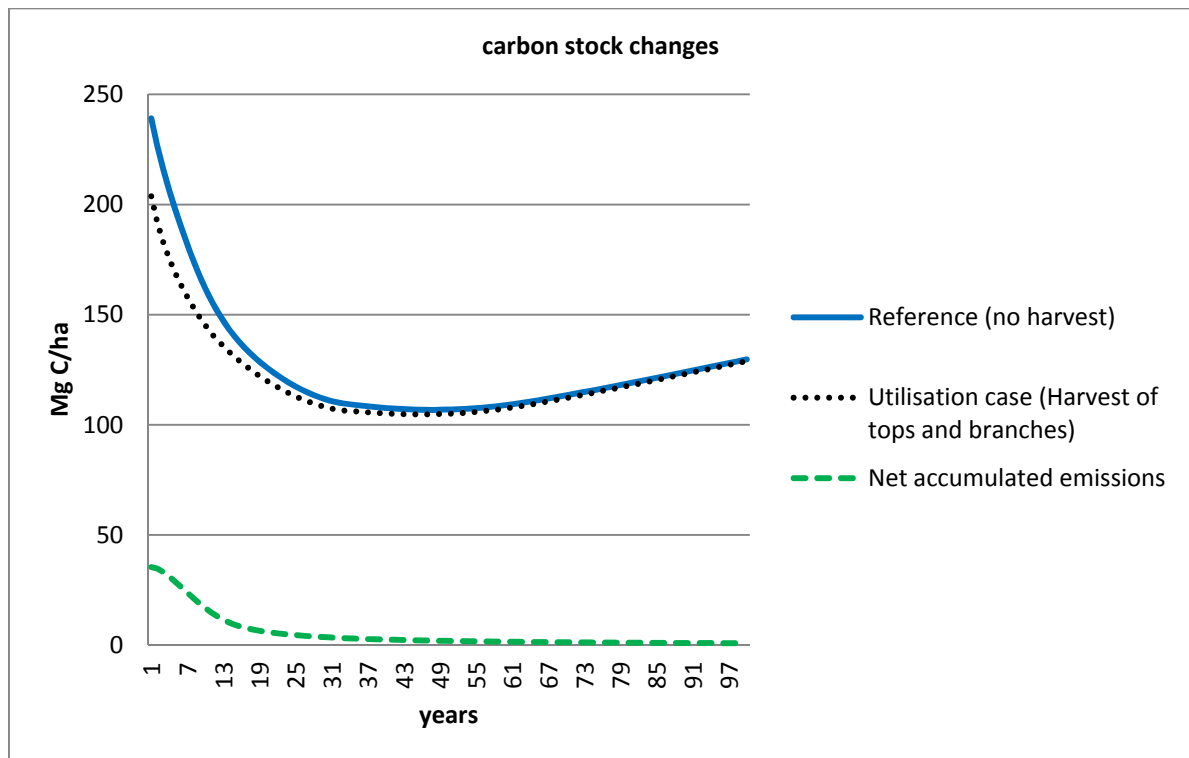


**Figure 7.** Illustration of how net accumulated emissions are calculated as carbon stock changes from the reference case (no harvest) minus carbon stock changes from the utilisation case (harvest of branches and tops). Data from Ågren (2011).

## 5.2 Calculated uptake rates, emissions, radiative forcing and temperature change for different biofuels

The time for the initial emissions to be reduced by 50 % or 75 %, which is a way to express the carbon uptake rate, is listed in Table 4.

**Table 4**. Carbon uptake rates for different fuels, expressed as the time to reach 50 % or 75 % reduction of combustion related emissions.

| Investigated fuel | Time to reach 50 % reduction $t_{50\%}$ (years) | Time to reach 75 % reduction $t_{75\%}$ (years) |
|---|---|---|
| **Branches and tops (Q-model)**. Branches and tops from spruce forest in southern Sweden. | 9 | 15 |
| **Branches (Yasso)**. Forest residues in the form of branches from southern Finland. | 6 | 25 |
| **Stumps (Q-model)**. Stumps from a spruce forest in southern Sweden. | 25 | 40 |
| **Stumps (Yasso)**. Stumps from southern Finland. | 30 | 100 |
| **Coal** | - | - |

Emissions for different fuels are calculated and presented in Figure 8. Figure a) shows emissions from using 1 MJ of fuel at t=0 (single event), expressed in g $CO_2$/MJ fuel. Figure b) shows the accumulated emissions from continuous use of 1PJ fuel per year for 100 years, expressed in Mt $CO_2$. Based on these fuel emission scenarios, instantaneous radiative forcing is calculated and presented in Figure c) single event; and Figure d) continuous use of 1 PJ per year. Positive values correspond to warming and negative values to cooling. Based on these radiative forcing calculations, average surface temperature change is calculated and presented in Figure e) single event; and Figure f) continuous use. In Figure 8a, the emission curves remind of exponential decay approaching zero in an asymptotic manner.  For all forest residues (branches, tops and stumps), there is an initial emission pulse at t=0, due to combustion, which is reduced over time due to avoided emissions from decomposition in the reference case. For coal, there is of course no uptake or avoided emissions, explaining why the emissions are constant over time. In Figure 8c (radiative forcing for a single event), the sloping form of the curves, reminding of

exponential decay is due to two effects. First, since the net emissions decrease over time (except for coal) the atmospheric concentrations decrease over time which in turn directly influences the radiative forcing. Secondly, a pulse emission to the atmosphere results in an instant increase of $CO_2$-concentration, but is reduced over time mainly due to uptake in the ocean. Figure 8c shows that after approximately 30 years, the instantaneous radiative forcing for branches and tops (Q-model) is negative. For stumps (Q-model) this occurs after approximately 40 years. The reason for this is that a part of the original emissions has been removed from the atmosphere, mainly due to uptake in the ocean. However, on average over 100 years all fuels lead to a warming. In Figure 8e (temperature change for single event) the curves show an increased temperature followed by a decrease in temperature. The reason for this is that the temperature is driven by the radiative forcing, but due to the inertia of the climate system it takes time for the temperature to respond to a forcing. The reduction in temperature later in time is due to a decreased forcing.
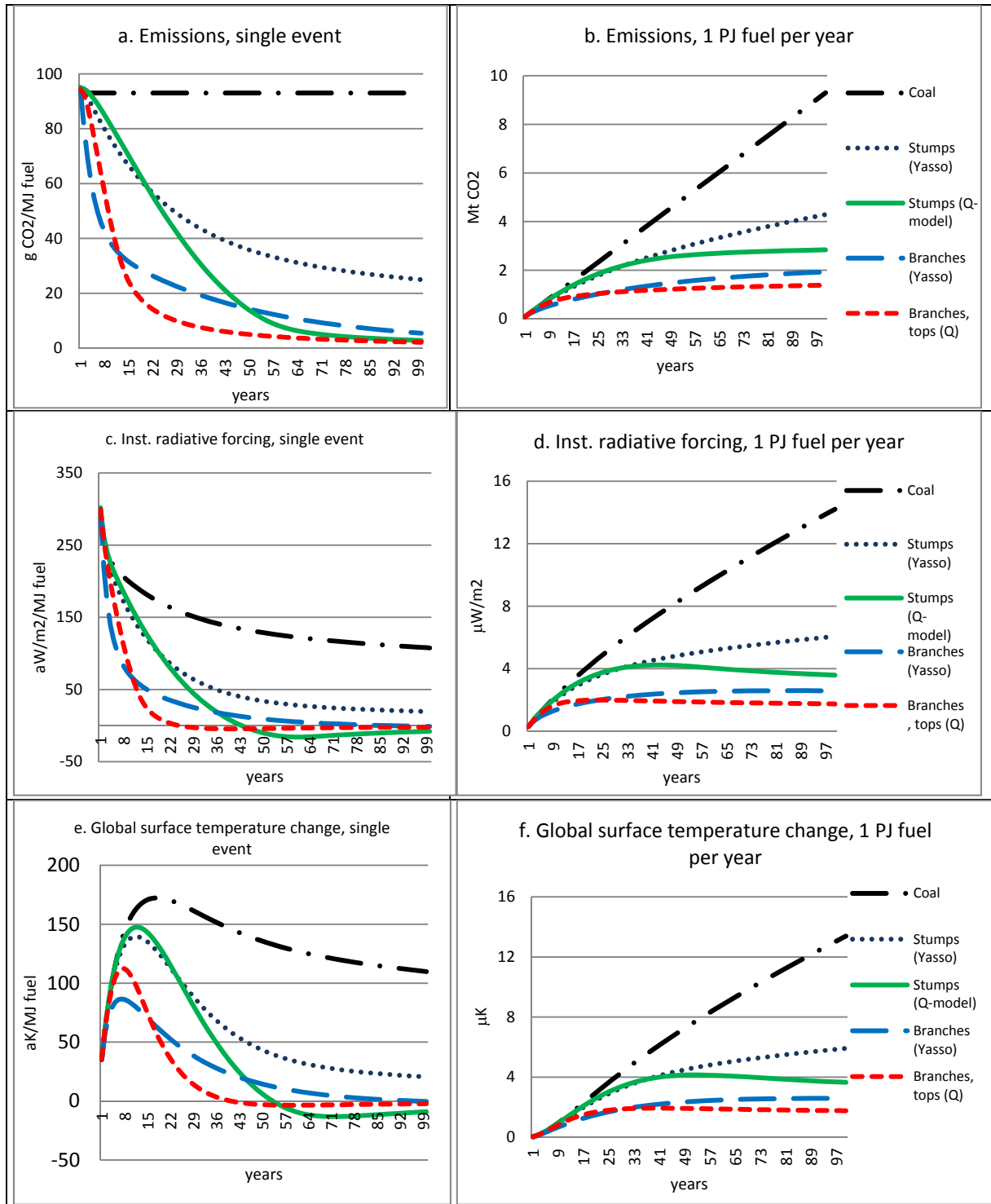
**Figure 8.** Climate impacts from fuels representing different uptake rates of atmospheric carbon. a) shows emissions from using 1 MJ of fuel at t=0 (single event). b) shows the emissions from continuous use of 1PJ fuel per year for 100 years. Based on these emission scenarios, instantaneous radiative forcing is calculated and presented in c) single event; and d) continuous use of 1 PJ per year. Positive values correspond to warming and negative values to cooling. Based on these radiative forcing calculations, average surface temperature change is calculated and presented in e) single event; and f) continuous production. aW, attowatt = $10^{-18}$ K; aK, attoKelvin = $10^{-18}$ K.

## 5.3  Willow

Willow differs from forest residues (branches, tops and stumps) in an important way. Forest residues are produced from land already established for forest production. The reference case is a scenario where the residues are left to decay naturally. Therefore, using forest residues for energy results in net emission compared to the reference case. Willow is usually established on arable land which has earlier been used for crops. According to simulations by Ågren et al (2010), the establishment of willow will increase the total carbon per area unit as compared to crops. So using willow for energy causes a *net carbon uptake* compared to the reference case crops. This puts willow at a significant advantage compared to forest residues, but requires additional land. Figures 9 a-c show calculated emissions, radiative forcing and global average surface temperature change for producing willow, with crops as the reference scenario. The functional unit is one hectare of land. For comparison corresponding emissions, radiative forcing and temperature is calculated if coal was used for energy instead of willow.
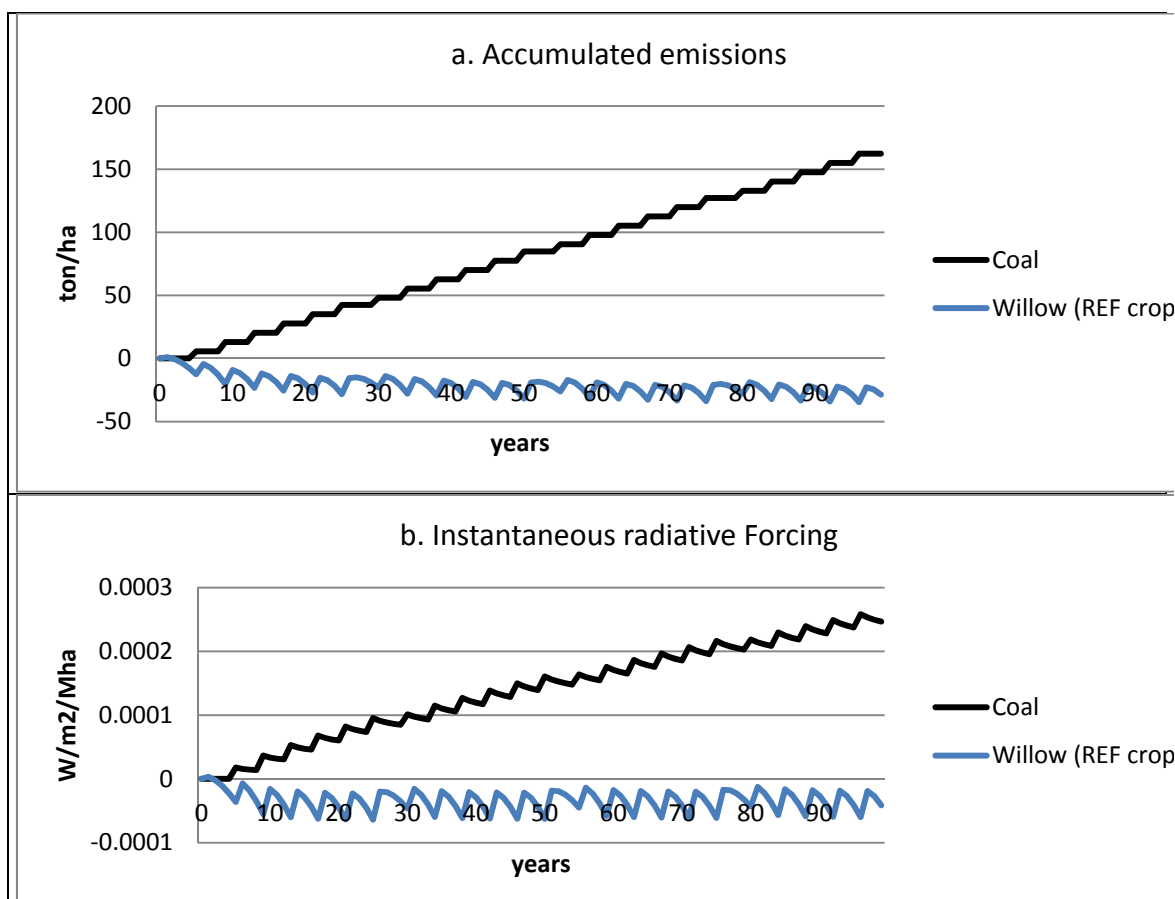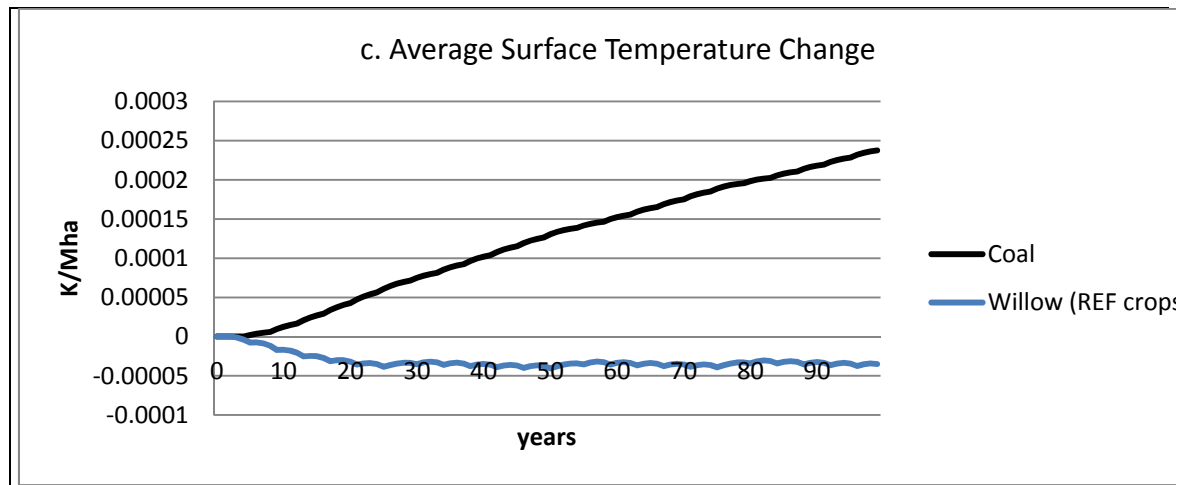
**Figure 9.** Climate impacts from producing willow for energy, with crops as the reference scenario. a)
shows emissions, b) instant radiative forcing and c) temperature change. Impacts from using
the corresponding amount of coal are shown for comparison.

## 5.4  High resolution climate simulations

Based on two schematic emission scenarios, the climate response over a 100 year period
has been calculated by the Planet Simulator and IMAGES. The main purpose is to see if a
General Circulation Model can produce a discernable climate response from a carbon
neutral emission scenario where there is a time lag between emissions and uptake. In
addition, these model simulations have been used to calibrate the IMAGES-model.
Emission scenario (a) starts with an emission pulse at t=0 (representing combustion)
corresponding to 30 ppmv atmospheric $CO_2$, followed by an annual uptake during 20 years
until the emission pulse is fully compensated[7]. Emission scenario (b) is identical to (a), but
with the difference that the order is changed, starting with an annual uptake, followed by a
pulse emission after 20 years. The Planet Simulator was executed five times for emission
scenario a (emissions before uptake) and three times for emission scenario b (uptake before
emissions). Figures 10 a-b show the change in global average surface temperature,
calculated as the average from the set of model runs. For comparison, results from the
Planet simulator and from IMAGES are presented in the same graph.

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[7] The value 30 ppmv is chosen for illustration. One ppmv $CO_2$ corresponds to approximately 5.5 Gt $CO_2$ in
the atmosphere.

a. Global average surface temperature change based on a schematic bioenergy emission scenario with emissions preceding uptake



b. Global average surface temperature change based on a schematic bioenergy emission scenario with uptake preceding emissions
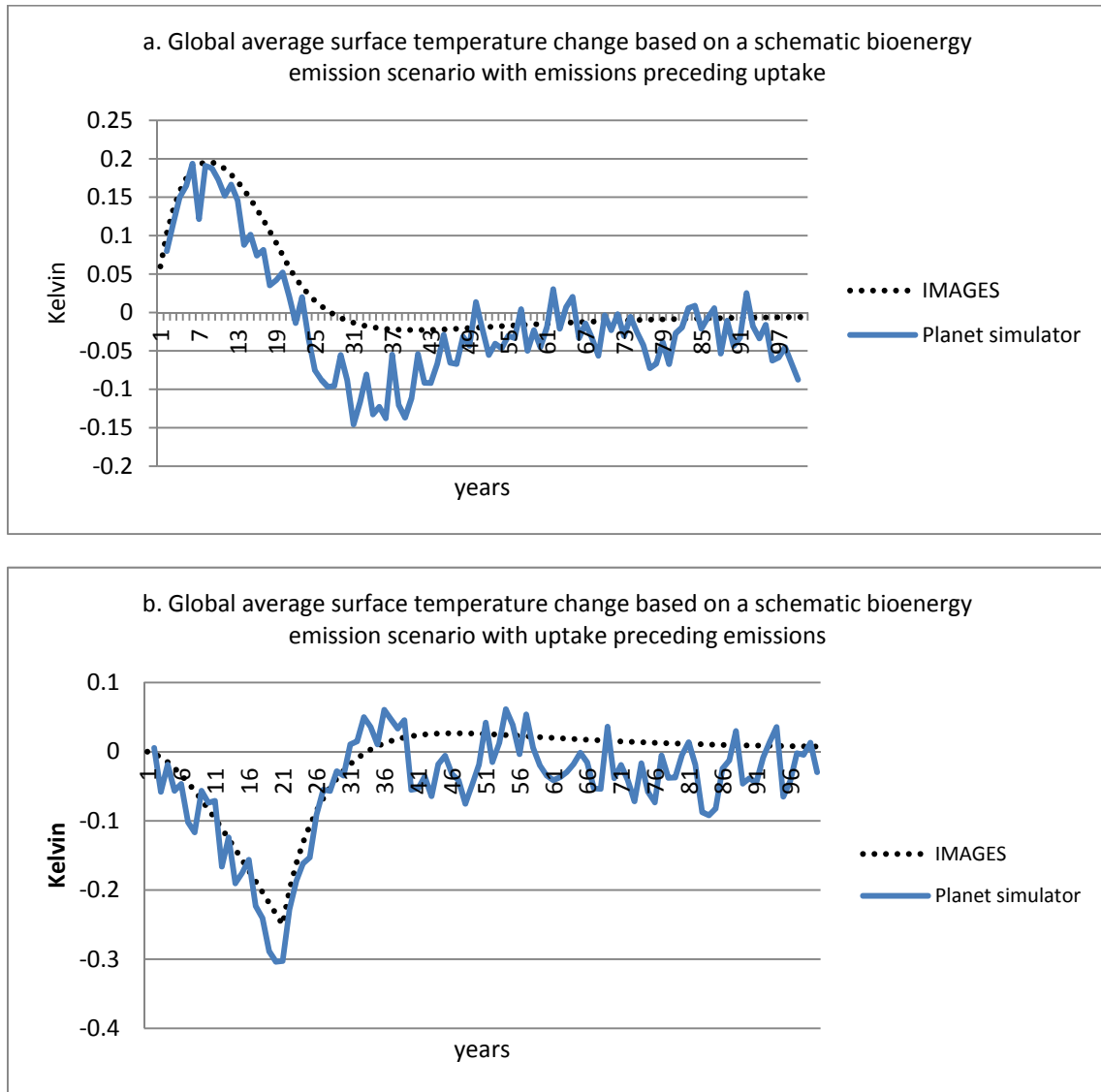
**Figure 10.** Global average surface temperature change calculated by the Planet simulator and IMAGES, based on two schematic bioenergy scenarios. Emission scenario (a) starts with an emission pulse at t=0 (representing combustion) corresponding to 30 ppmv atmospheric $CO_2$, followed by an annual uptake during 20 years until the emission pulse is fully compensated. Emission scenario (b) is identical to (a), but with the difference that the order is changed, starting with an annual uptake, followed by a pulse emission after 20 years.

According to the simulations by Planet Simulator, a carbon emission pulse at t=0, which is fully compensated over 20 years by an annual carbon uptake rate (emission scenario a) will lead to a change in global average surface temperature. If the first emission pulse corresponds to an instant increase of atmospheric carbon of 30 ppm $CO_2$, the maximum temperature change is 0.22 degrees above the reference level and occurs within the first decade after the emission pulse. The compensatory uptake clearly reduces the effects of the first pulse and leads to a negative temperature change, as compared to baseline, which reaches a minimum, 0.15 K below the baseline, 30-38 years after the initial pulse. Averaged over the first 100 years, the temperature change is -0.01 K. In the reverse bioenergy

scenario (b), an annual carbon uptake for 20 years, followed by an emission pulse at t=20, leads to a decrease in global average surface temperature, reaching a minimum, -0.30 K below the baseline at t= 19 years. The emission pulse at t=20, increases the temperature to a maximum level of 0.07-0.08 K above the baseline in the fourth and sixth decade. Averaged over the first 100 years, the temperature change is -0.05 K.

# 6.    Sensitivity analysis of model parameters

In this chapter, the importance of different model parameters to the simulations is analysed.

## 6.1  Importance of heat capacity, *mc* of the climate system

Here, the importance of the heat capacity of the climate system, mc, is analysed. Since the default simulation uses a low value for mc (corresponding to an e-folding time of 8.4 years), temperature changes have been re-calculated for all fuels when increasing the heat capacity by a factor 4 (corresponding to an e-folding time of 33.6 years). The result, presented in Figure 11 shows that increasing the heat capacity by a factor 4 reduces the temperature impact, and significantly so over a short time scale. However, the *relative* impacts between fuels are not sensitive to increasing the heat capacity.
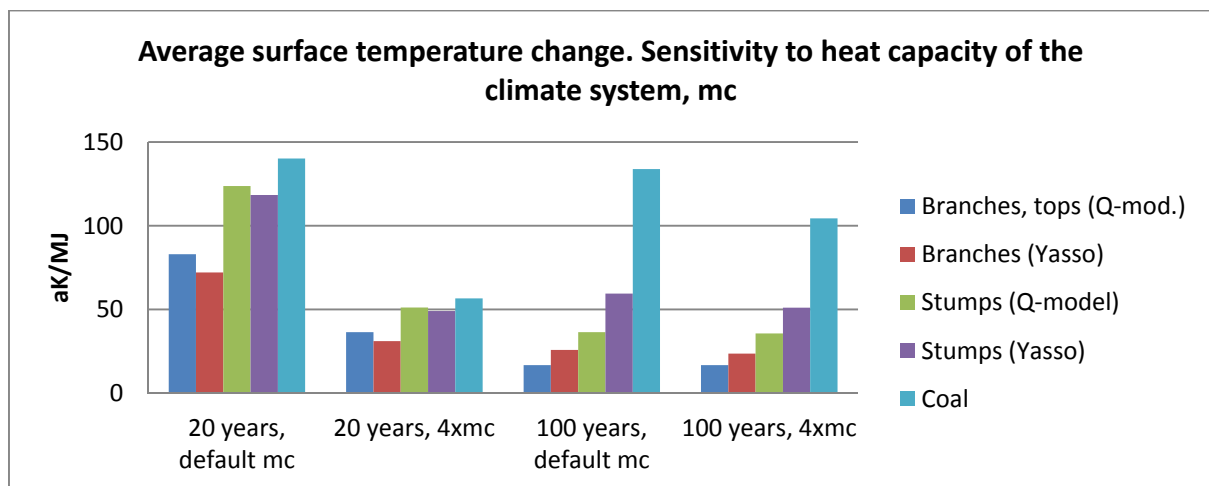


**Figure 11.** The importance of heat capacity of the climate system, *mc*. Calculated average surface temperature change [aK/MJ] for different fuels, grouped by time perspective and heat capacity of the model.

## 6.2  Importance of climate sensitivity, $\beta$

Here, the importance of the climate sensitivity parameter, β, is analysed. In general circulation models, β is usually within the range 0.83-2.5. The temperature change for all fuels have therefore been re-calculated using β-values of 0.83 and 2.5 $K^{-1}Wm^{-2}$. The results, presented in Figure 12 shows that the choice of β has significant impacts on the absolute values of global average surface temperature change. High β-values reduce the temperature impact. However, the relative impacts between fuels are not sensitive to changes in the climate sensitivity of the model.
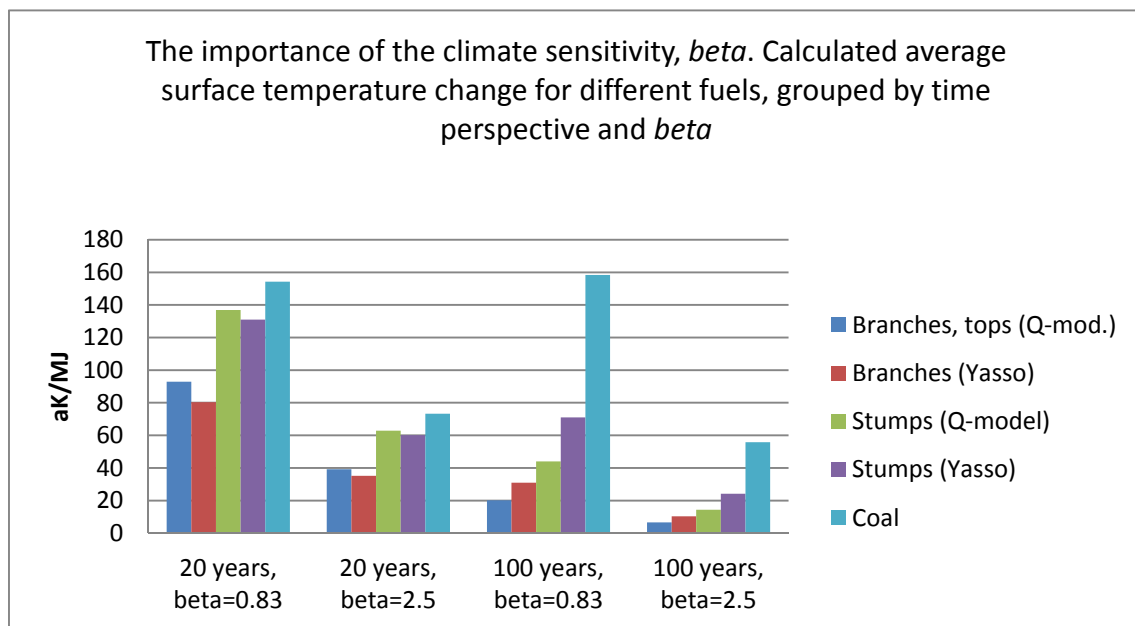


**Figure 12**. The importance of the climate sensitivity, *Beta* of the model. Calculated average surface temperature change [aK/MJ] for different fuels, grouped by time perspective and *Beta*

## 6.3  The importance of metrics for assessing dynamic climate change

The importance of metrics has been analysed by comparing the ratio between calculated temperature change and instant radiative forcing for different fuels assuming the continuous use of 1 PJ fuel per year. The results are presented in Figure 13.

**Figure 13**. The role of chosen metrics for assessing climate impacts. The ratio between instantaneous radiative forcing and temperature change for the continuous utilisation of 1 PJ fuel per year, grouped by time scale.
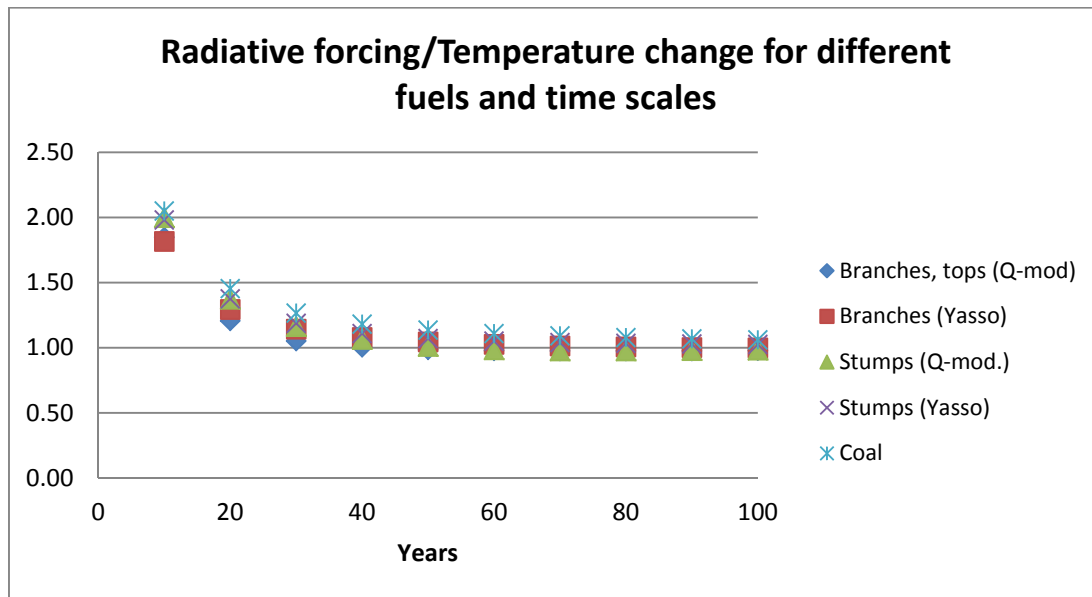
Over a long time scale instant radiative forcing and global average surface temperature change are well correlated. On a shorter time scale however, radiative forcing overestimates the temperature effect. This effect is enhanced if the heat capacity of the climate system, *mc* is increased (not shown in the figure).

# 7.  Discussion

This paper investigates the climate impacts from biofuels due to how fast the combustion related emissions are compensated by carbon uptake or avoided emissions. Different fuels, representing different uptake rates are investigated. Table 4 shows that branches and tops have faster uptake rates than stumps, which in turn have a faster uptake rate than coal. Climate impacts, expressed in emissions, radiative forcing and temperature change, presented in Figures 8 a-f, show that branches and tops have lower climate impacts than stumps, which in turn have lower climate impacts than coal.

**Comparison with earlier studies (Table 1).** The estimated emissions over a 100 year perspective for branches and tops, 2-5 g $CO_2$/MJ, are in the lower range of earlier studies which range between 2-26 g $CO_2$/MJ. Lindholm et al (2010) estimated **average** emissions over 100 years to be 20 g $CO_2$/MJ for branches and tops and 37 g $CO_2$/MJ for stumps. Corresponding values from this study are 14-19 g $CO_2$/MJ for forest residues and 28-43 g $CO_2$/MJ for stumps. In this study, estimated radiative forcing after 100 years for the continuous utilisation of 1 PJ branches and tops  per year, 1.7-2.6 μW/m², confirm results reported by Zetterberg et al (2004) and Holmgren et al (2007) which range between 1.6 and 2.6 μW/m². In this study, estimated accumulated radiative forcing over 100 years for branches and tops (single event), 55-81 nJ/m²/MJ, confirm results from Kirkinen et al,

which estimate the *RRFC* for forest residues to be 20-40, corresponding to an accumulated radiative forcing of approximately 40-80 nJ/m$^2$/MJ fuel.

**System boundaries**. This paper investigates the climate impact due to how the use of bioenergy influences biogenic carbon stocks and fluxes. The investigated system includes uptake of atmospheric carbon in the forest ecosystem and emissions of biogenic carbon from the forest ecosystem to the atmosphere either due to decomposition or combustion. In the case of calculated radiative forcing and global average temperature change, the global carbon sink processes that transports carbon to other pools, mainly uptake in mixed ocean surface water, are also included. A complete life cycle analysis of the investigated fuels has not been performed. For instance, emissions from fuel use related to harvest, collection and transportation of the forest residues are not included. Other studies estimate these emissions to be approximately 1-3 g/MJ, which can be compared to the carbon content of biofuels of approximately 95 g/MJ. Kirkinen (2010) presented the value 1.8 g $CO_2$/MJ ; Zetterberg et al (2004) estimated fossil fuel use for forest machines to be 3 g $CO_2$/MJ, Wihersaari (2005) estimated these emissions to be 1.1-1.9 g $CO_2$/MJ and Lindholm et al (2010) presented the range 1.5-3.5 g $CO_2$/MJ. Moreover, energy conversion losses, for instance in the production of heat or electricity, has not been considered in this study. Under the assumption that such conversion losses are largely fuel independent, omitting them will not have a major influence on the relative impacts between fuels. Other greenhouse gases than $CO_2$ are not included in the analysis. Lindholm et al (2010) and Wihersaari (2005) estimated the climate effects from combustion related methane and nitrous oxide to be approximately 2 g $CO_2$-equiv./MJ. Substitution effects, such as avoided emissions from fossil fuel use, are not included. Whether extraction of branches, tops and stumps may affect forest production in the next forest generation has not been analysed.

**The importance of time perspective**. The time perspective over which the analysis is done is crucial for the climate impact of biofuels. Over a 100 year perspective branches and tops are significantly better for climate mitigation than stumps which in turn are also significantly better than coal. Over a 20 year time perspective this conclusion holds, but the relative difference between biofuels and coal is smaller. This may have important implications from a climate policy context. If climate policy requires that impacts of biofuels are calculated over a 20 year period, then the benefits of avoided emissions for forest residues can only be accounted for during the first 20 years. Although our results indicate that forest residues have lower climate impacts than coal such policies would put forest residues at a significant disadvantage vis-à-vis coal and most likely other fossil fuels too.

**Establishing energy crops on new land**. Estimates from this study show that using forest residues for energy results in net emissions that decrease over time compared to the reference case where the residues are left to decompose. In contrast to the use of forest residues, willow is usually established on land which has earlier been used for crops. The analysis shows that establishing willow may result in a net accumulation of carbon in the soil thus and a net uptake of atmospheric carbon compared to the reference case of crops. This means that from a climate mitigation point of view, willow may have a significant advantage compared to forest residues, provided that new land is available. However, since

willow replaces crops, a relevant question to ask is how the crops are replaced. If the replaced crops are produced elsewhere through intensified agriculture or on new agricultural land, the analysis of the climate effects of willow should also include the net effects of moving the crops[8]. Such an expanded analysis has not been performed in our study. This makes it difficult to compare the climate impacts of forest residues with willow.

The issue is further complicated if alternative use of the crop land is considered. One could argue that if new land is acquired for willow production, there may be other ways to use this land that potentially could be even better for climate. Schlamadinger et al (1997), pointed out that "The question that has to be answered in the case of dedicated crops is: "Instead of what?" i.e. what would happen with the land if it were not dedicated for biomass productions. As an example, if corn is used for production of ethanol to displace the use of gasoline, then an alternative land use might be afforestation (with considerable uptake of carbon from the atmosphere)". Figure 14 illustrates the carbon stock changes for three different land use options: crops, willow and spruce. The figure shows that establishing spruce will also increase the carbon stock as compared to crops (after approximately 20 years). Moreover, spruce will surpass willow in terms of carbon stock (after approximately 30 years). Since a spruce forest also can be used for producing biofuels the question arises which option, willow or spruce, is best for climate. The analysis is beyond the scope of this paper, but it's likely that establishing spruce will create larger carbon pools than willow, but produce biofuels much later. Melin et al (2010) argue that there is an interesting trade-off between using stumps for bioenergy and adding them to the pool of dead organic matter. This problem also involves an important temporal dimension. What are the optimal alternatives in the short and long term and what does the transition between these options look like? In a broader context, land could also be used for other climate mitigation purposes, for instance wind power or solar energy parks.

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[8] However, if, for instance fallow land is available, energy crop production could be established without losing crop production.
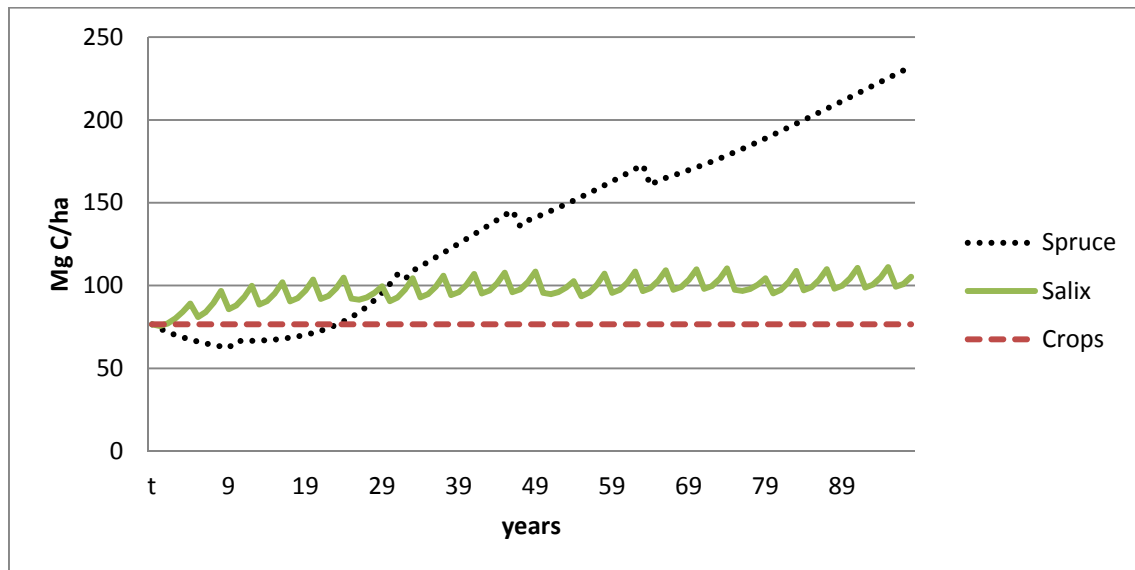
**Figure 14**. Carbon stock changes for three different options of land use. Illustration of what is the optimal land use option for climate mitigation, producing fuels or creating carbon pools? After 30 years, spruce surpasses willow in terms of carbon stock, while willow produces bioenergy earlier. Data is based on numerical simulations of carbon stock changes from the Q-model (Ågren et al, 2010).

**The importance of reference scenarios**. In this paper, the net emissions are defined as the difference between fuel utilisation and the reference case of not using this fuel. The convention for choosing reference scenario has been "business-as-usual". However the choice of reference case may have significant impact on the results, which the example of willow shows. With crops as the reference scenario, willow will reduce atmospheric carbon and have a net cooling effect.  However, if spruce is chosen as the reference case, willow will have a *net warming* effect from year 30 and onwards. This shows that the choice of reference case can significantly change the climate impact of willow and even the sign.

**What comes first, emissions or uptake?**

When the climate impacts of forest residues have been estimated, the analysis starts when the forest residues were extracted, not when the trees were planted. The calculated net emissions therefore show a pulse emission at t=0 corresponding to combustion. The combustion related emissions are then reduced over time due to avoided emissions in the reference case when the residues that are left on the ground to decompose. This reflects the typical situation in northern Europe with large areas of boreal forests.  It may be argued that uptake must come before emissions since if there is no growth, there can be no emissions. This is of course true, and is not in opposition to the assumptions of this investigation. In this paper, the point of departure is the decision to extract forest residues for energy instead of leaving them on the ground to decompose. This corresponds to a land use change and the consequent climate impacts are analysed. For forest residues the reference case is when the residues are left on the ground. Burning the residues for energy will result in net emissions compared leaving them on the ground.

In a hypothetical scenario, new forest could be planted on pasture land. When the forest is mature, say after 50-100 years, the trees are harvested, used for energy and the land is re-forested. Then the pasture land would have been the reference case. In this scenario there is an uptake of atmospheric carbon during the growth phase followed by emissions when the biomass is combusted. In this hypothetical case, uptake of atmospheric carbon clearly precedes emissions. However, the fuel is available only after 50 years.

**Metrics for assessing dynamic climate impacts from emission scenarios**. With the purpose of investigating dynamic climate change due to emission scenarios, global average surface temperature can serve as a complementary measure to radiative forcing. As compared to radiative forcing, global average surface temperature change gives a more direct measure of climate by and contains a relevant dynamic description in time as it accounts for the heat capacity of the atmosphere-ocean system. When comparing temperature change and radiative forcing, over shorter time scales (up to approximately 30 years) the radiative forcing overestimates the impact on global surface temperature change, which is due to the inertia of the climate system. Over longer time scales however (more than approximately 40 years) the climate impacts of different fuels are well described by radiative forcing.

Uncertainties regarding the climate sensitivity and heat capacity of the climate model lead to significant uncertainties in the *absolute* values of global average surface temperature change. However, the *relative* impacts between fuels are not sensitive to these factors.

**Impact of climate models used** A simpler energy balance model (IMAGES) can reasonably well capture the main features of the temperature response calculated by the Planet Simulator GCM, both with regard to the main dynamic features, their timing and amplitude. But there are differences too. The Planet Simulator yields high frequency features, which are not reproduced by IMAGES. Moreover, in the first scenario after 20 years when carbon uptake has stopped, the IMAGES temperature curve flattens out, whereas the Planet Simulator temperature continues to decrease significantly. Simulations with the Planet simulator shows that the temperature response is relatively fast with an estimated e-folding time of 8-9 years. This is rather short and is due to a rather simple ocean description in the planet simulator. In contrast, the $CO_2$-concentration responds significantly slower to an emission pulse, reaching $1/e$ only 97 years after an emission pulse.

**The development of carbon stocks** from a spruce forest in Växjö, presented in Figure 3, have been simulated by a dynamic ecosystem carbon model. According to these simulations, the forest is harvested when the annual growth is still high. This is in contrast to real conditions since forests are normally harvested when the annual growth rate is decreasing. Secondly, in the simulations extraction of forest residues is assumed not to affect the growth rates in the following generations. Moreover, our simulations do not include thinning events, which also differs from real conditions.

**Carbon dioxide emission factors** for the combustion of forest residues are compiled from different references and range from 95 to 115 g $CO_2/MJ_{fuel}$ (Table 3). The variation may be due to different assumptions of water content and calorific heating values. The

emission factors applied in this paper 94.4-95.0 g $CO_2/MJ_{fue}$ corresponds to calorific heating values of 19.2-19.3 MJ/kg dry fuel. Assuming a high water content would result in higher emission factors. However, power plants with flue gas condensation equipment can recover some of the heat energy bound in the water vapour. The carbon content is assumed to be 50 % for all fuels. This is probably a simplification since the lignin content, which affects the total carbon content, can vary significantly depending on species (Lundborg, 1994). If an alternative emission factor of 105 g $CO_2/MJ_{fuel}$ (+10 %) had been used in our analysis, the climate impacts of forest residues would increase by approximately 10 %. This would increase the climate impacts of forest residues compared to coal, but forest residues would still have lower climate impacts than coal, both over a 20 year and a 100 year time perspective.

# 8. Summary and conclusions

This paper investigates the climate impacts from biofuels due to how fast the combustion related emissions are compensated by uptake of atmospheric carbon or avoided emissions. A set of fuel types representing different uptake rates are investigated, namely willow, branches and tops, stumps and coal. Net emissions are defined as emissions from utilizing the fuel minus emissions from a reference case of no utilisation. In the case of forest residues, the compensatory "uptake" is rather avoided emissions from the reference case of leaving the residues to decompose on the ground. Climate impacts for different fuel types are estimated using the measures *emissions*, *radiative forcing* and *global average surface temperature change* and summarized in Table 5 below, grouped by fuel type and time perspective:

| ACCUMULATED EMISSIONS | Single utilisation of 1 MJ fuel at t=0 | | Continuous utilisation, 1 PJ fuel /year | |
|---|---|---|---|---|
| | Accumulated emissions (carbon stock changes) | | Accumulated emissions (carbon stock changes) | |
| | 20 years [g $CO_2$/MJ fuel] | 100 years [g $CO_2$/MJ fuel] | 20 years [Mton $CO_2$] | 100 years [Mton $CO_2$] |
| Branches and tops | 15 - 27 | 2 - 5 | 0.9 - 1.0 | 1.4 - 1.9 |
| Stumps | 57 - 58 | 3 - 25 | 1.6 | 2.8 – 4.3 |
| Coal | 93 | 93 | 2.0 | 9.3 |

| RADIATIVE FORCING | Single utilisation of 1 MJ fuel at t=0 | | Continuous utilisation, 1 PJ fuel/year | |
|---|---|---|---|---|
| | Accumulated Radiative Forcing | | Instantaneous Radiative Forcing | |
| | over first 20 years [nJ/m²/MJ fuel] | over first 100 years [nJ/m²/MJ fuel] | after 20 years [$\mu W/m^2$] | after 100 years [$\mu W/m^2$] |
| Branches and tops | 59 - 62 | 55 - 81 | 1.9 - 2.0 | 1.7 – 2.6 |
| Stumps | 103 - 107 | 113-193 | 3.2 - 3.4 | 3.6 – 6.1 |
| Coal | 129 | 450 | 4.1 | 14.2 |

| GLOBAL SURFACE | Single utilisation of 1 MJ fuel at t=0 | Continuous utilisation, 1 PJ fuel /year |
|---|---|---|

| TEMPERATURE | Average Temp change | | Temperature change | |
|---|---|---|---|---|
| | over first 20 years [aK/MJ fuel [9]] | over first 100 years [aK/MJ fuel] | after 20 years [μK] | after 100 years [μK] |
| Branches and tops | 72 - 82 | 18 - 26 | 1.4 - 1.6 | 1.8 – 2.6 |
| Stumps | 118 - 124 | 37 - 60 | 2.4 - 2.5 | 3.7 – 5.9 |
| Coal | 140 | 134 | 2.8 | 13.4 |

The analysis has focused on the importance of carbon uptake rates. However, a competed life cycle assessments of the investigated fuels has not been performed. The analysis has therefore not considered the use of fossil fuels for logging, transportation and refining, other greenhouse gases than carbon or energy conversion losses.

Based on the estimates, we conclude that:

- There is a climate impact from using bioenergy due to how fast the emission pulse is compensated by uptake of atmospheric carbon (or avoided emissions). Biofuels with slower uptake rates have a stronger climate impact than fuels with a faster uptake rate.

- The time perspective over which the analysis is done is crucial for the climate impact of biofuels. If only the carbon uptake rates are considered, our results show that over a 100 year perspective branches and tops are significantly better for climate mitigation than stumps which in turn are significantly better than coal. Over a 20 year time perspective this conclusion holds, but the relative difference between the investigated biofuels and coal is smaller.

- The choice of reference scenario is critical for the calculated net emissions from using biofuels and for the consequent climate impacts.

- Establishing willow on earlier crop land may reduce atmospheric carbon, provided new land is available. However, these results are inconclusive since we haven't considered the effects, if needed, of producing the crops elsewhere.

The conclusions are independent of choice of metrics (emissions, radiative forcing or temperature change) for assessing the climate impacts. *Radiative forcing* and *Temperature change* are both found to be appropriate measures for assessing the time dependent climate impacts of biofuels due to their carbon dynamics. *Temperature change* provides a more direct measure for climate impact. Over shorter time scales (in this study up to approximately 30 years), radiative forcing overestimates the impact compared with that expressed by global surface temperature change, which is due to the inertia of the climate system. On the other hand, calculating temperature change involves uncertainties related to the climate sensitivity and heat capacity of the atmosphere-ocean system. Uncertainties regarding the climate

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[9] aK, attoKelvin = $10^{-18}$ K

sensitivity and heat capacity of the climate model lead to significant uncertainties in the calculated *absolute* values of global average surface temperature change. However, the *relative* differences among different fuels considered are not sensitive to these factors. A simpler energy balance model can reasonably well capture the main features of the temperature response calculated by a much advanced General Circulation Model, both with regard to the main dynamic features, as well as their timing and amplitude.

Results from this study can help understanding the climate impacts from different bioenergy types, for instance for application in the design of efficient climate and energy policies. For instance, if policy requires that climate impacts from biofuels be calculated over 20 years, this may have important implications on the use of branches and stumps.

Results from this study can also help understanding the climate impacts from carbon neutral emission scenarios on a more principle level, beyond bioenergy use. One application could for instance be to understand the climate effects of "emissions compensation", i.e. when an emission from one activity is compensated by carbon uptake from another activity, for instance forestation.

# 9. Acknowledgements

# Appendix 1. Description of functions for calculating global surface temperature, used by *IMAGES*

The increased concentration of $CO_2$ creates a radiative forcing, $\Delta Q$, which drives the climate system to a new equilibrium. The dynamic response of global average surface temperature due to a forcing can be approximated by the feedback equation:

$$mc\frac{d}{dt}T = -\beta(T - T_{old\_equilib}) + \Delta Q \tag{12}$$

where $T$ is the global average surface temperature, $mc$ is the heat capacity of the climate system, and $\beta$ is the climate feedback parameter:

$$\beta\Delta T = \Delta Q \tag{13}$$

and where $\Delta T$ is the difference between the old and new equilibrium temperatures:

$$\Delta T = T_{new\ equilib} - T_{old\ equilib} \tag{14}$$

And by using (13) into (14):

$$T_{new\ equilib} = T_{old\ equilib} + \Delta Q/\beta \tag{15}$$

Solving equation (12) yields the dynamic temperature response:

$$T(t) = T_{new\ equib} - \Delta T * e^{-t\beta/mc} \tag{16}$$

In GCM:s, the climate sensitivity parameter $\lambda$ ($=\beta^{-1}$) is usually in the range of $\lambda = 0.4\text{-}1.2$ K $m^2W^{-1}$. This corresponds to a $\beta$ in the range of 0.83-2.5 $K^{-1}Wm^{-2}$. In this paper, we assume a default value of $\beta=1.0$ $K^{-1}Wm^{-2}$, and perform a sensitivity analysis for varying $\beta$ between 0.83-2.5 $K^{-1}Wm^{-2}$.

With an e-folding time of 8.4 years, this gives us a value for the system heat capacity, $mc=\beta*8.4$ years = 26.6 MJ/K/m2. For illustration, an equivalent heat capacity would be achieved by a combination of the atmosphere (m= 1300 $kg/m^2$, $c_p$= 1004 J/kg/K) plus 63 m of the ocean (m= 63 000 kg/ $m^2$; $c_v$=4218 J/kg/K). This e-folding time appears reasonable, since the mixed layer of the ocean is well integrated with climate system (over a time scale of some months); is approximately 100 meters deep; and the fact that the ocean corresponds to 70 % of the Earth's surface.

The dynamic temperature response, $dT$ is calculated by the IMAGES model for each time step $dt$. For this purpose, eq. (12) was re-written on the form:

$$dT = dt \cdot \frac{1}{mc} \left[ \Delta Q - \beta (T - T_{old\_equilib}) \right] \tag{17}$$

Simulation results from the *Planet simulator* were used to calibrate the IMAGES model in terms of climate sensitivity, *beta*, and the heat capacity of the climate system, *mc.*

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