Investigations of the mechanisms behind the carbon loss in a Swedish pine & spruce forest, with the ecosystem model LPJ-GUESS

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2015
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Abstract

Vegetation on land is globally taking up about 30% of the CO_2 that is emitted by human activities (oceans take up 30%, while 40% remains in the atmosphere). This ability to store carbon in the vegetation and in the soil is very important to mitigate the climate changes, but all land based ecosystems are not carbon sinks. Ecosystems that are losing carbon needs to be further investigated, so we can predict if more ecosystems are going to become carbon sources in the future and to find better management practices for the forests and farmlands.

The forest stand in Norunda, about 30 km north of Uppsala, Sweden, is one of few forest ecosystems with a healthy production and long term continuous CO_2 flux measurements that is losing carbon. Pine and spruce are the dominating plant species in Norunda and the soil is spatially heterogeneous with a fraction of about 10% peatland and 90% moderately moist land. The management history of the site includes e.g. drainage in the year 1890 and clear-cut in the year 1900. Measurements suggest that the soil respiration is unusually high in Norunda and this is probably a contributing factor to the loss of carbon.

The ecosystem model LPJ-GUESS is the tool used to test different hypotheses for the carbon source in Norunda. The model parameters were calibrated such that the model result for soil moisture, evapotranspiration, photosynthetic carbon assimilation, biomass increment and soil carbon content, had a good fit to in-situ measurements. The gaps between model result and measurements for soil respiration and net ecosystem exchange was left remained with purpose, because the idea was to test if the different simulated hypotheses could decrease these gaps.

The model was modified to test the hypotheses for drainage, peatland, clear-cut and thinning and the 20th century temperature increase. The result for the drainage and peatland modification suggests that these factors contributes with 1% - 47% of the observed carbon loss in Norunda. The simulation of clear-cut and thinning indicates that this slightly decreased the loss of carbon in Norunda 100 years after the clear-cut. A simulation with detrended temperature was performed, to test the effect of the 20th century temperature increase and the result suggests that the increase in temperature increased the carbon loss in Norunda with 17% over the period 1995-2003.

Other hypotheses for the carbon loss in Norunda might need further investigation, such as the possibility of net inflow of carbon from surrounding areas by the groundwater or by horizontal advection, which is common during calm nights.

Populärvetenskaplig sammanfattning

Den här studien har handlat om att försöka reda ut varför en produktiv tall- och granskog i Norunda allmänning, 30 km norr om Uppsala, förlorar kol. Att det är viktigt att studera kolbalansen i just den här skogen beror på att den är ett undantag som förlorar kol, eftersom skogarna på norra halvklotet globalt sätt tar upp en betydande del utav den koldioxid som släpps ut av människan och således mildrar de troligtvis växthuseffekten. Det är möjligt att svaret på gåtan om varför Norunda skogen förlorar kol kan hjälpa oss att ta hand om skogarna på ett bättre sätt ur ett klimatperspektiv och det är också möjligt att svaret på gåtan kan öka vår kunskap inom detta område, så att vi bättre kan förutse framtida klimatförändringar.

En ekosystemmodell som heter LPJ-GUESS var verktyget som användes för att finna svaret på gåtan. Den här modellen används framför allt till utbildning och forskning på Lunds Universitet, men den används också av forskare i andra delar av världen. Modellen simulerar bl.a. hur koldioxid tas upp från atmosfären och hur detta kol lagras i vegetationen och i marken, samt hur respirationen i växtligheten och nedbrytning i marken gör så att en viss del av kolet återförs till atmosfären. Att modellen simulerar hela ekosystemets kolcykel gör den till ett lämpligt verktyg för att studera kolbalansen i Norunda skogen.

Ett antal parametrar i LPJ-GUESS ändrades så att det simulerade ekosystemet skulle stämma väl överens med mätdata från Norunda. Skogen i Norunda är en tacksam plats att studera, eftersom det finns gott om mätdata därifrån.

Norunda skogen har en historik som inkluderar dränering år 1890 och skogsavverkning år 1900 följt av tre gallringar under 1900-talet. Två av hypoteserna till kolförlusten grundade sig på dessa historiska ingrepp i skogen. En tredje hypotes var baserad på variationen av fuktighet i marken. Det finns lokala våtsänkor som sammanlagt täcker ca 1/9-del av ytan i Norunda, där det finns mycket kol i marken lagrat i torv. Resterande del av skogen har en mer normal markfuktighet med mineraljord. Även en hypotes, som baserade sig på att temperaturökningen under 1900-talet kan vara en bidragande orsak till kolförlusten, inkluderades i projektet. För att kunna testa dessa hypoteser så modifierades källkoden i LPJ-GUESS så att hypoteserna kunde simuleras. Resultaten från simuleringarna jämfördes med mätdata av det uppmätta nettokolflödet för perioden 1995-2003, för att undersöka hur stor del av den observerade kolförlusten som kunde förklaras av de olika hypoteserna.

De mest väsentliga stutsatserna från resultaten är att att dräneringen har bidragit med upp till 32% av den uppmätta kolförlusten i Norunda. Resultaten från en kombination av dränering och våtsänkorna visar att dessa har orsakat 1%-47% av kolförlusten. En jämförelse mellan en simulering med orörd skog och en simulering med skogsavverkning och gallring pekar mot att avverkningen inte hade någon märkbar effekt på skogens kolbalans 100 år efter att skogen avverkades. Resultaten från simuleringarna med och utan temperaturökning tyder på att 1900-talets temperaturökning bidrog till att skogen i Norunda förlorade kol.

Resterande del av kolförlusten kan möjligtvis ha orsakats av att den horisontella lufttransporten, som är högst under vindstilla nätter, kan ha skapat ett horisontellt nettoinflöde av koldioxid, vilket skulle kunna ha gjort att mätinstrummenten registrerade en för hög kolförlust. Ytterligare en hypotes är att det kan ha funnits ett nettoinflöde av vattenlösligt organiskt material som transporterades med grundvattnet in i Norunda skogen och där brutits ner i marken, vilket kan ha givit upphov till ett förhöjt koldioxidflöde från marken till atmosfären.

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1. Introduction

1.1 Global climate change

Climate change and the greenhouse effect have the last decades been intensely debated in the media and in the political arenas. In the meantime the wheels of the scientific community have kept spinning, with an increasing acknowledgment and a growing economic budget for research. Many gaps in our understanding of the climate have been filled and computer models are continuously being more accurate and reliable. The picture of human contribution to climate changes is now much clearer and the skeptics have a reduced influence on the debate. Even globally important policymakers have more and more embraced the idea that it is urgent to take comprehensive measures. The problem is that climate issues are easily moved down on the priority list, when there are other political issues that seem more urgent to deal with for the moment, such as a new cold war, terrorism and global economic crises. The complexity of the global climate system is one difficult obstacle for the climate researchers in their struggle to reach out to the public and the politicians. Thus today's most important assignment for the climate researchers is to further increase the knowledge about the processes affecting the climate and how we can expect them to act in the future. Hopefully the policymakers could be convinced to really change direction if the story of the future could be told with even more certainty than today. Otherwise we will probably have to wait until the convincing power of catastrophes, disasters and suffering is strong enough. We can of course hope that an economic incitement will appear, such as increased fossil fuel prices or technological progress that creates a cheaper sustainable energy source/consumption. However, to put all our eggs in one basket that is the appearance of an economic incitement would be like forcing our planet to play Russian roulette. The effort in developing a sustainable energy source/consumption could also gain from a better understanding of the climate. This makes it as urgent as ever to intensify the research of all aspects concerning climate change, because the time can run out to change direction of this ship.

Global warming is a central part of climate change, because it is probably the primary cause of many of the climate changes that have been observed. Rising sea levels and increase in e.g. drought, flooding and hurricanes are all likely to originate from global warming (IPCC, 2014). 9 out of 10 of the warmest years since 1850 until 2014 are all after the year 2000 (NOAA: web source). The only earlier year in that record is 1998. The average global temperature has increased 0.85°C over the period 1880-2012 (IPCC, 2014). The statement that the global temperature is remarkable rapidly increasing, is strongly supported by a newly published article by Marcott (et al., 2013). Their study has a uniquely global coverage of the data and reaches over a longer time period than most other studies. Their conclusion is that the global temperature in the year 2100 will be higher than ever for the last 11,300 years, even with the IPCC scenario with least human impact on the climate.

CO_2 is a key player in climate change. It is 'extremely likely' (this term means an estimated probability of 95%-100%) that most of the increase in global temperature since the mid-20th century is caused by anthropogenic (human created) greenhouse gases and CO_2 is the most important of those (IPCC, 2014). The atmospheric concentration of CO_2 increased in an exponential way from 280 ppm in 1750 to a level just beneath 400 ppm at present (IPCC, 2014). The present CO_2, CH_4 and NO_2 concentrations are at their highest levels for the last 800 000 years (IPCC, 2014) and even for the last 20 million years, according to Pearson et al. (2000).

1.2 Terrestrial carbon uptake

Scientists were confused for many years, because their calculations of known CO_2 emissions did not add up to the rise in atmospheric carbon. There was less CO_2 stored in the atmosphere than expected and the search for the "missing sink" begun. The unknown carbon uptake appeared to take place in terrestrial areas (land areas) by vegetation and in the oceans. The terrestrial uptake from 2000 to 2006 was 30% of the CO_2 that was emitted by fossil fuel combustion and land-use change (Canadell et al., 2007). The mid-latitudes of the northern hemisphere are responsible for most of this carbon uptake (Solomon, 2007). The ocean uptake is also about 30%, while about 40% remains in the atmosphere (IPCC, 2014). Thus, the climate change is reduced by these carbon sinks, but the CO_2 emission increases faster than the uptake (Le Quéré et al., 2009) and the terrestrial uptake is especially variable.

A sign of the terrestrial carbon uptake can be found in a recently published study, which includes 25 European countries (Luyssaert et al., 2009). It shows an increasing carbon uptake in forests, both in the vegetation and in the soil. The strengthening in growth is probably due to land management practices, increased CO_2 in the air, which acts as a fertilizer because it is a main component in the photosynthesis, and increased nitrogen deposition (Denman et al., 2007), which is the most growth limiting nutrient in the northern forests (Schindler et al., 1999). However, efficiency of CO_2 fertilization is expected to decrease when the vegetation adapts to higher CO_2 concentration levels (Bonan 2002) and there is a concern for nitrogen saturation which should decrease its fertilizing effect (Schindler et al., 1999). Both carbon uptake by photosynthesis and carbon release by respiration in the forest vegetation and by the soil decomposition are affected by climate, atmospheric composition, nutrients, and management methods like clear-cut and thinning, drainage and agriculture, but there are serious gaps in the knowledge about these factors. Especially soil processes are covered by a blanket of uncertainties, but are crucial part of the equation, because the soil stores almost three times more carbon globally than the vegetation (Bonan, 2002). Thus, the future fate of the carbon balance in forest ecosystems is still highly uncertain and this is really an important piece of the global climate jigsaw puzzle, which needs to be placed to reveal the overall picture.

Most forest ecosystems where the carbon flux has been continuously monitored for several years, appear to be carbon sinks (e.g. Valentini 2000 and van Dijk 2004). The only forests that have been reported as long lasting major carbon sources, are a pine and spruce forest in Norunda, central Sweden (Lindroth 1998), a Russian Taiga spruce forest (Milyukova 2002), a pine and oak forest in Brasschaat, Belgium (Carrara et al., 2003) and a Black spruce forest in Canada (Goulden 1998). The carbon source in Russia could probably be partly explained by the existence of many dead decaying trees due to severe droughts and a storm in the 1990s (Milyukova 2002). Carrera (et al., 2003) emphasis the intensive thinning in the Brasschaat forest since the 1980s as one probable explanation to the carbon loss. Falge (2002) also mentions that the data from Brasschaat could be biased by anthropogenic sources in the residential areas. One interesting thing is that all these four studies have higher than normal temperature as one of their main hypotheses to the carbon source. If this is the case, then it is truly alarming in a continuously warming world. The fact that these forests are spread out over the globe, in latitudes that are assumed to be responsible for the terrestrial carbon uptake, really highlights the importance to investigate the mechanisms behind these carbon sources.

1.3 The forest stand in Norunda

The forest in Norunda is the chosen candidate for this study. It is located about 30 km north of Uppsala in central Sweden and the 100 year old forest is a mixture dominated by Scots pine and Norway spruce. A 102 meter high tower was built in 1994. It was equipped with instruments for continuous measurements of carbon fluxes, water fluxes and meteorological parameters. Many campaigns and studies have taken place in this forest since then. The combination of the access to nearly continuous data and a great amount of available literature about this forest, are necessary ingredients to make this study possible.

The carbon flux measurements from the tower reveals that the forest is losing carbon in the long term. The instruments for carbon flux measurements were updated a few years ago and results from the new equipment show an even greater carbon loss than before (Mölder, personal communication). Also studies based on up-scaled compartment measurements (soil and branch chambers), show a loss of carbon (Morén, 1999 and Widén 2001). The discovery of a forest that is losing carbon got great attention when it was published by Lindroth et al. (1998). The common idea that a healthy growing forest is always taking up carbon, was put to the test. There is still no certain explanation to the carbon loss, even though the numerous attempts to solve this question during the last 20 years. It is very exciting to be given the opportunity to approach this problem from a new angle and to have a chance to contribute to the long sought explanation, which can also be a meaningful contribution to a better understanding of how the forest affects the global climate in the big picture.

1.4 Why is the forest stand in Norunda a carbon source?

So, why is the forest in Norunda losing carbon? A chronosequence study (i.e. a study of similar stands at different ages) in Sweden by Lindroth et al. (2003) shows that Norunda has similar photosynthesis as the other younger stands, but it has a much higher total ecosystem respiration. Granier (2007) and Lindroth (2008) also support the statement, that Norunda has an unusually high ecosystem respiration. Several studies confirm that the carbon uptake declines with age because of higher maintenance respiration and decreased growth (Bonan, 2002 and Gower, 2003), but the 100 year old forest in Norunda is still growing strong with a tree increment above 200 g C m^{-2} yr^{-1} (Lindroth et al., 2003). The conclusion must be that it is the soil that is losing carbon and the chamber measurements of the soil carbon flux that is presented in Widén (2001), show that there is in fact a high out-flux of carbon from the soil in Norunda compared to other similar forest stands.

The mechanism behind the carbon source in Norunda could perhaps be found in the extensive human impact of the site. The history of management practices includes drainage at the end of the 19th century, clear-cut in the year 1900 followed by three occasions of thinning and the forest was fertilized with nitrogen in the 1970s. One main hypothesis in this project is that drainage is the key factor behind the carbon loss. The forest could probably be classified as a mixture of wetland and poorly drained forest before the drainage. Carbon accumulates in wet soils, as the lack of oxygen limits the activity of the microbes that decompose the soil organic material (Chapin III et al., 2002). The decomposition increases after drainage when the oxygen demand is satisfied, as long as the soil does not get too dry. This will often result in a loss of soil carbon. Exceptions have been reported, for example from drained peatlands in Finland

(Minkkinen, 1998), where the increase of tree growth, litter fall and fine root turnover were higher 60 years after drainage than the increase of soil decomposition. Von Arnold (et al., 2005a) studied four coniferous forests in Sweden 30-50 years after drainage and found that the sites which had a minor lowering of the ground water table acted as carbon sinks, whereas well-drained forests (such as Norunda) were carbon sources. After all, a well-drained forest has in general much less soil carbon content than a wetland, according to the numbers of mean soil carbon content for the world's terrestrial vegetation (Bonan, 2002), which must be interpreted such as the usual long term effect of substantial drainage is a shift from a higher to a lower level of soil carbon content. Perhaps it could be this transformation to a lower soil carbon level that is detected in Norunda.

Decomposition of soil organic matter decreases exponentially with time, as the soil organic material is decomposed and transforms into a more recalcitrant form. Thus, one task in this project was to answer if it is possible that the soil still contains enough old soil organic matter from the period before drainage and if this is labile enough to be responsible for the loss of soil carbon that is detected at the present, over 100 years after drainage. This question was also processed in a more complex way, where the calculations included that about 10% of the area surrounding the tower is classified as peatland with a high level of accumulated soil carbon (Schrumpf, personal communication).

Clear-cut usually result in a loss of carbon, mainly because of decreased photosynthetic activity after the trees are removed from the ecosystem. A couple of studies suggest that the carbon source after clear-cut will last about 15 years (Lindroth et al., 2003, Schulze et al., 1999), but this will obviously depend on the amount of left residuals, soil disturbance, vegetation type and the regrowth ability. The vegetation will then recover and the ecosystem will turn into a carbon sink, which it remains as until an age of 150 years according to Gower (et al., 2003), or at least 200 years according to Pregitzer (et al., 2004), when it turns into neutral or a carbon source. The high increment in Norunda rules out the high stand age theory as a possibility and the forest is much younger than the age where a forest turns from a sink to a source. The effect of clear-cut and thinning was still investigated, even though this is unlikely to be the cause of the carbon source.

Lindroth et al. (1998), suggest that temperature could be one of the factors behind the carbon source in Norunda. This hypothesis is based on the fact that the photosynthetic activity has an optimum temperature and it declines above that, whereas respiration increases exponentially (Bonan, 2002). The summation of these fluxes gives a net ecosystem flux with an optimum uptake for a certain temperature, with a decrease above that and the respiration will be the dominating flux for higher temperatures, at least if every other influencing factor is kept constant. Thus, the idea that the global warming is the cause to the carbon source in Norunda, agrees with our knowledge about a forest's carbon balance and a simple test of this hypothesis was included in the project.

1.5 LPJ-GUESS – the tool to investigate why the forest stand in Norunda is losing carbon

The ecosystem model LPJ-GUESS (Smith et al., 2001) simulates all important parts of the ecosystem carbon cycle, both a dynamic vegetation and the soil. This model also simulates the biogeochemical and physical processes that produce an in-flow or out-flow of carbon and water of the ecosystem compartments. These processes have mechanistic representations in the model, i.e. the processes in the model are designed to simulate real ecosystem processes instead of just using some function that is fitted to e.g. the resulting fluxes.

To approach this subject by using a model that is fully coupled between the different components in an ecosystem, instead of using just a soil carbon model (such as Materia, 2004), increases the realism of the simulations and increases the reliability of the results. This kind of model makes it possible to address the subject from different angels and it also makes it possible to 'step in to' the simulation and analyze how a certain ecosystem process is affecting the result.

Different modifications of LPJ-GUESS were made to simulate and test the hypotheses of clear-cut, drainage, peatland and temperature increase.

1.6 Aim of this study

The major objectives in this project was to:

1. Calibrate the model, with clear-cut and thinning, in such way that the model output had a good fit to in-situ measurements, except for soil respiration and *NEE* (net ecosystem exchange). The reason to let the simulated soil respiration deviate from the measurements on purpose, was based on the assumption that the carbon loss is caused by an unusually high soil respiration in Norunda.
2. Incorporate a function that decreases decomposition at high soil moisture, to be able to simulate the hypothesis of drainage and peatland.
3. Modify LPJ-GUESS to the different hypotheses/scenarios:
    a) *Drainage:* This hypothesis was based on the idea that soil carbon content must have been higher prior the drainage and perhaps the exponential decrease of soil carbon after the drainage could have created a net out-flux of carbon from the forest 100 years after the drainage. The conclusions from other studies, showing that the transformation of soil organic matter from a labile form to a more recalcitrant form is suppressed by high soil moisture, had to be incorporated in the model to get enough decrease of soil carbon, so the effect in *NEE* was noticeable 100 years after drainage.
    b) *Peatland:* About 10% of the area in the forest stand, at the locally lower depressions, have higher soil moisture and high soil carbon content accumulated in peat. The hypothesis was that decomposition in these areas could explain the observed carbon loss in Norunda.
    c) *Minimum and maximum*: These were scenarios with weighted result with a fraction of 10% for peatland and 90% for the moderately moist areas. The reason for these scenarios was the uncertainty in the soil carbon content in the wet areas and to what extent high soil moisture can suppress the transformation of soil organic matter to a recalcitrant form. The minimum scenario used the values from a realistic range of these uncertainties that gave the minimum effect of closing the gap between simulated and observed *NEE* during the period 1995-2003. Maximum scenario used the values that gave the maximum effect of closing the gap in *NEE*.
    d) *Clear-Cut and thinning:* This simulation is performed to test if clear-cut and thinning had an effect on *NEE* 100 years after clear-cut.
    e) *Temperature increase:* The 20th century temperature increase is suggested to have been a contributing factor to the observed loss of carbon in Norunda. This was tested by a

comparison with the baseline scenario (the clear-cut & thinning scenario), between a simulation with standard temperature as input and a simulation with detrended temperature as input.

4. Use the program Matlab to calculating e.g. accumulated *NEE* for the measurement period (1995-2003) and to visualize the result in figures.
5. Analyze the result, especially how the different scenarios affected the gap between the baseline simulation and observed *NEE* for the measurement period (1995-2003)

2. Background - Forest ecosystem carbon cycle

Only a brief review of the carbon cycle terms and their relations are presented here.

- ***GPP*** (gross primary production): *GPP* is the photosynthetic assimilation of carbon from the atmosphere. Photosynthesis is dependent of sunlight within a certain wave length (*PAR*: photosynthetic active radiation). Photosynthesis has optimum relations to soil moisture and temperature (i.e. optimum photosynthesis for certain values of these climatic variables). *GPP* increases with ambient atmospheric CO_2 concentration.
- $\boldsymbol{R}_{\mathbf{auto}}$ (autotrophic respiration): R_{auto} is the vegetation respiration. It is the summation of maintenance respiration, growth respiration and reproduction cost. R_{auto} is exponentially increasing with temperature.
- ***NPP*** (net primary production): *NPP* is the net vegetation CO_2 flux:

$$NPP = GPP - R_{\mathrm{auto}} \tag{1a}$$

$$NPP = biomass_{\mathrm{increment}} + biomass_{\mathrm{turnover}} \tag{1b}$$

- $\boldsymbol{R}_{\mathbf{hetero}}$ (heterotrophic respiration): R_{hetero} is the CO_2 flux that originates from decomposition of organic material in the soil. Also known as soil respiration. $\mathrm{R}_{\mathrm{hetero}}$ is exponentially increasing with temperature and decreases if the soil moisture level are too low or too high.
- $\boldsymbol{R}_{\mathbf{eco}}$ (ecosystem respiration): $\mathrm{R}_{\mathrm{eco}}$ is the total ecosystem respiration:

$$R_{\mathrm{eco}} = R_{\mathrm{auto}} + R_{\mathrm{hetero}} \tag{2}$$

- ***NEE*** (net ecosystem exchange): *NEE* is the total net CO_2 flux for an ecosystem to the atmosphere (a positive sign represents a loss of carbon from the ecosystem):

$$NEE = R_{\mathrm{auto}} + R_{\mathrm{hetero}} - GPP \tag{3}$$

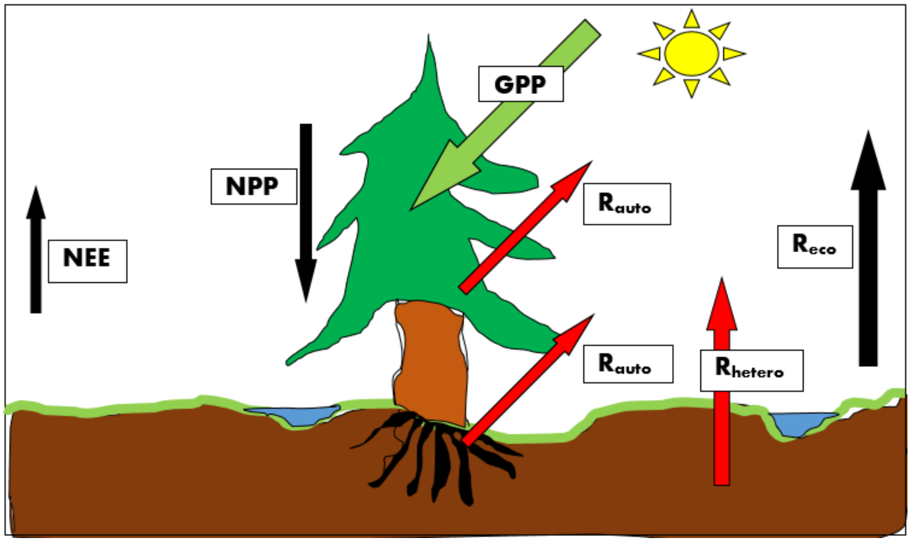


Fig. 1 Forest ecosystem carbon cycle. Observe that R_{auto} includes root respiration. The arrow directions (to/from the ecosystem) represents positive values for the fluxes.

3. Methods

3.1 Site description – Norunda flux-tower forest stand

Fig. 2 The location of Norunda, Sweden (CC: Creative Commons, Wikimedia Commons)

The Norunda ecosystem flux site is located about 30 km north of Uppsala (60°05′N, 17°29′E) (fig. 2). Average annual air temperature is 5.6°C and the annual average precipitation is 544 mm (for the data period 1961-1990 at SMHI's station in Uppsala).). The area is fairly flat with small-scale local altitude variation up to 10 m. The stand age of an area within a radius of about 300 m around the flux tower, was about 100 years during the measurement period and the canopy height was about 25 m. Scots pine (Pinus sylestris) and Norway spruce (Picea abies) are the dominating tree species with 98% of the total basal area of the forest site and 2% is deciduous, mainly birch (Betula sp.) (Lagergren, 2008). The soil of the area is heterogeneous (Marion Schrumpf, personal communication), with about 90% moderately moist podzolized soil (sandy loamy tills) with a carbon content of about 9 kg/m^2. The remaining 10% of the area, at the locally lower depressions, have much higher soil moisture, *Sphagnum sp.* (peat moss) is the dominating plant species and peat is accumulated with a soil carbon content of 25 kg/m^2 (Lindroth et al. 2003) up to 69 kg/m^2 (Widén, 2001), down to a depth of 50 cm.

The 102 m high flux tower was built in 1994. It was equipped with instruments for continuous measurements of carbon fluxes, water fluxes and meteorological parameters. The site is still highly in use with continuous measurements and the site is popular as a research location for different surveys.

The history of the site includes drainage in the year 1890, followed up with a regular routine of cleansing of the channels. Aron Engström, who lived in 1908-1976, had been told how the forests in Norunda was like before the drainage and his description is cited in Lovén (2003): Before 1893 this area had no roads. The forest was large with wet marshes spread out over the landscape, which made the area impossible to pass through, especially in the spring and in the autumn. The inundation in spring time was so severe that you could stand on upland sites near Nävergårdsbäcken (a stream) and look out over kilometers of water mirrors.

The forest around the tower was clear-cut in the year 1900 and three thinning occasions followed in the 20th century. Fertilization with nitrogen started in the 1970th.

3.2 LPJ-GUESS – A model description

3.2.1 LPJ-GUESS history and applications

The model LPJ-GUESS is a dynamic process-based ecosystem model suited for studies at regional to continental scale. The name LPJ stands for Lund-Potsdam-Jena. LPJ was originally developed in a consortium led by Martin Sykes (Lund University), Wolfgang Cramer (PIK: Potsdam Institute for Climate Impact Research) and I. Colin Prentice (Max-Planck-Institute for Biogeochemistry in Jena). The first version, LPJ-DGVM (Sitch et al. 2003), was coded 1997-2003 and the lead authors were Stephen Sitch (PIK) and Ben Smith (Lund University). LPJ version 2 or LPJ-GUESS (Smith et al 2001) was developed by Ben Smith. GUESS stands for General Ecosystem Simulator and it has a more realistic competition between species, more detailed representation of the vegetation and some improved ecosystem processes. LPJ version 3 was developed at PIK in 2005 and they have ceased the development of all other versions. Even so, the development of LPJ-GUESS is still going on, e.g. a resent published article by Smith et al. (2014) describes the important incorporation of nitrogen cycle into the model and other improvements. The starting-point model for this project is the LPJ-GUESS version described in Smith et al. (2001) with improvements of hydrology by Gerten et al. (2004) and a modification of the growth efficiency mortality described in Hickler et al. (2012).

LPJ-GUESS is a useful tool for many different types of studies, such as simulation of historical or present ecosystem to better understand the vegetation distribution. Zaehle et al. (2006) incorporated forest management with clear-cut and thinning in LPJ-GUESS and successfully reproduced the present age structure in European forests. Another application field is the study of water and carbon fluxes in forests; Morales et al. (2005), e.g., compared eddy covariance measurements of water and carbon fluxes from different forest sites in Europe to simulations of LPJ-GUESS and three other models. LPJ-GUESS can be driven by input from climate model projections, to study future changes of vegetation; Hickler et al. (2012), e.g., modeled a projection of which impact a climate change can have to the potential natural vegetation across Europe in the future. It is also possible to couple LPJ-GUESS to a climate model, to study the water, carbon and albedo (light reflection) feedback interactions. The feedbacks of climate changes on vegetation and in return, the effect of vegetation changes on climate is an important subject for further research. One example of this is the work by Wramneby et al. (2010), who studied the water and albedo feedbacks with LPJ-GUESS coupled to a climate model.

The description of the model LPJ-GUESS, will here give emphasis to the parts that have been changed in this project. A more detailed description is available in Smith et al (2001).

3.2.2 Plant functional type - A basic generalization

LPJ was developed with the purpose of global applications. This could seem to be impossible if we reflect on the worlds about a half million higher plant species, all different types of ecosystems and also with the limitations of computer performance of the time when LPJ was created. The method to solve this is to generalize as much as the current knowledge and computer performance demand, while the functionality of the model still needs to be maintained. The parameters included in the model must be selected carefully so that the model can be applied globally (it is not workable to do every type of measurement everywhere in the world). It also has to be considered that a too complex model will be like a black box where the user will find it difficult to see what processes creates a specific outcome.

One basic generalization in LPJ-GUESS is the plant functional type (PFT), which is mainly adopted from the BIOME model family. LPJ-GUESS consisted originally of 10 PFT:s, 8 woody PFT:s such as Boreal Needle-leaved Evergreen and Temperate Broad-leaved Summergreen and 2 PFT:s for grass (C3 and C4 photosynthetic pathway). These PFT:s are representing all plant species of the world and the intention is to include all of the most common larger species and grass, because they have the highest global cover and biomass and the largest impact on the global carbon and water cycle. The model distinguishes the PFT:s from each other, for example by different climatic (e.g. temperature or light) constraints for establishment and mortality. Additional parameters controlling the possibility and magnitude of establishment and mortality are also distinguished. The PFT:s have different parameters that controls how the assimilated carbon will allocate to roots, stem or leaf. They differ in optimum, minimum and maximum temperature for photosynthesis. The leaf phenology (evergreen, summergreen and raingreen) is different and the rates of leaf and root turnover and conversion rate of sapwood to heartwood are also PFT specific. Most parameters in LPJ-GUESS are carefully chosen from the literature and some from other sources of measured data.

Some of these parameter differences represent that plant species in the real world have different bioclimatic niches (plant species thrives best in a certain range of environmental conditions). Thus, it is possible to use LPJ-GUESS to study nature's response to a changed climate.

Also life strategies (e.g. Bonan, 2002) are represented by the differences in the parameters, e.g. some PFT:s represent species with early succession, which have high requirements for light, so their strategy is to establish and grow fast in high light environments such as after a disturbance. Other PFT:s represent species with later succession with lower light requirements. The tradeoff for low light tolerance is that they establish and grow at a slower rate, but they are able to establish in a closed forest and if the forest stand remains undisturbed they will eventually become the dominating plant species. These life strategies and how competition for limited resources (light and water) is represented in the model, is the reason why LPJ-GUESS have gap-model dynamics (Bugmann, 2001), unlike LPJ-DGVM.

3.2.3 Carbon and water compartments and flows

The compartments of carbon and water are the fundamental ingredients in LPJ-GUESS. The rest of the ecosystem simulation part of the model consists almost only of mathematical functions representing processes creating flows of carbon or water between compartments or between the ecosystem and the atmosphere. Here is only a brief overview given and more detailed descriptions are assigned to later chapters.

The carbon compartments in woody PFT:s are fine-roots, sapwood, heartwood and leafs (see fig. 3). The grass PFT:s only have roots and leafs. The model is using the amount of carbon of these compartments, some allometric rules and PFT specific parameters such as wood density and specific leaf area, to calculate the spatial properties such as height, stem diameter and *LAI* (leaf area index).

The soil has three carbon compartments; Litter pool, fast SOM (soil organic matter) pool and slow SOM pool.

A model run starts with empty compartments. The first flow of carbon is establishment of new PFT objects, which can be seen as creating new objects with carbon compartments. The initial carbon amount in these sapling (young trees) is calculated from the potential *NPP* at the forest floor. Photosynthesis is the only other carbon flow, besides establishment, that is a flow of carbon from the atmosphere to the ecosystem.

The flows between carbon compartments is turnover of leaf and fine-roots, killing of vegetation objects by mortality or disturbances and the carbon lost by the reproduction process. These events transfer the carbon from vegetation to the litter pool. The carbon in the litter is later transferred to the atmosphere and the two SOM pools. The conversion of sapwood to heartwood is also a transfer between compartments.

The carbon flows from the ecosystem to the atmosphere is partly autotrophic respiration (R_{auto}). This is vegetation respiration and is caused by leaf respiration (the carbon loss in the photosynthetic process), maintenance respiration (maintenance cost for living tissue) and growth respiration (the cost of creating new plant tissues). The other process of ecosystem carbon loss is heterotrophic respiration (R_{hetero}), which is the decomposition by microorganisms (bacteria and fungi) of dead organic matter in the soil. There is also a fire routine included in LPJ-GUESS, but that is excluded from this project.

NPP is simulated as a quasi-compartment. The daily *NPP* is accumulated in this compartment and it is, at the end of each year, subtracted by the reproduction cost and the rest is allocated to the different vegetation compartments, according to four allometric rules.

The water compartments are two soil layers, a dynamic snowpack and intercepted water in the canopy. Water is entering the system in form of precipitation. Depending on the temperature, the portion of precipitation that is not intercepted in the canopy is either entering the top-layer of the soil or goes into the snowpack. The melting of the snowpack is dependent of the temperature and time. Water in the soil can move from the upper to the lower soil layer according to the percolation function. After entering the soil, the water can be lost from the ecosystem in four ways; surface runoff of excess water, base-flow runoff (percolation beneath the lower soil layer), lateral runoff from the lower soil layer, evaporation to the atmosphere and transpiration (loss of water through leaf stomata). A PFT specific parameter determines the distribution of roots in the upper and lower soil layer. This root distribution determines from which layer, the water that is lost through transpiration, is taken from. The water in the interception compartment is lost by evaporation.

The interested reader can find a more detailed description about the hydrology routine in Gerten et al. (2004).

The unit in LPJ-GUESS for carbon is kg(carbon)/m^2. The unit for precipitation, evapotranspiration and intercepted is mm(H_2O)/m^2 and soil moisture has the unit less fraction of available water divided by the water holding capacity.

3.2.4 Driving data, grid cells, patches, cohorts and spin-up

The driving data (input) needed to run LPJ-GUESS are daily or monthly values of air temperature (°C), precipitation (mm(H_2O)/m^2) and sunshine (user have a choice between different units and the model will calculate the absorbed *PAR*: photosynthetic active radiation), yearly values of ambient atmospheric CO_2 concentration (ppm) and constant values of soil characteristics (such as fraction of water holding capacity, percolation rate parameter and thermal diffusivity). The time step in LPJ-GUESS is one day, but an interpolation routine is included in the model for monthly input.

The typical spatial resolution is 0.5°x0.5° for a grid cell in LPJ-GUESS for global or continental applications. The user has to give driving data for every grid cell that is included in the model simulation. The grid cell is also the resolution of the simulation itself and for the result. LPJ-GUESS systematically simulates one grid cell at the time for all chosen grid cells, but this project only uses one grid cell, since it is a study of only one forest stand.

Stochastic (random) processes are one improvement of LPJ-GUESS compared to LPJ-DGVM. The processes that could be set to stochastic is disturbance and the ones controlling the population dynamics; establishment and mortality. A natural forest (unmanaged) often shows a fragmented mosaic distribution of different plant species. This can be due to factors such as a variety in soil moisture, soil nutrients, soil type and local disturbances. A well designed coding of stochastic processes can capture some of this fragmentation, but we need to simulate several forest stands for each grid cell to mimic this. Several forest stands are also needed so the simulation does not end up with only one of the extreme possibilities from the probability distribution, because that is often not what the users are striving for. These smaller land objects are called patches (see fig. 3). The area is usually set to 0.1 ha (1000 m^2), which is approximately the area of influence for one adult tree. The hydrology is modeled separately for each patch. The usual model setup is 10-100 patches for which average states and fluxes are given as output.

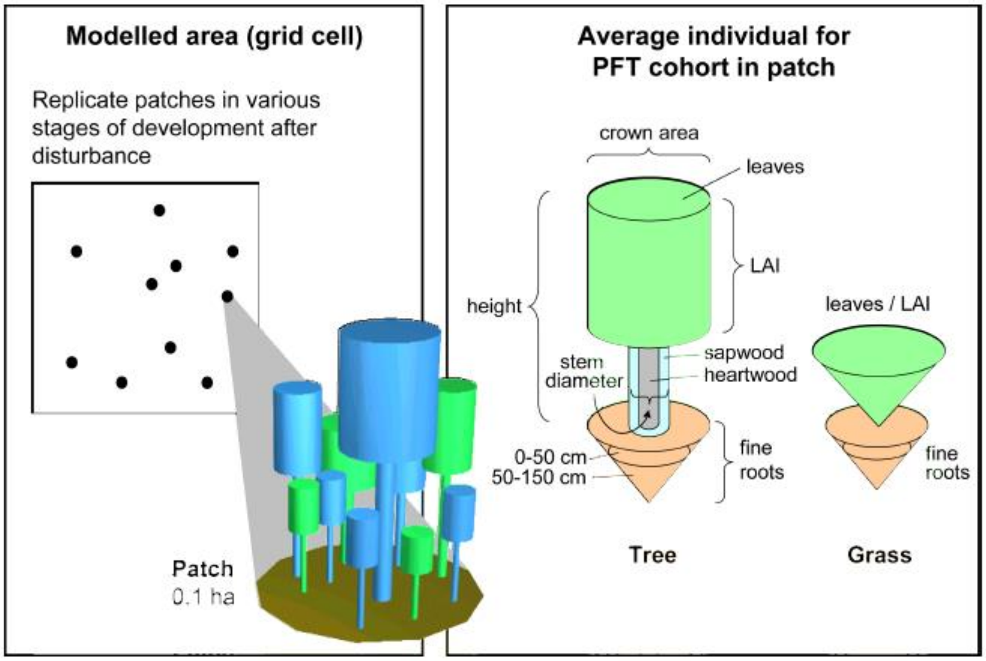


Fig. 3 Patches and structure for average individuals of cohorts. (From Smith et al. 2014)

When LPJ-GUESS is run in cohort mode as in this project, the vegetation objects are not individuals, but instead an object type called cohorts is used (see fig. 3). The use of cohorts is a generalization to gain computational efficiency. A cohort object is an age group of a PFT, manifested by an average individual and a density property (trees/m^2). Cohort is an object belonging to a specific patch. An average individual has all of the vegetation object properties mentioned above (such as carbon compartments). As an example, patch number 42 can have a Boreal Needle-Leaved Evergreen cohort, with an age of 20 years, a density of 0.07 trees/m^2 and certain values for the rest of the properties. Grass is modelled as one object per patch. The establishment interval is set to 5 years in this project, so the age of cohorts can only be multiples of 5.

A simulation starts with bare ground (i.e. no cohorts, soil carbon or soil water). The first face of a simulation has to create a vegetation and soil carbon content that is in equilibrium (balance) between the fluxes of gain and loss, so we have an ecosystem that resembles an ecosystem in reality. This face is called the spin-up and the standard length of the spin-up is three times the disturbance interval. The SOM pools are the slowest to reach equilibrium, so it is solved analytically after 300 spin-up years.

3.2.5 The temporal scale for processes in LPJ-GUESS

Photosynthesis, R_{auto}, R_{hetero}, hydrology and leaf and root phenology are simulated on a daily scale, while biomass allocation (growth), turnover, mortality and disturbances are simulated on the last day every year and the establishment function is called on the last day for every five years. It is important to remember these differences in temporal scale, when seasonality variations of an output variable are analyzed.

3.2.6 Photosynthesis, R_{auto} and NPP

The photosynthesis module has not been modified in this project, so only a very brief review will be given here. The underlying model for the photosynthesis routine is the Farquhar photosynthetic model (Farquhar et al., 1980). The Farquhar model makes it possible to calculate the carbon assimilation from environmental variables; absorbed *PAR*, temperature, ambient partial pressure of CO_2 and soil moisture. There is no nitrogen limitation in the model.

Absorbed *PAR* is calculated from the incoming *PAR* above the canopy, separately for each cohort in different canopy layers by the Lambert–Beer law (Monsi et al., 1953). The calculations is stepping through each half meter canopy layer for each cohort. A shadowing effect is produced by an integration of the accumulated *LAI* for all cohorts above that layer. The result is an exponentially decreasing absorption of *PAR* down through the canopy. This creates a competition for light between cohorts and it is one of the advantages of LPJ-GUESS over LPJ-DGVM.

Temperature is used in the temperature inhibition function, which has an optimum carbon assimilation rate at a certain temperature and it declines above or below that temperature.

The photosynthetic routine is coupled to the calculations of evapotranspiration (evaporation and transpiration). If the water demand of evapotranspiration is more than the soil can supply, a special photosynthetic function for water stress is called, which limits the canopy conductance (stomata are closing to a certain degree, dependent of the level of water stress).

GPP is calculated by subtracting the total assimilation of carbon with leaf respiration. In LPJ-GUESS, leaf respiration is the carbon loss in the photosynthetic reactions (not maintenance respiration).

LPJ-GUESS has only maintenance respiration for sapwood and roots. Maintenance respiration is exponentially increasing with temperature as many other chemical reactions, because the number of particles that have at least the energy of the activation energy level will increase exponentially with temperature. There are several empirical functions for this, such as Q_{10}. The one that LPJ-GUESS is using is a modified Arrhenius function (Lloyd et al., 1994). This function can be expressed as:

$$f(T) = \exp\left[308.56 \cdot \left(\frac{1}{56.02}\right) - \frac{1}{T + 46.02}\right] \tag{4}$$

where T is temperature in °C (T_{air} for sapwood and T_{soil} for roots). This is combined with maintenance respiration dependency of the tissue *C:N* ratio (Sprugel et al., 1996):

$$R \propto \frac{C_{\text{mass}} \cdot f(T)}{C:N} \tag{5}$$

where R is respiration rate, *C:N* is the *C:N* ratio, which is different for sapwood and roots. The excluded parameters (*respcoeff* and *phen* for root respiration) in the expression above is 1 for the needle-leaved trees, which are the important vegetation objects in this project.

Growth respiration is accounted for as 25% of the *GPP* that remains after subtracting maintenance respiration. The sum of these processes can be expressed as:

$$\begin{aligned} NPP &= Carbon_{\text{total\_uptake}} - R_{\text{leaf}} - R_{\text{auto}} \\ &= GPP - R_{\text{auto}} \\ &= GPP - R_{\text{maintenance}} - R_{\text{growth}} \\ &= (GPP - R_{\text{maintenance}}) \cdot 0.75 \end{aligned} \tag{6}$$

3.2.7 Soil carbon and soil respiration

Soil carbon transfer between soil carbon pools and decomposition is the most important part of LPJ-GUESS for this project. The three soil carbon pools, litter, fast SOM and slow SOM have decomposition rates k_{10} at 10°C of 0.35/year, 0.03/year and 0.001/year respectively. These rates gives half-times (when only half of the beginning carbon remains) of 2 years, 23 years and 693 years. Decomposition rate in LPJ-GUESS is calculated in the same way as e.g. radioactive decay. This can be expressed with an ordinary differential equation:

$$\frac{\mathrm{d}C}{\mathrm{d}t} = -k \cdot C \tag{7}$$

where C is carbon content in kg/m^2 and k is the decomposition rate. Integration of both sides with respect to time will give:

$$\int_{t=0}^{t} \frac{\mathrm{d}C}{\mathrm{d}t} \mathrm{d}t = \int_{t=0}^{t} -k \cdot C \, \mathrm{d}t \tag{8}$$

$$\Leftrightarrow$$

$$C = C_0 \cdot \mathrm{e}^{-k \cdot t} \tag{9}$$

where C is the carbon content at any given time and C_0 is the carbon content at t=0. From this we can find an expression for the daily decomposition:

$$R_{\mathrm{hetero}} = C_0 \cdot \mathrm{e}^{-k/365} \tag{10}$$

As mentioned in the background, R_{hetero} is not only a time dependent process, but is also affected by temperature and soil moisture. The temperature dependence is the same modified Arrhenius function as for R_{auto} (eq. 4). The original soil moisture response function in LPJ-GUESS is a simple linear function adopted from Foley (1995) and is only accounting for the decomposition limiting effect of low soil moisture, not the limiting effect in anaerobic conditions. The maximum soil moisture content in LPJ-GUESS is at field-capacity and the soil cannot be saturated. This function was replaced as part of this project.

The decomposed carbon of the litter pool is transferred in three directions. 70% is calculated as a flux to the atmosphere and of the rest is 98.5% transferred to the fast SOM pool and 1.5% to the slow SOM pool. The percentage of how the decomposed litter is transferred is based on empirical observation of e.g. the degradation of soil carbon to more recalcitrant forms (Foley, 1995).

The total daily R_{hetero} flux to the atmosphere can now be expressed as:

$$\begin{aligned} R_{\mathrm{hetero}} = 0.7 \cdot C_{\mathrm{litter}} \cdot \mathrm{e}^{-\frac{0.35}{365} \cdot f(T_{\mathrm{soil}}) \cdot f(W)} + C_{\mathrm{fastSOM}} \cdot \mathrm{e}^{-\frac{0.03}{365} \cdot f(T_{\mathrm{soil}}) \cdot f(W)/365} \\ + C_{\mathrm{slowSOM}} \cdot \mathrm{e}^{-\frac{0.001}{365} \cdot f(T_{\mathrm{soil}}) \cdot f(W)/365} \end{aligned} \tag{11}$$

where 0.7 is the atmospheric fraction of the decomposed litter, $f(W)$ is the soil moisture response function and $f(T_{\mathrm{soil}})$ is the soil temperature response.

3.2.8 Allocation

NPP is accumulated over the year and at the last day of the year a 10% reproduction cost is subtracted. The rest is allocated to the three living tissue compartments; roots, sapwood and leafs. The allocation is determined by four allometric rules (Sitch et al., 2003). One of the rules is the pipe model (Shinozaki et al., 1964), which is based on the justified assumption that a certain leaf area needs a certain area of transport tissue:

$$LA = k_{\mathrm{la:sa}} SA \tag{12}$$

where LA is leaf area, SA is sapwood cross section area and $k_{\mathrm{la:sa}}$ is one of the PFT specific parameters that were used for calibration in this project.

Another allometric rule is treating the effect of water stress in such way that more carbon is allocated to the roots than leafs if there were water stressed conditions during the last year.

The final two rules are empirical relationships for height to stem and crown area to stem diameter.

3.2.9 Establishment, mortality and disturbance

The processes of establishment, mortality and disturbance are stochastic and they are simulated on the last day of the year (every fifth for establishment). Establishment is the process of creating new cohorts. Before the establishment function is called, there are a number of requirements that have to be fulfilled. The bioclimatic limits for establishment is determined by the PFT specific parameters for the minimum coldest month temperature, the maximum coldest month temperature and the minimum warmest month temperature. The averages of the warmest and coldest month for the past 20 years are compared to the limits mentioned above. 5°C is often seen as a limit for growth and a requirement for establishment is that the accumulated sum of degrees above 5°C for days with temperature equal or above 5°C have to reach a PFT specific limit. There is also a PFT specific parameter with a requirement of a minimum *PAR* level at forest floor that have to be reached before the establishment function is called.

If a PFT meets all the above requirements, a new cohort is created with the density (trees/m^2) as a random number from a Poisson distribution with expectation value est:

$$est = est_{\max} \cdot (k_{\mathrm{repr}} \cdot C_{\mathrm{repr}} + k_{\mathrm{bgestab}}) \cdot \mathrm{e}^{\alpha_{\mathrm{r}}(1-\frac{1}{F})} \tag{13}$$

where $est_{\max}$ is the maximum establishment, k_{repr} is a parameter (maximum plausible value for $k_{\mathrm{repr}} \cdot C_{\mathrm{repr}}$ should be approximately equal to 1), C_{repr} is equal to the reproduction cost and this propagule pool is shared between patches in a grid cell, k_{bgestab} is a parameter that concerns background establishment, α_{r} is a is a non-linear shape parameter for recruitment rate (recruitment rate declines faster for shade intolerant PFT:s, when e.g. light decreases). All these parameter are PFT specific. F is the fraction of maximum potential productivity at the forest floor. The value of F is determined of the *PAR* at the forest floor, temperature and soil moisture. The initial biomass for new saplings (young trees) is calculated from potential *NPP* at the forest floor and the height is approximately 1.2 m.

When mortality occur in LPJ-GUESS, the density of a cohort is decreased and the carbon is transferred to the litter pool. The factors causing mortality are age, lack in growth efficiency and shading. The equation of age mortality is:

$$mort_{\mathrm{age}} = \min\left(1, \frac{3 \cdot KMORTBG\_LNF}{age_{\mathrm{max}}} \cdot \left(\frac{age \cdot age_{\mathrm{max}}}{age_{\mathrm{max}}}\right)^2\right) \tag{14}$$

where *KMORTBG_LNF* is a parameter common to all PFT:s and age_{max} is a PFT specific parameter.

Growth efficiency is *NPP* for a cohort divided by the leaf area. This project is using the same function for growth efficiency mortality as is described in the appendix to Hickler et al. (2012):

$$mort_{\mathrm{greff}} = \frac{0.1}{1 + \left(\frac{greff_{\mathrm{mean}}}{greff_{\mathrm{min}}}\right)^5} \tag{15}$$

where $greff_{\mathrm{mean}}$ is the last five years running average of growth efficiency for a cohort and $greff_{\mathrm{min}}$ is a PFT specific parameter that is lower for shade tolerant trees, which are supposed to handle years of low *NPP* better than shade intolerant trees.

Shading mortality is calculated as an increase of $mort_{\mathrm{greff}}$ if summed crown area within a cohort exceeds 1, as a self-thinning function for shade intolerant trees, which means that there is no competition between cohorts or PFT:s in this function.

The overall mortality is expressed by the equation:

$$mort = mort_{\mathrm{age}} + mort_{\mathrm{greff}} - mort_{\mathrm{age}} \cdot mort_{\mathrm{greff}} \tag{16}$$

This is not the same function as in Smith et al. (2001), but this is the one that was included in the LPJ-GUESS version received at the start of this project. The value of mort is a number between 0 and 1. A random number with even distribution between 0 and 1 is assigned to every tree (patch area times density = number of trees in a cohort) and if the random number for a tree is less than its cohort's mort value, the tree is killed (the cohort density is decreased) and the carbon is transferred to the litter pool.

Disturbance in LPJ-GUESS is representing events such as insects-outbreaks, wind throw and flooding. It is a random process with a probability of (disturbance interval)$^{-1}$ for each patch. If a patch is affected by disturbance, every cohort is killed and the carbon is transferred to the litter pool.

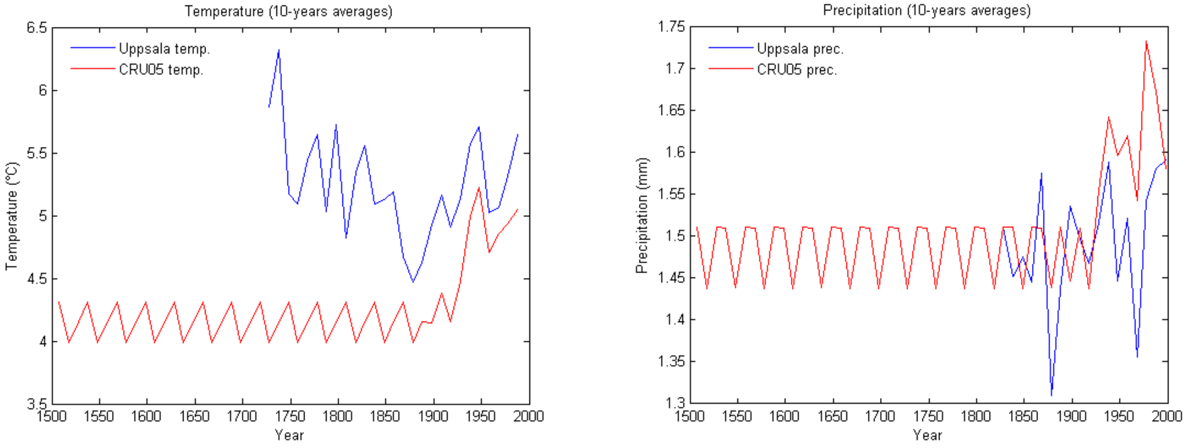
3.3 Driving data – input

The driving data were collected from three different sources; CRU05, Norunda and Uppsala. The Climate Research Unit (CRU), University of East Anglia (New et al. 1999, 2000) is a data set for 1901-1998 on a global 0.5°x0.5° grid with data of soil classes and monthly data of temperature, precipitation and cloud cover (used to derive *PAR*). LPJ-GUESS interpolates the monthly data to daily values. The day to day variation of climate is thereby missed when the monthly values are interpolated to daily values, thus real daily data is better. Measurements from the research site in Norunda provided such daily data. The Norunda data were necessary to be able to give input until 2003 (last year of in-situ data), which was the final simulation year. The data used from Norunda for the period 1995-2003 was precipitation, temperature and downward shortwave radiation. Thanks to Hans Barnström (SMHI: Swedish Meteorological and Hydrological Institute), long time series of daily data from Uppsala (30 km south of Norunda) were provided for temperature (1722-1994) (fig. 4 a) and precipitation (1836-1994) (fig. 4 b).

The data from Norunda were assumed to be the best data for this particular site and linear regressions were done to test if it was preferable to use Uppsala data for the years that were provided instead of CRU05. The equations for the linear regression of the temperatures for Uppsala-Norunda and CRU05-Norunda were y=1.02x+0.19 (R^2=0.999) and y=1.05x-0.09 (R^2=0.998) respectively, which is almost equal, but Uppsala temperature have the advantage to cover more years and to be real daily values. The equation for the precipitation linear regression, in the unit mm water, were y=0.92x+2.2 (R^2=0.75) for Uppsala-Norunda and y=0.65x+16.9 (R^2=0.62) for CRU05-Norunda, thus it was preferable to use the precipitation data from Uppsala. It was decided to use Uppsala data for all years available, up to the year 1995 where Norunda data takes over. CRU05 data was the driving data for all years and variables that was not covered by Norunda data or Uppsala data.

The CO_2 data for the period 1901-1998 comes from ice-core measurements (Ethering et al., 1996) and atmospheric observations (Keeling et al., 1995). CO_2 data for the period 1999-2003 were NOAA observations at Mauna Loa in Hawaii (web source).

The spin-up period (1501-1900) was partly forced by the driving data from Uppsala for the years available and the rest of the input is the 30 first years of the CRU05 data that were repeated continuously until the year 1900 (this procedure gives an important inter-annual variation of the input). The CO_2 data for the spin-up were fixed at 270 ppm, the CO_2 level of the year 1901 (first year of the CO_2 data).



a. Temperature

b. Precipitation

Fig. 4 Temperature and precipitation from Uppsala and the standard input from CRU05. Note: The high Uppsala temperature during the 18th and 19th century has not been analyzed, but it can have been real or it can have been biased by e.g. changed measurement instrument, changed measurement location or changes of the location of measurements.

3.4 Comparison data

Diurnal values of CO_2 fluxes were received from my supervisor Fredrik Lagergren (Lund University) and comes from the eddy-covariance (EC) instruments at the 35 m level of the flux tower, about 10 m above the canopy. Gaps in the data for less than two hours had been filled via interpolation. The EC data is the total net CO_2 flux (*NEE*). Day time ecosystem respiration (R_{eco}) had been derived with a function, with exponential temperature dependency and a linear soil water dependency, to night time fluxes (when R_{eco} is the only contributor to *NEE*). The daytime photosynthetic assimilation of CO_2 (*GPP*) was calculated from the equation; $NEE=R_{eco}–GPP$.

Biomass increment in pine and spruce came from measurement and calculations done by Lagergren (unpublished result).

Soil carbon content from podzolized soil in moderately moist areas was measurements done by Lagergren (unpublished result).

Soil moisture data was received from Harry Lankreijer (Lund University).

3.5 The PFT Boreal Needle-leaved Evergreen replaced by pine and spruce

The PFT Boreal Needle-leaved evergreen was replaced by two PFT:s that are parameterized to represent the two dominant tree species in Norunda, Scots pine and Norway spruce. The parameterization was based on the work by Koca et al. (2006), but with several parameter values changed in the calibration process described below.

3.6 Model settings (the instruction file)

The table 1 below, shows the common settings in LPJ-GUESS. Disturbance is only applied until the year 1900, because no records of major disturbances during the last century could be found. The 200 year disturbance interval was chosen with respect to fit the soil carbon content to measurement data.

Table 1. The common settings in the LPJ-GUESS instruction file.

Setting name	Value	Description
nyear	400	Number of spin-up years
ifdailyNPP	yes	Calculate daily *NPP* (otherwise monthly)
ifdailydecomp	yes	Calculate daily soil respiration (otherwise monthly)
ifcalcsla	yes	Calculate *SLA*[1] from leaf longevity
iffire	no	Implement fire
npatch	100	Number of replicate patches
patcharea	1000	Patch area (m^2)
estinterval	5	Years between establishment events
ifdisturb	yes	Implement disturbance
distinterval	200	Disturbance interval
ifbgestab	yes	Background establishment
ifsme	yes	Whether to use C_{repr}[2] in the establishment
ifstochestab	yes	Stochastic establishment
ifstochmort	yes	Stochastic mortality
ifcdebt	yes	Whether to allow vegetation carbon storage

[1] *SLA*: Specific leaf area index (m^2/kgC).
[2] C_{repr}: Reproduction carbon mass cost.

The 400 years spin-up deviates from the standard setting, which is a spin-up length of three times the disturbance interval. To rule out that this did not create an unreliable result, a simulation was performed with 10 000 spin-up years and with exclusion of the SOM equilibrium function. The result showed a negligible difference, therefor this was allowed to remain.

3.7 Clear-cut & thinning modifications – the control scenario

Modifications have been done to mimic the real history of the forest site. The management history of clear-cut in the year 1900 is simulated by killing all cohorts in all patches. The following three thinning events (1930, 1948 and 1961) were simulated by a reduction of 25% of every cohort's density (stem/m^2) on all patches. Leaf and root carbon in the thinned fraction was transferred to the litter pool, while the carbon in the sapwood and heartwood of the thinned trees simply was lost from the ecosystem.

This is the basic scenario that is most similar to the real forest site in Norunda with exceptions of the absence of e.g. water depressed regions or drainage, hence this is the control scenario that is used for calibrations and for further comparisons with other scenarios to see if their modifications produce any differences.

3.8 Output and carbon closure

Coding were done in this project for writing output to text files of daily values, were made in this project with LPJ-GUESS for several variables (e.g. GPP, R_{auto}, R_{hetero}, soil moisture and carbon in the vegetation and in the soil). A program was made for Matlab that read in these text files, it also did further calculations and analyzes of the LPJ-GUESS output and finally visualized the result in form of figures.

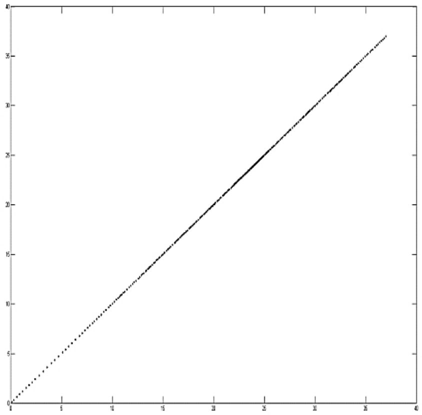


Fig. 5 Carbon closure. A linear regression between accumulated *NEE* on the *y*-axis and total ecosystem carbon storage on the *x*-axis. $y=k\cdot x$ where k=1.000 and R^2=1.000

A carbon closure test was performed to ensure that no error had sneaked into the output code in LPJ-GUESS or into the calculation in the Matlab program. This test had to be done with exclusion of the SOM equilibrium function and without clear-cut and thinning. A linear regression were made between accumulated *NEE* and total carbon changes in vegetation and in the soil for the same time period (se fig. 5). Both the slope and R^2 was 1.000, i.e. a perfect carbon closure.

3.9 Modification of the soil moisture response function

The original soil moisture response function by Foley (1995) was replaced by a function by Fang and Moncrieff (1999, Moncrieff and Fang 1999) that includes both water and oxygen dependencies for microbial respiration (see fig. 6). This is necessary to be able to simulate the soil carbon accumulation and reduced decomposition in the simulations of a poorly drained forest and peatland. The upper limit of soil moisture in the original LPJ-GUESS is at field capacity and effects of oxygen deficit on decomposition is shown at higher levels of soil moisture. The upper limit was therefore changed to the saturation level (when all pore space is filled with water). Field capacity in Norunda is about 17 vol. % (equals to 100% of water holding capacity) and a saturation level at approximately 41 vol. % (equals to 290% of water holding capacity).

Fang and Moncrieff are using the soil respiration water dependency function:

$$f(W) = 1 - \mathrm{e}^{(-a \cdot W + c)} \tag{17}$$

where W is soil moisture (g water / g dry mass), a is a parameter with value 15.05 and c is a parameter equal to 0.13. The parameters a and c are equally weighted for the values for litter and mineral soil, because the new soil moisture function is used for the decomposition of all three soil carbon compartments.

The oxygen dependency function used by Fang and Moncrieff can be expressed as:

$$f([O_2]) = \frac{1}{1 + K_\mathrm{M}/[O_2]} \tag{18}$$

where K_M is the Michaelis-Menten constant for $[O_2]$ and a value of 0.02 is used. $[O_2]$ is the oxygen concentration in the soil gas. $[O_2]$ was calculated by a self-made linear function based on that oxygen concentration is 21% in the atmosphere, it is high in dry soil and decreases when the soil gets wetter (Fang and Moncrieff, 1999):

$$[O_2] = 0.21 \cdot (1 - \frac{W}{W_\mathrm{max}}) \tag{19}$$

where W_max is soil moisture at saturation level. Soil respiration dependency of the new soil moisture functions is summarized by:

$$f(W, [O_2]) = k_\mathrm{norm} \cdot f(W) \cdot f([O_2]) \tag{20}$$

where k_norm is a normalization constant (calculated such that $\max(f(W,[O_2])) = 1$). The appearance of the $f(W,[O_2])$-function in fig. 6 is slightly different compared to the figure in Moncrieff and Fang (1999), which has its maximum closer to saturation. This difference might be due to the unusual large difference between field capacity and saturation that is reported from Norunda.

The model by Fang and Moncrieff also incorporates a calculation of the time it takes for the CO_2 to be transported out from the soil, but this part was excluded because it is negligible with respect to the time scale of interest for this project.

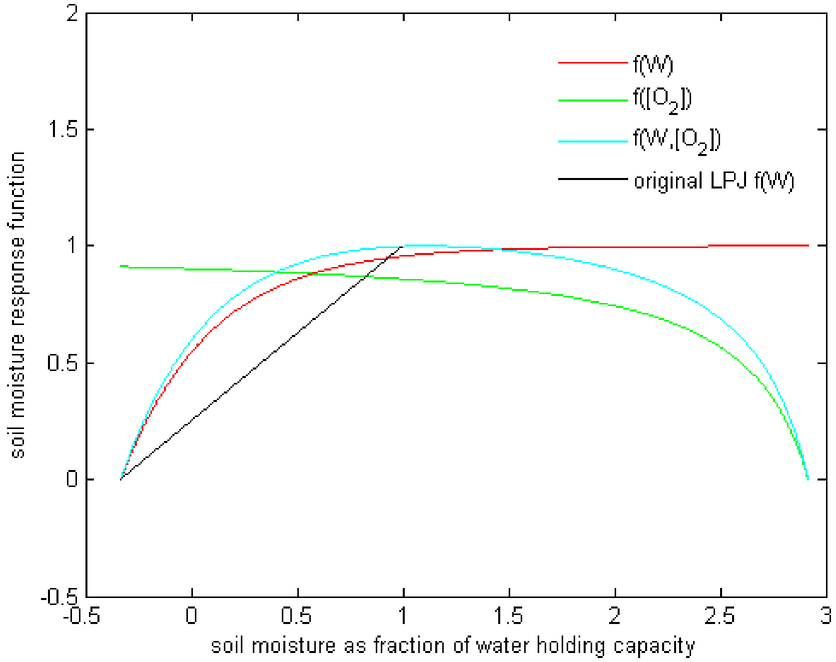


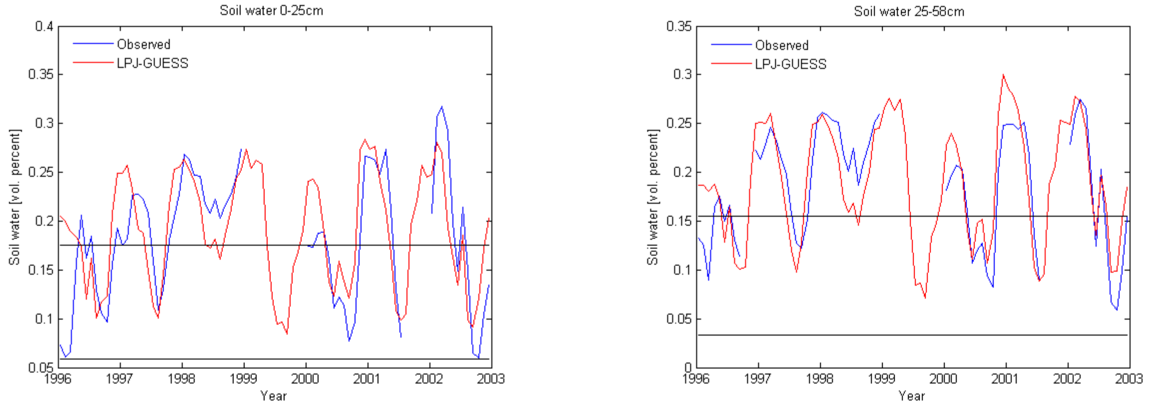
Fig. 6 Soil respiration response to moisture and oxygen based on Fang and Moncrieff (1999) and the original LPJ-GUESS soil moisture response.

3.10 Soil moisture calibration

Calibration parameters were incorporated in the soil hydrology routine for percolation, surface runoff, lateral runoff and base-flow runoff (appendix 1). The calibration of soil moisture for the upper and lower soil layer was then performed by visually adjusting model output to measured data. The visual tuning was done with help of figures for monthly averages (see fig. 7 a, b) and for average monthly values for all years to fit the seasonal trend (see fig. 7 c, d). Also the averages for all years were used in the calibration. A rough calibration of photosynthesis, by tuning the parameter *ALPHAA* (scaling factor for absorption of *PAR*), had to be done simultaneously, because of the relationship between transpiration and photosynthesis.

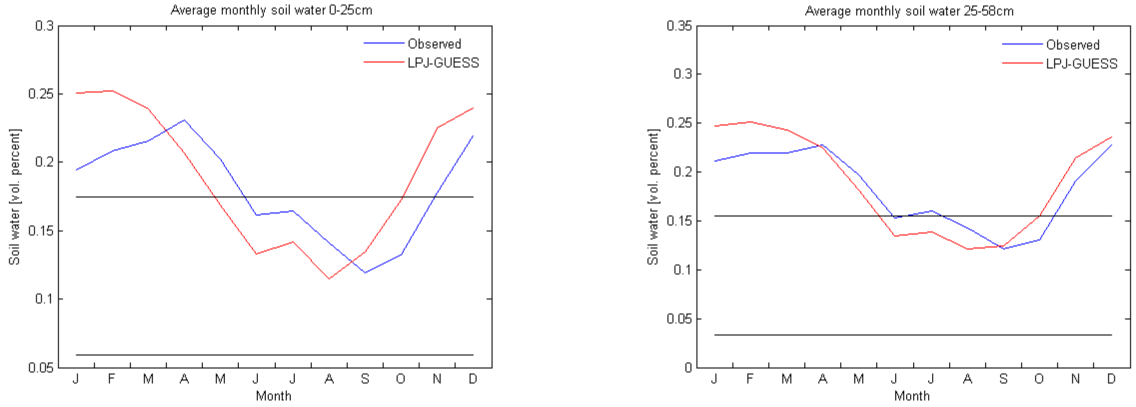
Linear regression would perhaps have been a more scientifically correct calibration method, but it was easier with the selected method to do a visual fit for the amplitudes, seasonal variations and the average value for both soil layers simultaneously.

As seen in fig. 7, the depth for the upper soil layer was changed from 500 mm to 250 mm and the depth of the lower soil layer was changed from 1000 to 330 mm. This does not affect the soil carbon content, only the soil moisture.



a. Soil water 0-25 cm

b. Soil water 25-58 cm

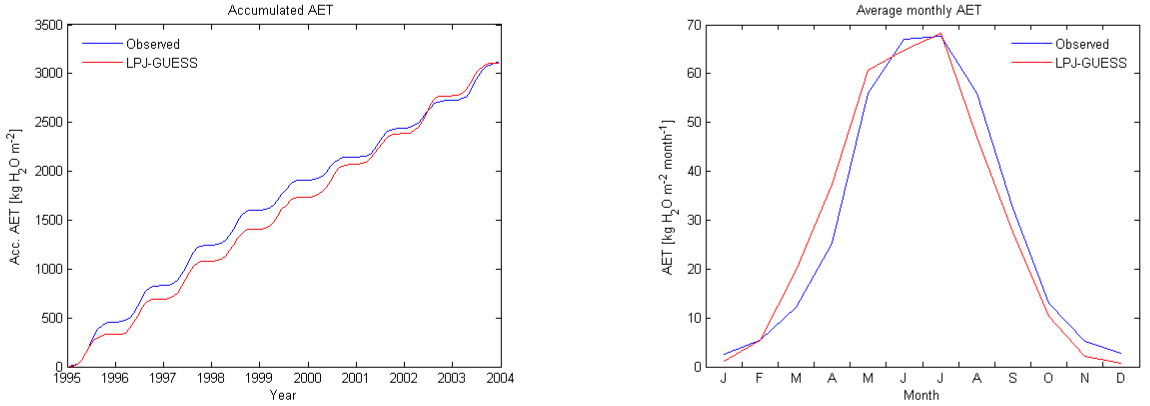


c. Average monthly soil water 0-25 cm

d. Average monthly soil water 25-58 cm

Fig. 7 Soil water in volume percent for Norunda measurements (blue line) and model output (red line). The upper black straight line is field capacity that is the maximum soil moisture level in the original LPJ-GUESS. The lower black straight line is the wilting point.

The new calibrated soil water content, soil layer depths and photosynthesis, also happened to give a very good fit for the actual evapotranspiration (*AET*) (see fig. 8 a, b). To have a good fit between observed data and model output for both soil moisture content and *AET*, is a great indication that the whole hydrology routine in the model is working as it should.



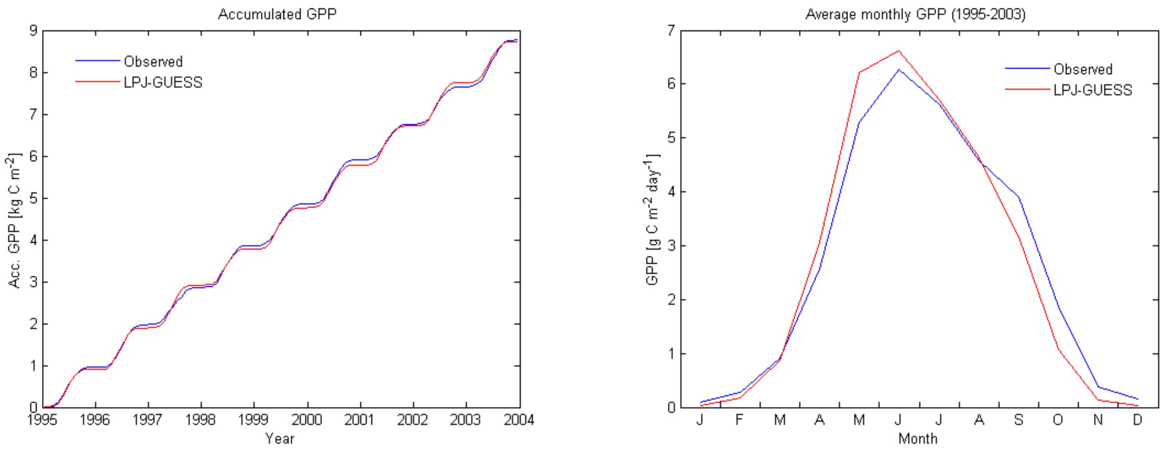
a. Accumulated *AET*

b. Average monthly *AET*

Fig. 8 Actual evapotranspiration (*AET*) for Norunda measurements (blue line) and model output (red line).

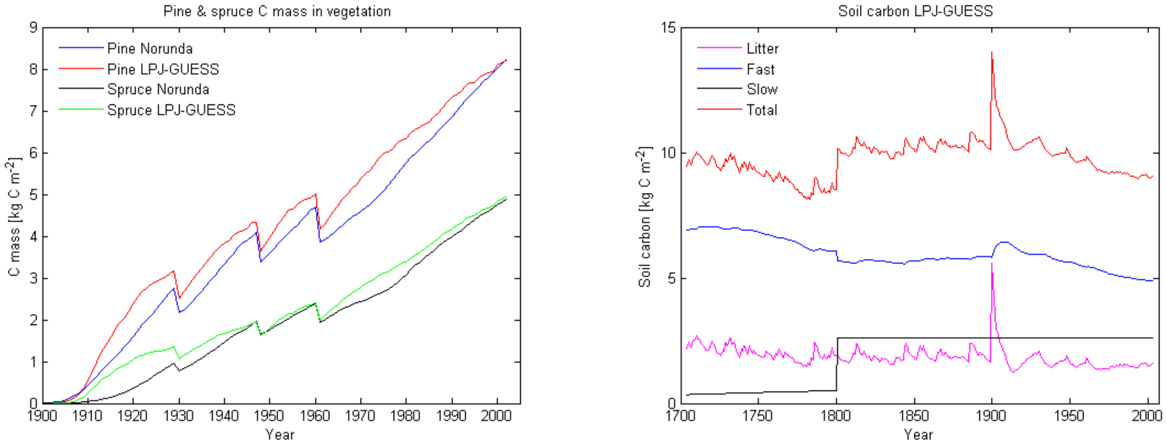
3.11 Calibration of *GPP*, biomass and soil carbon

As mentioned before, calibration of the carbon balance was based on the assumption from observations that the soil respiration is unusually high in Norunda. Therefore, the idea was to fit every variable between Norunda measurements and LPJ-GUESS output, except for R_{eco} and *NEE*. The idea was then to test if the different scenario modifications could increase R_{hetero} and thereby decrease the gaps in R_{eco} and *NEE*. The reason to study R_{eco} was that measurements of its two parts, R_{auto} and R_{hetero}, was not available for Norunda.



a. Accumulated *GPP*

b. Average monthly *GPP*



c. Carbon in pine and spruce

d. Soil carbon content

Fig. 9 Final result of the calibration. These figures were used in the calibration process. *GPP* are for all PFT:s.

The calibration method partly aimed to create a visual overall good fit between the model output and the observed data (se fig. 9), but the priority was to get as small differences as possible between observed data and model output for the accumulated *GPP* for the measurement period (1995-2003), for biomass during the measurement period and for total soil carbon content at the end of the simulation (year 2003). The idea to fit the accumulated *GPP* for the measurement period is that this variable could then be neglected in the analysis of R_{eco} and *NEE* for the different scenarios. A good fit for *GPP* and biomass increment with the assumption that the loss of biomass (controlled by turnover and mortality) is correct, implies that the simulated R_{auto} is approximately equal to the real R_{auto} ($R_{auto} = GPP - C_{increment} - C_{turnover} - C_{mortality}$). Hence, the reason to fit biomass for the measurement period is to be able to rule out R_{auto} from the analysis of R_{eco}, so it can be assumed that it is the soil respiration part of R_{eco} that is responsible for the deviation between the measured and simulated R_{eco}. The reason to compare the final value of simulated total soil carbon content is simply that this is closest in time to the measurements reported for this variable. The reported value from the research site in Norunda of the total soil carbon content in the moderately moist areas is about 9 kg /m^2.

To calibrate these output variables without a real optimization method is best described as solving the Rubik’s cube without cheating with a strategy from internet. Anav et al. (2009) used a data assimilation method to optimize some parameters in LPJ-DGVM from daily observations of *GPP* and evapotranspiration, but it could have been difficult to apply that method to this project because of the larger number and more complex (with the shapes for pine and spruce biomass) output data that was calibrated here.

The majority of the changed parameters was PFT specific (or species specific) for pine and spruce. The most difficult part to calibrate was to get the right shapes and levels in the figures for pine and spruce biomass. The parameterization of pine and spruce started from the values found in Koca et al. (2006) and it turned out to be a really delicate balance between these two species. The following calibration was partly based on the fact that pine has an earlier life strategy than spruce, is less shade tolerant, requires more light for establishment, but has on the other hand a higher establishment rate in environments with good light conditions and is more sensitive to a low growth efficiency than spruce (Lundmark, 1988). Other literature sources (e.g. Zaehle, 2005) were also used to find the realistic ranges of the parameters and a realistic competition between pine and spruce. Pine and spruce are so dominant in Norunda, so other woody PFT:s were neglected in the calibration. Other woody PFT:s also became more or less extinct in the simulation during the 20th century.

One of the reasons that it was difficult to find the right balance between pine and spruce could have been that that removal of spruce is prioritized over removal of pine in real thinning management (Lagergren, personal communication).

The final values after calibration are displayed in table 2. All new values are within the acceptable range except for *rootdist*. The maximum portion of roots distributed in the lower soil layer is 50% according to Zaehle et al. (2005). On the other hand, pine is known to have taproots that are deeper than spruce roots (Lundmark, 1988). Hence, the new differentiation of root depths are assumed to give a more realistic competition for the soil moisture resources, even though the values are a bit out of the realistic range.

The fine tuning of the competition and observed balance between pine and spruce was very sensitive to the parameter $k_{la:sa}$ and it was difficult to choose fixed values for $k_{la:sa}$ from the literature. According to Köstner et al. (2002) $k_{la:sa}$ for spruce increases from 2600 to 4800 with stand age and height, with a value of approximately 4000 for 100 years old spruce forests, while $k_{la:sa}$ for pine decreases with stand age. Rundel et al. (1998) reports values of $k_{la:sa}$ for pine in the range 1000-3000. The original LPJ-DGVM (Sitch et al. 2003) use a $k_{la:sa}$ value of 8000 for all PFT:s and Koca et al. (2006) selected the value 2000 for both pine and spruce. From this literature review, the new values for $k_{la:sa}$ seem to be within acceptable limits.

Table 2 Parameters changed in this project. Original values in parenthesis. Original parameter values specific for pine and spruce are adopted from Koca et al. (2006) and original values for common parameters are from the source code in LPJ-GUESS.

Parameter name	Value		Description
	Common to all PFT:s and species		
ALPHAA	0.385 (0.5)		Scaling factor for absorption of *PAR*
KMORTBG_LNF	1 (3)		Parameter in the mortality (eq. 14)
	Parameters specific for pine and spruce		
	Pine	*Spruce*	
rootdist	0.33/0.67 (0.67/0.33)	0.67/0.33 (0.67/0.33)	Distribution of fine-roots in the upper/lower soil layer
$k_{\mathrm{la:sa}}$	3890 (2000)	3905 (2000)	Sapwood to leaf area parameter (eq. 12)
turnover_sap	0.05 (0.075)	0.05 (0.05)	Conversion rate of sapwood to heartwood
wooddens	200 (250)	200 (250)	Sapwood and heartwood carbon density
parff_min ($\times 10^6$)	1.5 (missing)	1 (missing)	Min *PAR* at forest floor for establishment
est_{max}	0.1 (0.1875)	0.075 (0.125)	Max establishment rate (eq. 13)
α_{r}	6 (6)	3.5 (3)	Shape parameter for establishment (eq. 13)
$greff_{\mathrm{min}}$	0.095 (0.1)	0.07 (0.0001)	Min growth efficiency parameter (eq. 15)

3.12 Extra control of carbon balance – *NPP* and the ratio *NPP*/*GPP*

Waring et al. (1998) studied annual carbon budgets from 12 forest sites in USA, Australia and New Zealand. They found a great consistency in the ratio *NPP*/*GPP*, with a value of about 0.47. The ratio of *NPP*/*GPP* for the control scenario in this project gave a value of 0.51. The absent *NPP* data for Norunda had to be calculated to be able to compare this with observed Norunda data. The relation increment = *NPP* – turnover (eq. 1b) was used, because increment data were available and total turnover for Norunda could be derived from Materia (2004). The *NPP*/*GPP* ratio from Norunda measurements was 0.51, the same as for the model.

These calculations also show that the modeled *NPP* is very close to the observed and as mentioned before, *GPP* has a very good fit between model and observations, which also makes it possible to conclude that modeled R_{auto} is very close to the observed R_{auto} ($R_{\mathrm{auto}}=GPP–NPP$). These conclusions are very important, because they make it possible to isolate the soil respiration in following analyses.

With several assumptions that is put in to the model and with all parameter uncertainties, it is important to test the model output with real in-situ data. The good result of the calibrations, that have been presented here, creates a good level of reliability of the model

3.13 Different scenarios and the associated model modifications

3.13.1 Changing the parameter FASTFRAC

When the litter decomposed is simulated in the LPJ-GUESS the standard setting is that 70% is respired directly to the atmosphere, 98.5% is transferred to the fast SOM pool and 1.5% to the slow SOM pool. The parameter *FASTFRAC* is the fraction that goes to the fast SOM pool, and the default value is therefore 0.985. The range for this parameter is 0.85-0.99 under normal soil water conditions (Zaehle et al., 2005). The observations that oxygen deficit leads to a decrease in degradation of soil carbon to a less labile form (Chapin et al., 2002, Jandl et al., 2006), must infer that *FASTFRAC* should have a higher value than 0.985 in a high soil moisture environments. The lack of knowledge of how exactly the LPJ-GUESS parameter *FASTFRAC* is effected by high soil moisture content led to the decision to use a possible minimum value that is the standard value 0.985 and a maximum value of 1 (100% transferred to the fast SOM pool). Therefore, the real value should be found in the range between those values.

3.13.2 Drainage scenario

The modifications for this scenario started with the basic clear-cut & thinning scenario. The idea was then to see if the exponential decrease after the drainage (1890), of the larger amount of soil carbon accumulated before the drainage, could have an effect on *NEE* during the measurement period (1995-2003). The soil carbon was calibrated to reach a level of about 9 kg/m^2 at the end of the simulation.

The model modifications for this was to have *FASTFRAC*=1 before drainage and *FASTFRAC*=0.985 after drainage. The reason to use these values was to have a maximum possible value for the effect of an increased *FASTFRAC*, while the clear-cut & thinning scenario with *FASTFRAC*=0.985 is considered to be the minimum effect of possible *FASTFRAC* values during the undrained period.

Fast SOM alone decomposes faster than a combination of fast and slow SOM. That is the reason why carbon could be accumulated to a higher level before drainage and still end-up with the same total soil carbon content as in the clear-cut & thinning scenario, at the end of the simulation. The accumulation of soil carbon before drainage was achieved by adjusting the soil water calibration parameters (appendix 1), so that the higher soil moisture level decreased decomposition through the new soil moisture response function (eq. 20). The soil moisture parameters were changed after drainage to the same values as in the clear-cut & thinning scenario.

To get the high soil moisture level needed for this, an extra water pool had to be included in the model (appendix 1). The new water pool does not participate in the evapotranspiration routine, but the evapotranspiration still occurs from the two soil layers as in the original LPJ-GUESS. The in-flow of water to this pool comes from precipitation if both soil layers are saturated. The outflow of water from the extra water pool goes to the upper soil layer if that is not saturated. The extra water pool is not based on any physical laws of hydrology, it is rather a quick-fix method to get high enough soil moisture levels. In any case, water above ground level is not something unrealistic, since it was actually observed for large areas before drainage and can still be seen periodically in the 10% wet areas.

3.13.3 Peatland scenarios

This scenario is a simulation of peat accumulation for the 10% wet areas. Minimum peatland scenario had a constant *FASTFRAC*=0.985 and 25 kg/m^2 in soil carbon at the end of the simulation. Maximum peatland scenario had a constant *FASTFRAC*=1 and 69 kg/m^2 in soil carbon at the end of the simulation. The different soil carbon values are the minimum and maximum measurements of soil carbon content from the wet areas. The calibrations of the final soil carbon values were performed by adjusting the soil moisture parameters (appendix 1) and these parameters were constant throughout the whole simulation.

3.13.4 Minimum scenario

The minimum effect of closing the gap between simulated and observed accumulated *NEE* (1995-2003), is given by this scenario. It is a weighted scenario with the fractions of 10% wet areas and 90% moderately moist areas. The minimum of moderately moist areas is given by the clear-cut & thinning scenario with *FASTFRAC*=0.985 (the basic control scenario). The minimum effect for wet areas is produced by the minimum peatland scenario. The weighting was achieved by multiplying the output from the peatland scenario with 0.1 and add the clear-cut scenario multiplied by 0.9.

3.13.5 Maximum scenario

The maximum scenario has the same weighting procedure as the minimum scenario, but with the scenarios that give the maximum effect of closing the gap in *NEE*. The maximum for moderately moist areas is the drainage scenario and the maximum for wet areas is the maximum peatland scenario.

The minimum and maximum scenarios are therefore the upper and lower limits of how much of the carbon source in Norunda that could be explained by the scenarios and modifications done in this project.

3.13.6 Description of the vegetation

The primary focus in this project was to analyze the mechanisms affecting the soil carbon content and soil respiration and the vegetation was of less concern. So, pine and spruce were the plant species in all scenario simulations and did not include bryophytes PFT (such as e.g. Bond-Lamberty et al., 2007), but it was important that the vegetation gave the correct *NPP* and litter input to be able to make this simplification.

The idea is that the observed *NPP* is an average for the wet and moderately moist areas of the forest stand and if all scenarios included in the weighted scenarios also had the same *NPP* as the observed, then it should be possible to conclude that the total weighted simulated *NPP* is the same as the total observed *NPP*. It is the total *NPP* (total net flux for the vegetation) that is important in the study of *NEE* (the total net flux for the forest stand).

The same argument does not work for the soil respiration, because the simulated soil respiration for the moderately moist areas is less than the observed, thus the soil carbon and decomposition had to be simulated separately and as realistically as possible for the wet and moderately moist areas.

The litter input for the wet areas had to be simulated in a realistic way. The assumption was that the simulation of wet areas, with the same vegetation of pine and spruce as in the simulations for moderately moist areas, gives approximately a realistic amount of litter input. This assumption can be made because the majority of the wet areas are small, trees grow up to the edge of these areas and a considerable part of the wet areas is covered with an overlying tree canopy layer, so the real wet areas get almost the same input from leaf-litter fall and dead fallen trees as the moderately moist areas. There will be a difference in root turnover input to the soil in wet areas, but the difference to real root turnover is probably small enough, compared to the total litter input, that this could be neglected.

3.13.7 Natural scenario – Unmanaged scenario

The purpose of this scenario is to investigate the effects of clear-cut and thinning modifications and to see if they have any significant effect on *NEE* during the measurement period.

The modifications are simply exclusion of clear-cut and thinning from the clear-cut & thinning scenario.

3.13.8 Detrended temperature scenario

This scenario is included in the project to analyze if the temperature increase since the year 1901 had any effect on e.g. *NEE* for the measurement period. A linear regression of the driving temperature data for the period 1901-2003 was performed. The linear regression showed a temperature increase of 0.95°C for this period. The temperature variable in the model was subtracted every day from the year 1901 by:

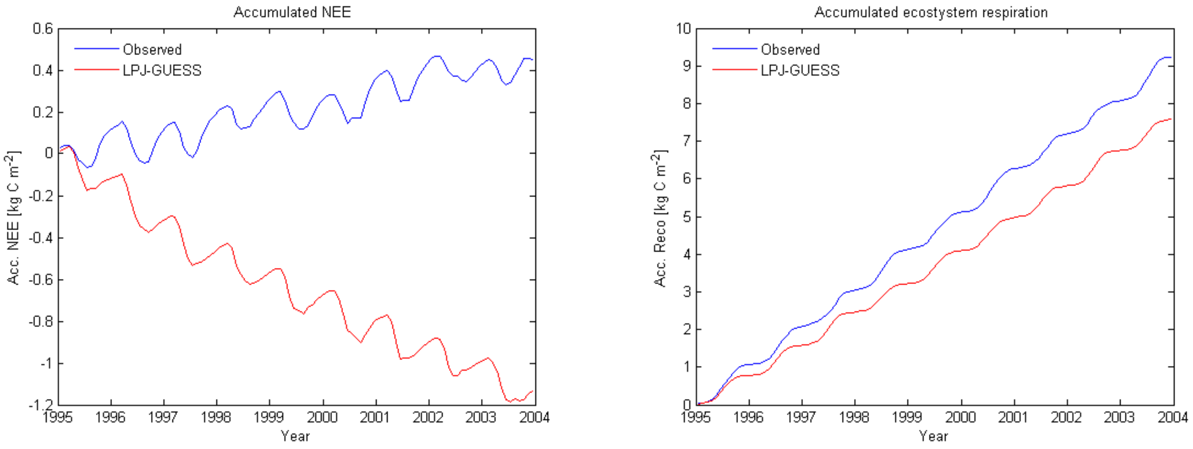
$$\frac{0.95}{103 \cdot 365} \cdot days \tag{21}$$

where *days* is the number of days after January 1st, 1901.

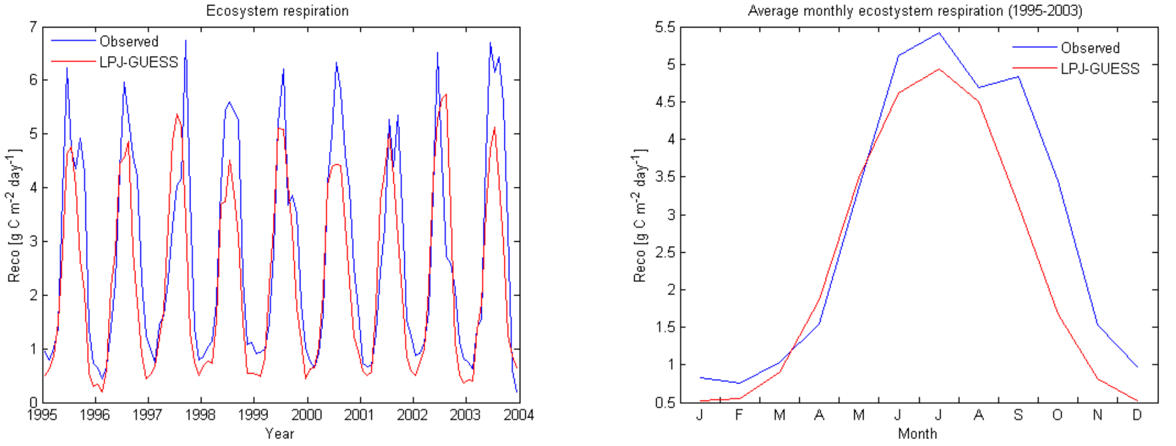
4. Results and discussion

4.1 Clear-cut & thinning scenario result

The focus here will be the result of *NEE* and R_{eco}, with a main focus in the analyses of the variable R_{eco}, because the assumption is that an unusually high soil respiration (that is a part of R_{eco}) is responsible for the carbon source in Norunda. Some of the other results for this scenario have already been presented in the calibration description. The comparison between observed and simulated *NEE* and R_{eco} for the clear-cut & thinning scenario (fig. 10 a, d) shows wide gaps between observed data and model output, so this scenario does not explain why Norunda is losing carbon. The LPJ-GUESS result was compared to EC data from 15 European forest sites presented in Dijk et al. (2004), to control if the LPJ-GUESS result was in a realistic range. The average accumulated *NEE* for the 15 forest sites, summed over 9 years, was -2.9 kg/m^2, with the range -6.5 kg/m^2 to 1.35 kg/m^2. Thus, the model result with accumulated *NEE* of -1.15 kg/m^2 is a realistic amount of carbon uptake. The R_{eco}, derived from the EC data, gives the average value 11.1 kg/m^2 summed over 9 years, with the range 7.8 kg/m^2 to 14.7 kg/m^2. This means that accumulated R_{eco} of 7.6 kg/m^2 from the model is just below the observed range.



a. Accumulated *NEE*   b. Accumulated R_{eco}



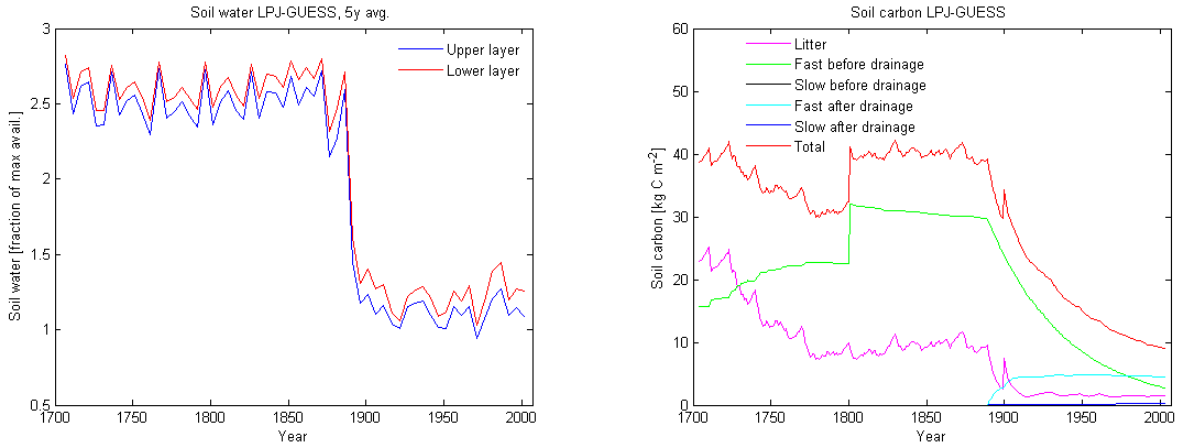
c. Monthly R_{eco} d. Average monthly R_{eco}

Fig. 10 *NEE* and R_{eco} for the clear-cut & thinning scenario.

The deviation between observed and modeled R_{eco} seems to be steady over the years (fig 9 c). The deviation seems to be mostly during the summer and the autumn with a closure of the gap during spring time (fig. 10 d). It is difficult to analyze the seasonality trend at this stage, but will come back to this in the discussion of the other scenarios.

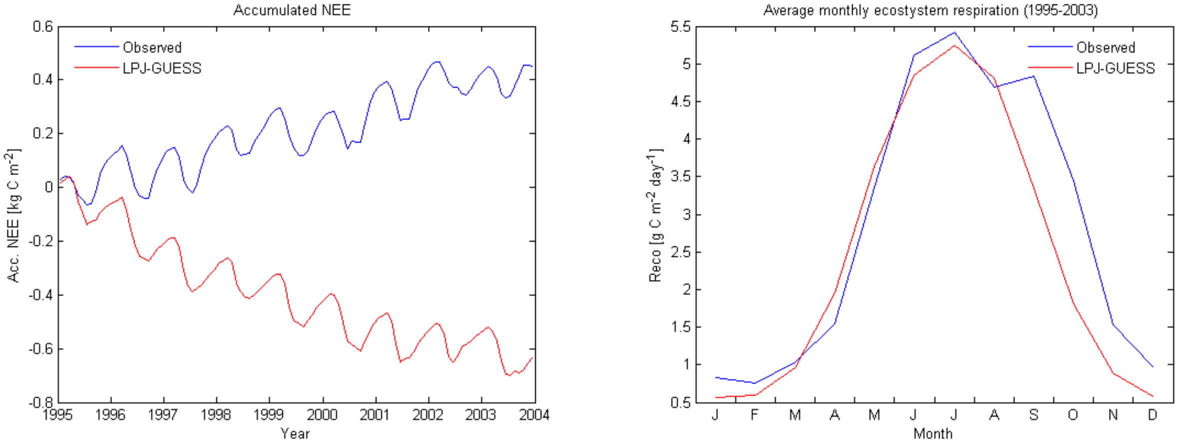
4.2 Drainage scenario result

In the drainage scenario (with clear-cut and thinning and with *FASTFRAC*=1), the 5 years averages of soil moisture (fig. 11 a) demonstrates how the runoff was dampened to simulate a poorly drained forest until 1890 and the subsequent drained period, when the soil routine parameters were changed to the same values as in the clear-cut & thinning scenario.



a. Soil moisture, 5 years averages

b. Soil carbon pools



c. Accumulated *NEE*

d. Average monthly R_{eco}

Fig. 11 Figures for the drainage scenario.

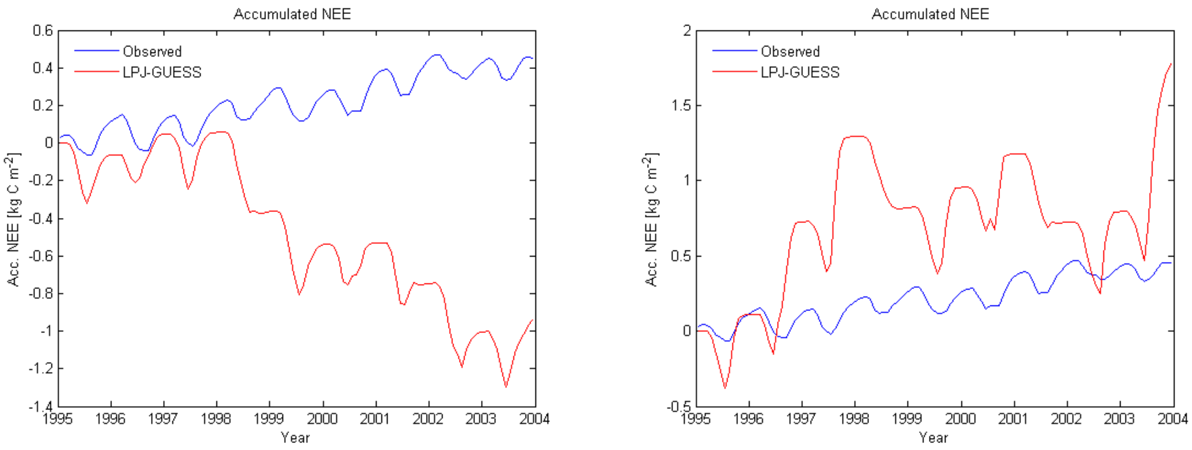
The soil carbon accumulation and the following decline, are presented in fig. 11 b. It is this exponential decrease in soil carbon and the effect that it has on *NEE*, during the measurement period (1995-2003), that is the basis for the drainage hypothesis. Bonan (2002) presents an average global soil carbon content for boreal forest of 14.9 kg/m^2 and average for wetlands of 68.6 kg/m^2, so the model output with ca 40 kg/m^2 prior the drainage could be realistic.

The effect of the decline in soil carbon was an increase of the simulated accumulated *NEE* from -1.15 kg/m^2 to -0.63 kg/m^2.

It is interesting to see that this effect was created by a narrowing of the gap between observed and modeled R_{eco} in the summer and the autumn where the clear-cut & thinning scenario deviated most, meanwhile the good fit during the spring remained (fig 10 d).
Both simulated *GPP* and *NPP* were very close to the observed *GPP* and *NPP*.

4.3 Peatland scenario result

The scenario results presented here are the minimum peatland scenario (with *FASTFRAC*=0.985 the whole simulation and calibrated to a total soil carbon of 25 kg/m^2 in the year 2003) and the maximum peatland scenario (with *FASTFRAC*=1 the whole simulation and calibrated to a total soil carbon of 69 kg/m^2 in the year 2003). The comparison scenario, clear-cut and thinning, has an accumulated *NEE* of -1.15 kg/m^2 and this carbon uptake was slightly decreased in the minimum peatland scenario to an accumulated *NEE* of -0.94 kg/m^2 (fig. 12 a). The maximum peatland scenario resulted in a carbon source with an accumulated *NEE* of 1.77 kg/m^2 (fig. 12 b).



a. Minimum peatland scenario

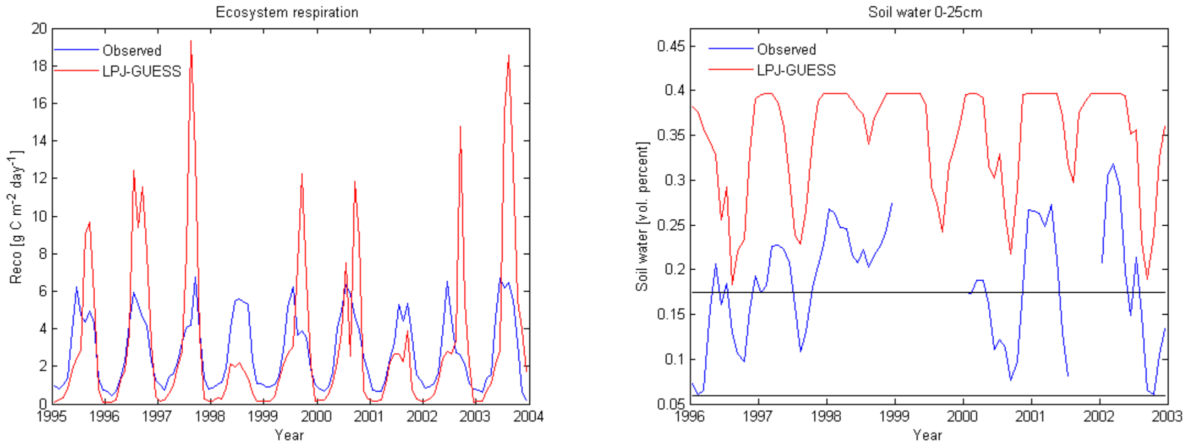
b. Maximum peatland scenario

Fig. 12 Accumulated *NEE* for minimum peatland scenario and maximum peatland scenario

The accumulated *GPP*, for both peatland scenarios, had equally good fits as the clear-cut & thinning scenario. The model only limits photosynthesis at low soil moisture levels, thus an unaffected *GPP* means that the soil moisture is already high enough in the clear-cut & thinning scenario for an optimum photosynthetic rate, with respect to the soil moisture variable.

NPP was a little bit higher for the peatland scenarios. The good fit for *GPP* means that the reason must be too low an R_{auto} in the simulations. Thus, the simulation result for *NEE* would have been less carbon uptake or a larger source of carbon if the R_{auto} was correctly simulated for the peatland scenarios. A correction for this, by replacing R_{auto} in the peatland scenarios with the R_{auto} from the clear-cut & thinning scenario, gives an accumulated *NEE* of 2.13 kg/m^2 for the maximum peatland scenario and -0.71 kg/m^2 for the minimum peatland scenario. Such a correction would only give a few percent difference to the final weighted scenarios, so this bias is only taken care of by presenting the corrected numbers.

The irregularity in the fig. 12 a, d can seem a little bit peculiar, but R_{eco} in fig 12 a, d shows that this behavior comes from the high sensitivity to soil moisture at high soil moisture levels (when the soil moisture response function declines fast) and because of high soil carbon content. It can be seen in fig. 13 a, d how the years with lower soil moisture levels gives a higher carbon release from the ecosystem and vice versa for the wet years. This is also similar for the minimum peatland scenario, but less pronounced.



a. Monthly R_{eco}

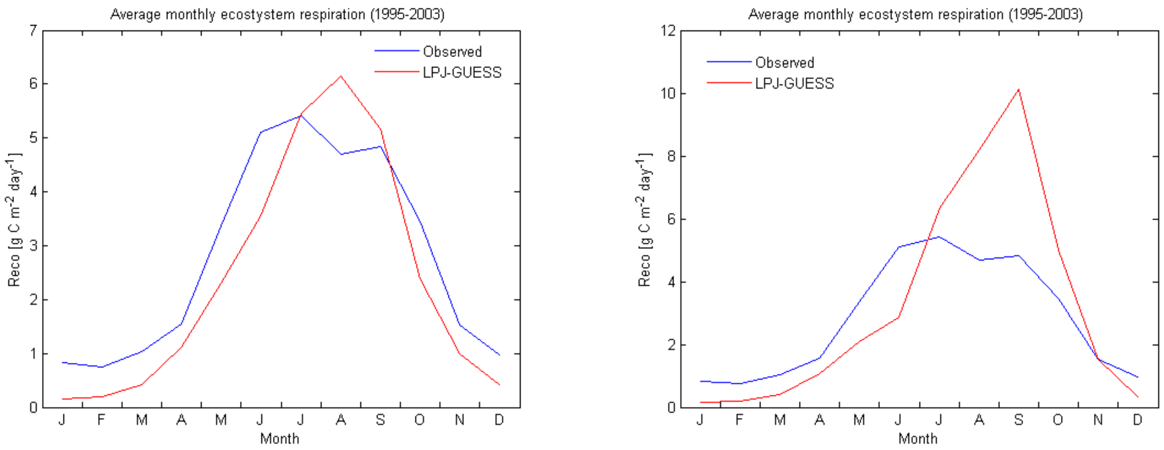
b. Monthly soil moisture for the upper layer

Fig. 13 Monthly R_{eco} and soil moisture for the maximum peatland scenarios.

The result for seasonal trends in R_{eco} is very interesting (fig. 14 a, d), with increased R_{eco} for summer and autumn, where the clear-cut & thinning scenario showed the greatest gap. So this means that the modifications for the peatland scenario catches some of the cause to the carbon source in Norunda.

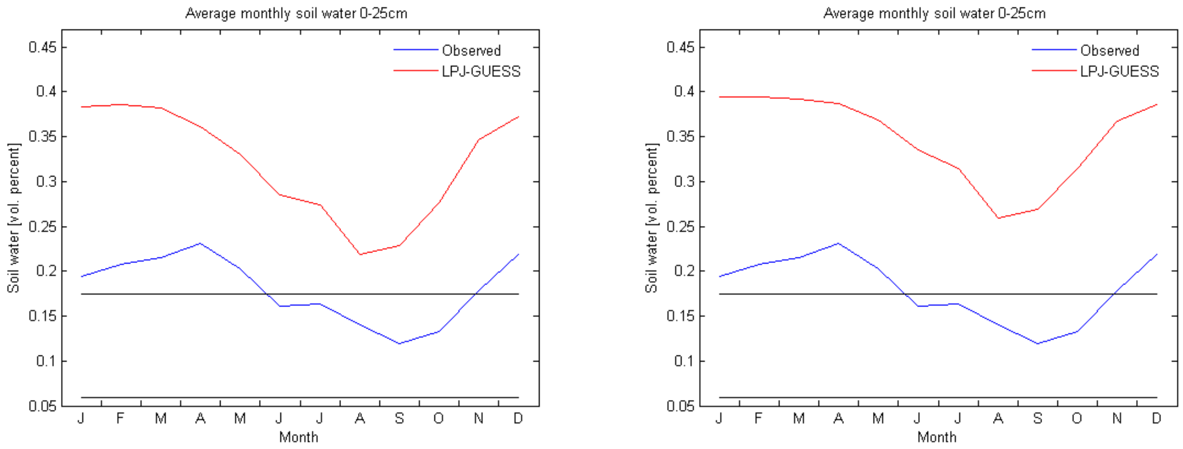
The reason that the model simulates this seasonal trend is probably because the modifications of the hydrology routine (fig. 14 c, d) in the peatland scenario shifts the less moist period forward to the late summer and the autumn. The soil moisture response function then produces a faster decomposition of the large soil carbon stock in the less wet season and thereby creates this ‘gap-filling’ result.

Unfortunately the model does not seem to improve R_{eco} during winter and spring. It is rather an increase in the gaps for this period, which could be due to too high a simulated soil moisture during these seasons and/or that the soil moisture response function decreases the decomposition too much at high soil moisture levels. A third reason for the seasonal trends, could be that these results actually catches the reality, since the observed result is for the whole forest stand, while the simulated only represents the wet areas, which perhaps have lower respiration rates during the winter and the spring in the reality. If this is true, then it is the scenario for moderately moist areas (clear-cut & thinning scenario) that should simulate a higher respiration rate during these seasons.



a. Average monthly R_{eco} for minimum peatland scenario

a. Average monthly R_{eco} for maximum peatland scenario

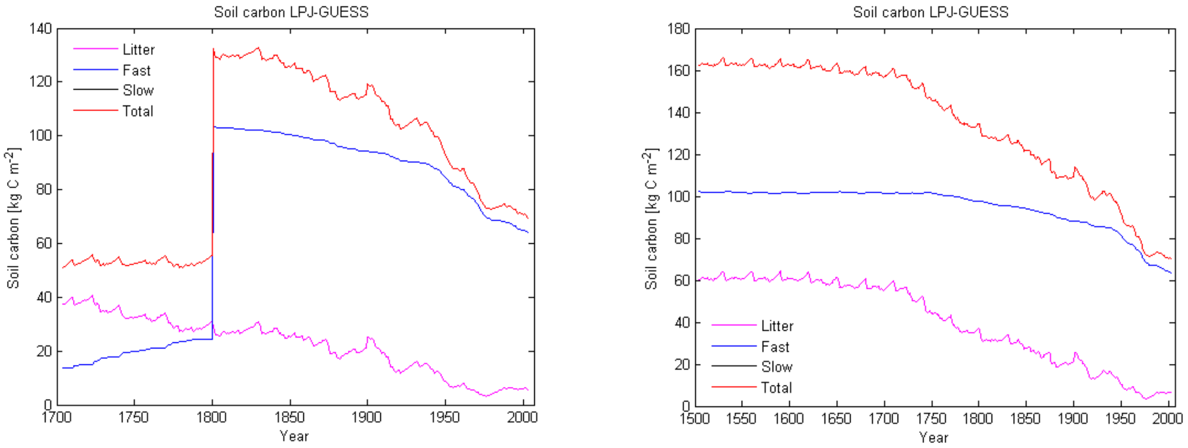


c. Average monthly soil moisture for the upper layer for minimum peatland scenario

d. Average monthly soil moisture for the upper layer for maximum peatland scenario

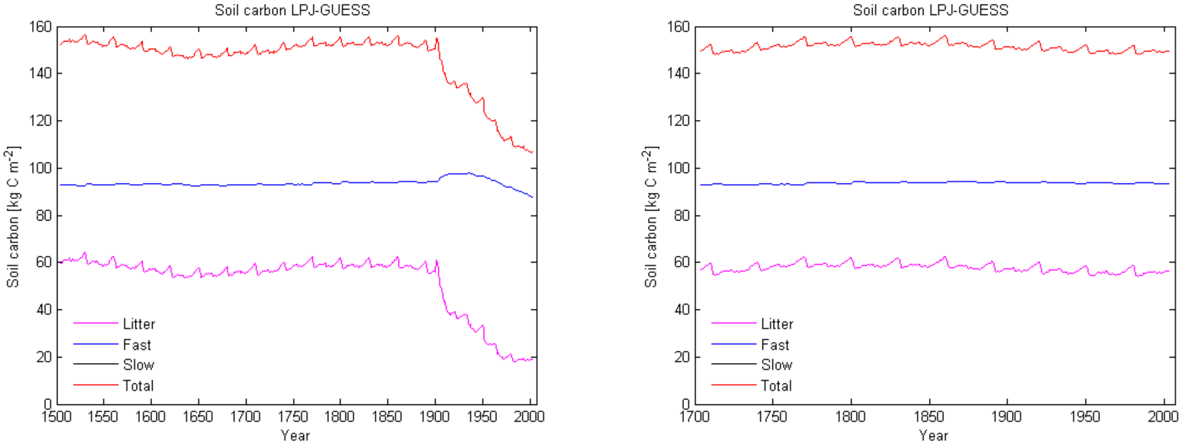
Fig. 14 Seasonality trends in R_{eco} and soil moisture for minimum and maximum peatland scenarios.

The distinct decrease of total soil carbon, in the maximum peatland scenario, raised a question mark during the work with this (fig. 15 a). *FASTFRAC* and the hydrology parameters (including the damping parameters) were held constant for the whole simulation. A simulation with 10 000 spin-up years, 300 patches and exclusion of the SOM equilibrium function was done to extract this decrease. It can be seen in fig. 15 b that the decline starts in the 18th century, when the Uppsala temperature replaces the CRU05 loop temperature. Uppsala temperature was 1°C-2°C higher than the CRU05 temperature during the 18th century (see fig 3 a). So, could this be the cause to the decrease? The next step was to only force the model with the 30 years CRU05 loop and constant CO_2 for the whole simulation. Fig. 15 c shows that some of the decrease vanished and the soil carbon was now at a stable level until the year 1900. The two events executed in the model for this year are exclusion of disturbances and the clear-cut. A simulation was done with exclusion of these two events (and thinning) together with the CRU05 loop and constant CO_2. The result finally showed stable levels of the soil carbon pool for the whole simulation (fig. 15 d). Thus, it is a combination of climate, changes in the disturbance and clear-cut and thinning that are the causes to this decrease in soil carbon pools. The decrease of soil carbon pools in the peatland minimum scenario was not this clear at all. That scenario only showed a decrease from 34 kg/m^2 (year 1889) down to 25 kg/m^2 (year 2003) (appendix 2 fig. 2). This could partly be the cause to the very different effect they had on the *NEE* during the measurement period. The other cause to their different effect on *NEE* was probably the different soil carbon pool sizes, where a larger carbon pool produces a higher respiration rate if the environmental conditions are the same.



a. Soil carbon pools

b. 10 000 spin-up years, no SOM equilibrium function



c. As in b, but only with the CRU05 loop climate and constant CO_2

d. As in c, but with constant disturbance and no clear-cut or thinning

Fig. 15 Soil carbon pools and analysis of the decrease for the maximum peatland scenario. Observe that fig. a, d are for the period 1700-2003, while b, c are for 1501-2003 (to really see were the decrease begins). The jump in soil carbon in fig. 15a is due to the equilibrium SOM function.

4.4 Minimum scenario result

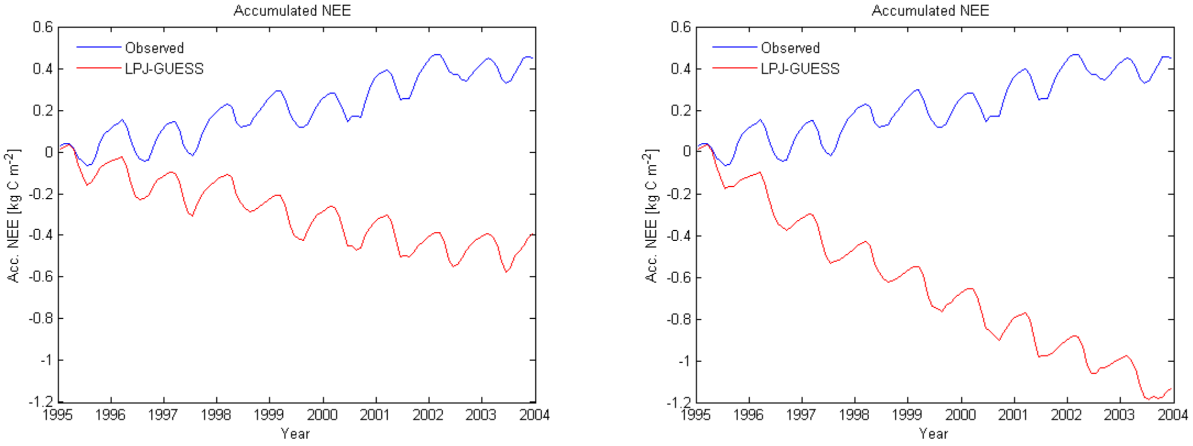
This is the weighted scenario with 90% from the clear-cut & thinning scenario and 10% from the minimum peatland scenario (*FASTFRAC*=0.985 and 25 kg/m^2 in soil carbon 2003). The weighted accumulated *NEE* (1995-2003) is -1.12 kg/m^2. Although no error analyses has been performed, it can certainly be said that this number (compared to the accumulated *NEE* of -1.15 kg/m^2 for the clear-cut & thinning scenario) is within the margin of errors.

The figures for the minimum scenario will not be presented here, because they are too similar to figures for the clear-cut & thinning scenario.

4.5 Maximum scenario result

This is the weighted scenario with 90% from the drainage scenario and 10% from the maximum peatland scenario (*FASTFRAC*=1 and 69 kg/m^2 in soil carbon 2003).

The weighted accumulated *NEE* was -0.39 kg/m^2 (1995-2003) (fig. 16 a), which is a significant decrease of the gap compared to the clear-cut & thinning scenario (fig. 16 b). The decrease in the gap was caused by a simulated loss of soil carbon of 0.8 kg/m^2 for the maximum scenario during the measurement period (appendix 2 fig. 1).

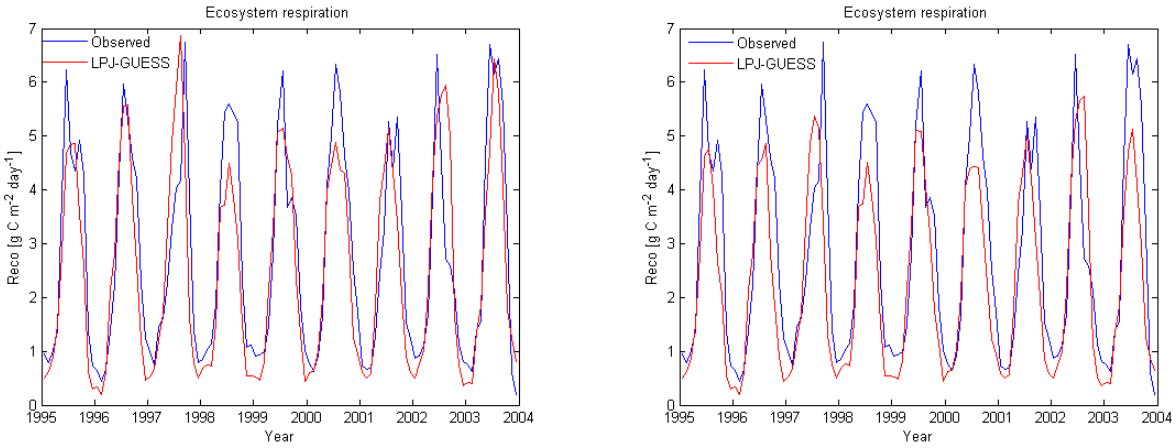


a. Maximum scenario

b. Clear-cut & thinning scenario

Fig. 16 Accumulated *NEE*.

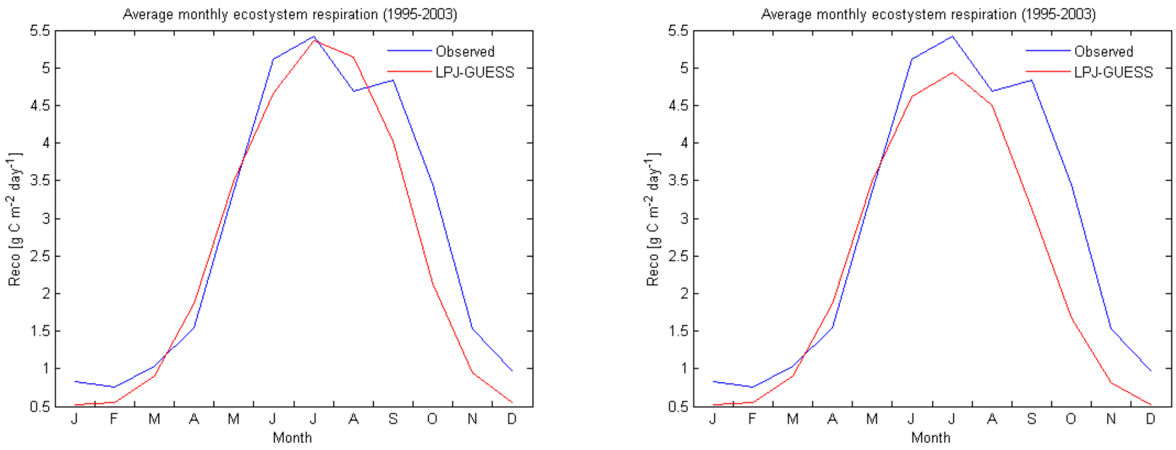
Fig. 17 a, b compares the monthly R_{eco} for the maximum scenario and the clear-cut & thinning scenario. It is clear that the model modifications done in the maximum scenario improved the fit for the peaks of R_{eco} for several years (1995, 1996, 1997, 2000 and 2003). The low respiration period in winter had a small decrease of fit for the maximum scenario, because the high soil moisture (see fig 12 b and fig. 14 d) that was simulated in the winter, decreases the soil respiration to zero in the winter.



a. Monthly R_{eco}, maximum scenario b. Monthly R_{eco}, clear-cut & thinning scenario

Fig. 17 Comparison of monthly R_{eco} between maximum scenario and clear-cut & thinning scenario.

The comparison for the seasonal trends in R_{eco} between the maximum scenario and the observations (fig. 18 a, b) really illustrates that the model modifications performed well in catching the seasonal trend in R_{eco}. Both the drainage scenario and maximum peatland scenario improved the fit for the seasonal trend without any significant changes in the already good fit during the spring (March-May). As already pointed out, the model modifications was only unsuccessful to improve the fit for winter, but apparently the improvement for the rest of the year overweights this since the gap in accumulated *NEE* decreased.



a. Average monthly R_{eco}, maximum scenario b. Average monthly R_{eco}, clear-cut & thinning scenario

Fig. 18 Comparison of average monthly R_{eco} between maximum scenario and clear-cut & thinning scenario.

4.6 Natural scenario result

The accumulated *NEE* (1995-2003) for the natural scenario was -1.05 kg/m^2. This means that the incorporation of clear-cut and thinning in the model increased the forest carbon uptake by 0.1 kg/m^2 over the measurement period. Thus, the conclusion is that clear-cut and thinning does not contribute to the carbon source that is observed in Norunda; instead these past management event rather decreased the carbon source slightly during the measurement period.

Spruce was the only dominating tree at the end of the simulation, because spruce is a late successional tree and the model succeeded to simulate this in a fairly realistic way.

4.7 Detrended temperature scenario result

The accumulated *NEE* (1995-2003) for the detrended temperature scenario was -1.44 kg/m^2. Apparently the model simulates a larger carbon uptake over the measurement period if the 20th century temperature increase is removed. This could have been caused by an increased R_{eco} in the simulation with higher temperature. Thus, this result supports the hypothesis in Lindroth et al. (1998) that the temperature increase contributes to the observed carbon loss in Norunda.

The larger total carbon uptake over the measurement period for the detrended temperature scenario than for the clear-cut & thinning scenario is due to a 0.5 kg/m^2 higher increment of biomass and 0.1 kg/m^2 less soil carbon accumulation for the detrended temperature scenario (appendix 2 fig. 1).

4.8 Summarizing the results for accumulated *NEE*

The bar diagram in fig. 19 summarizes the accumulated *NEE* for the different scenarios. Most of this is already discussed, but it is worth noticing the results from the peatland scenario with *FASTFRAC*=1 and 25 kg/m^2 in soil carbon (2003) and the peatland scenario with *FASTFRAC*=0.985 and 69 kg/m^2 in soil carbon (2003). These two scenarios give a sense of how the *NEE* is effected inside the range between the maximum and minimum peatland scenarios.

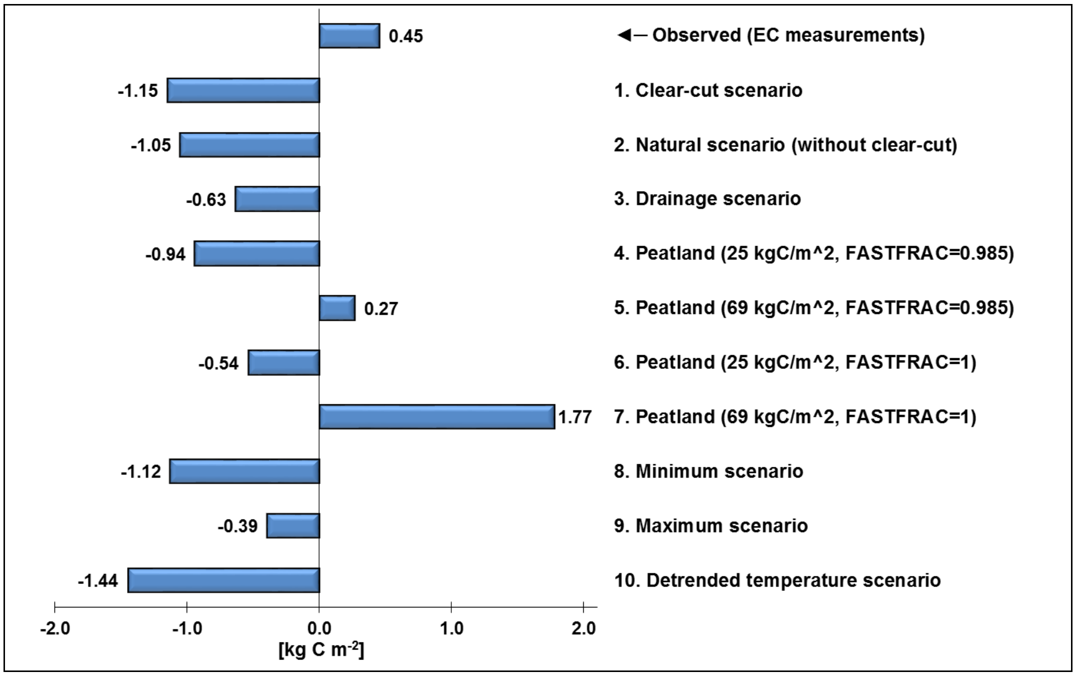


Fig. 19 Accumulated *NEE* over the measurement period (1995-2003).

Fig. 20 summarizes how much the different scenarios contribute to the carbon source. The figure presents the percentage that the different scenarios are filling the gap between the clear-cut & thinning scenario (the comparison scenario) and the observed accumulated *NEE* for the measurement period (1995-2003).

The drainage scenario could explain on its own (without being a part of the weighted maximum scenario) 32% of the carbon source. The result for the minimum scenario with 1% has to be interpreted as a 'no significant effect' scenario. The maximum scenario filled the gap with 47%. It is questionable if the average soil carbon content in wet areas could have been 115 kg/m^2 in the year 1889 and *FASTFRAC*=1 is probably unrealistic. The minimum scenario is on the other hand unrealistic in the other direction, but the idea was to catch the truth between these two extreme scenarios. Thus, the truth, according to the modifications in this project, is that the combination of drainage and wet areas can explain between 1% and 47% of the carbon source in Norunda (if we choose the reference system where the clear-cut & thinning scenario explains 0% of the carbon source).

A correction of the bias in *NPP* for the peatland scenario, by replacing R_{auto} in the peatland scenarios with the R_{auto} from the clear-cut & thinning scenario, gives the percentages of 2.5% and 50% for the minimum and maximum scenario respectively.

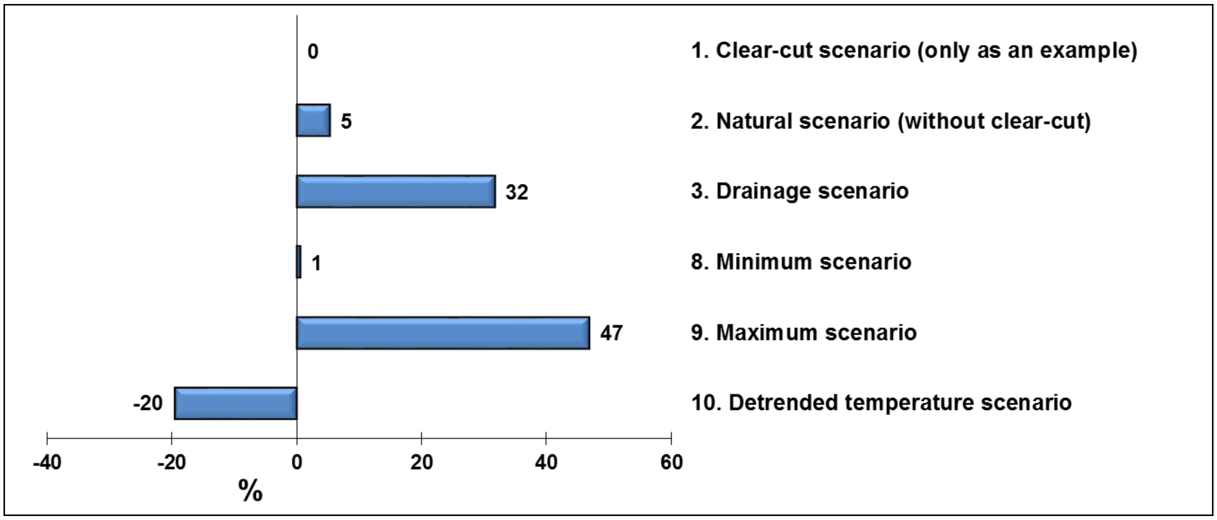


Fig. 20 The fraction of the gap in accumulated *NEE* (1995-2003), between the clear-cut & thinning scenario and the observed that is filled by the different scenarios. Above 0% and up to 100% represents a gap filling effect.

4.9 Possible further improvements

4.9.1 More realistic peatland simulations

The simulation of peatland is the greatest simplification in this project and it would have increased the reliability of the model if the peatland was more realistically simulated, such as in the newly developed LPJ-GUESS WHyMe (Tang et al. 2015).

One important biological mechanism in wet conditions is stomatal closure. Many plant species close their stomata when the root environment is flooded; this results in a decreased photosynthesis. This is missing in the LPJ-GUESS version used in this project, but it would have been possible to incorporate some modifications similar to the ones in Bond-Lamberty et al. (2007).

Another important component in peatland is the vegetation that is usually dominated by bryophytes (mosses), which have several important biological differences compared to vascular plants. As an example, bryophytes do not have stomata, so their photosynthesis is not decreased by flooding. The LPJ-GUESS WHyMe (Tang et al. 2015) has two wetland-specific PFT:s incorporated, namely mosses and flood-tolerant graminoids.

LPJ-GUESS WHyMe (Tang et al. 2015) also simulates the process of CH_4 production in peatland, which is a complex process but often more important in peatland and for the climate than the decomposition process that produces CO_2.

4.9.2 Improvements to and evaluation of the soil respiration dependency of soil temperature

R_{hetero} increases exponentially with soil temperature (eq. 4). The soil temperature calculations in the model used in this project are quite simple and the thermal diffusivity parameter for the soil is the same for all scenarios. A better soil temperature function, such the one used in Tang et al. (2015), should have improved the simulations of R_{hetero}. Separate values of thermal diffusivity for the scenarios with mineral soil and those with peat soil, should have made the simulations of R_{hetero} more realistic.

4.9.3 Include the effect of nitrogen fertilization

The forest stand in Norunda is fertilized with nitrogen since the 1970th. Nitrogen fertilization enhances photosynthesis, but this effect probably levels out when the nitrogen demand is satisfied (Schindler et al., 1999). Also decomposition is affected by nitrogen (Rousk et al., 2007). There are no nutrient limitation in the version of LPJ-GUESS, used in this project, but the parameters are on the other hand selected to be applicable on a global scale, which includes nitrogen limited ecosystems. The newer LPJ-GUESS version, described in Smith et al. (2014), includes the ecosystem nitrogen cycle and it e.g. limits the decomposition rate if the soil nitrogen content is too low. Thus, the effect of nitrogen fertilization could be simulated with the newer version of LPJ-GUESS.

4.9.4 Multi compartment and multi transformation soil routine

The soil carbon processes would be more realistic with a soil routine similar to the one in Yurova et al. (2007). They have compartments for different stages of humification and miniralization stages with transformation functions that have different soil water dependency and are representing degradation by e.g. bacteria, fungi and earth worms.

4.9.5 Pine and spruce

There are still a lot improvements to be done with the model description of pine and spruce. One example is that spruce is more productive than pine in moderately moist and nutrient rich soils and vice versa for less moist and nutrient poor soils (Lundmark, 1988).

Another example is that spruce has two different types of leafs. One type is adapted to sunny conditions and the other type are more suited for low light conditions. It takes some time for the spruce to change leaf and to be productive again after the light increases e.g. when a gap appears after a neighboring tree has fallen. Pine has only one type of leafs, so it has an advantage when a gap appears (Lundmark, 1988).

Spruce has a threshold for productivity at 2.6°C; it does not show any productivity below this temperature and the productivity increases faster than for pine up to about 15°C. The threshold value for pine is higher, so pine is more suited for a continental climate, while spruce prefers a maritime climate (Lundmark, 1988). These temperature responses should be quite easy to include in LPJ-GUESS by changing parameters that already exist in the model.

4.10 Other causes to the carbon source in Norunda

4.10.1 Advection

One hypothesis to the carbon source in Norunda is based on the research by Feigenwinter et al. (2008). They studied the vertical and horizontal flow of CO_2 in i.a. Norunda during July to September in 2006. They found that the horizontal advection was negative in average in the flux tower site in Norunda, which means that it was an inflow of CO_2 to the site from surrounding areas. The observed carbon source 1995-2003 could have been overestimated because of this horizontal advection. Unfortunately they did not measure this for a longer time period, so it is not possible to conclude that this is continuous in the long term.

4.10.2 Footprint

Footprint is the source area of the EC measurements. The footprint changes with changed wind direction and it depends on how stable or turbulent the conditions are. No study of the footprint and annual CO_2 flux could be found for Norunda, but Morén (1999) studied wind directions combined with EC measurements for Norunda and concluded that the prevailing wind direction at the flux tower site comes from south-west. She also a scaled-up soil and branch chamber study and found that a 70-year old forest stand in the south-west direction acted as a large carbon source, but this was partly masked at some extent by a changing wind direction. Her result showed that there was both several stands that acted as carbon sinks and several that acted as carbon sources and therefore the EC measurement was very sensitive to the wind direction.

4.10.3 DOC- Dissolved organic matter

DOC is dissolved organic matter transported with the ground water. It is possible that more DOC is entering a forest stand from other areas than the amount that flows out. An accumulation of DOC in a forest stand would increase the soil respiration for that area. This could be a contributing factor to the observed carbon source in Norunda. Materia (2004) did a field study of this and found that Norunda lost more DOC than what was received. A more rigorous study might be needed to get reliable annual measurements of the whole catchment area with values for the total inflow and outflow of DOC to the flux tower forest stand.

4.10.4 The immediate surroundings of the wet areas

What is hiding beneath the ground surface in the immediate surroundings of the wet areas? This question was raised because the 10% fraction that has been used for wet areas in this project, must have been larger before the drainage. Can there still be a lot of old peat with high carbon content in the surrounding of the wet areas? The received measurement data does not precise if they were taken in such areas. The whole subject with a heterogeneous and diverse soil is complex and perhaps a 3-dimensional model combined with a GIS program (geographic information system) would be needed to really solve this question. This should be possible, since Tang et al. (2014) included spatial distributed topographic indices into LPJ-GUESS to improve the simulations of the hydrology in Abisko, Sweden.

5. Conclusions – Key findings

- It was possible to calibrate LPJ-GUESS to a specific forest stand for most of the output variables, without using parameter values outside the realistic range. An automatized method for calibration would have been preferred, because of the difficulty to grasp all the cross-interactions between the parameters and the variables in the model.
- Drainage in the year 1890 could explain 32% of the carbon source (1995-2003), if it is realistic that the soil contained in average 39 kg C/m^2 just prior to the drainage event.
- The minimum and maximum scenario, weighted with a fraction of 90% for the moderately moist areas and 10% for the wet areas, could explain between 1% and 47% of the carbon source observed in Norunda. The true percentage should be found inside this range.
- Clear-cut and thinning did not contribute to the carbon source in Norunda in the period 1995-2003. It rather slightly increased the carbon uptake.
- The detrended temperature scenario increased the carbon uptake with 20% in the measurement period (1995-2003). Thus, the 20th century temperature increase of 0.95°C in Norunda contributes to the observed carbon source in Norunda.
- A more realistic peatland formulation in the model, with e.g. a bryophytes PFT and stomatal closure at anaerobic conditions, should have improved the reliability of the simulations.
- Other hypotheses of the carbon source in Norunda, such as DOC and advection that can cause an overestimation of the EC measurements, should be further studied.

6. Acknowledgements

I want to thank my supervisor Fredrik Lagergren since he always took his time to help me with this thesis and that he delivered most of the Norunda measurement data.

I also want to thank Thomas Hickler for setting me up with this project from the beginning.

Finally I want to direct a special thanks to my family, whom have given me more support than one could ask for.

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7.3 Web sources

NOAA (temperature record), 2015-06-01: http://www.ncdc.noaa.gov/sotc/global/201413

NOAA (observations at Mauna Loa in Hawaii), 2015-06-01: http://www.esrl.noaa.gov/gmd/ccgg/trends/

Appendix 1 – Hydrology

This appendix goes through the code segments in the hydrology module that have been changed in this project, as part of the calibration or to simulate drainage and peatland. The original LPJ-GUESS segments have normal font, while the new segments have bold font. All parameters created in this project ends with "_NEW". Fig. 1 is an illustration of the two soil layers and water flows in the model. Table 1 describes some of the parameters briefly. The new parameter values for the different scenarios are listed in table 2.

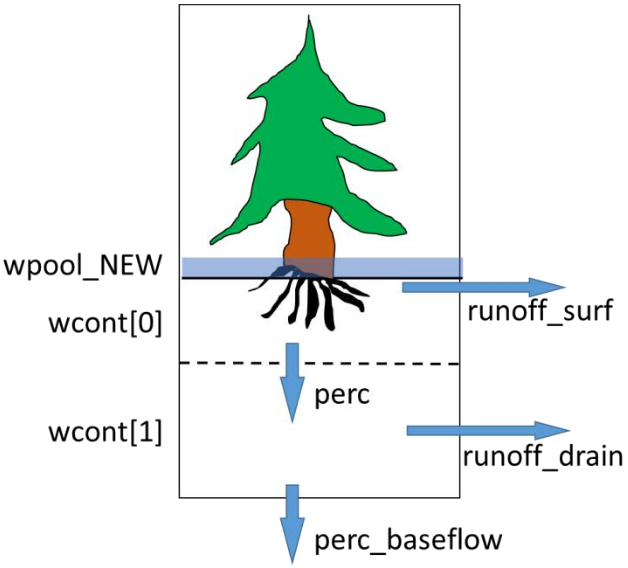

Fig. 1 An illustration of the soil hydrology in the model.

Table 1. Some of the parameters in the hydrology module.

Parameter	Description
wmax_NEW	The new maximum of wcont (saturation, value=2.9167)
runoff_surf_roof_NEW	The 'roof' of upper soil layer
runoff_surf_tuner_NEW	Calibration parameter to surface runoff
perc_tuner_NEW	Calibration parameter to percolation from upper to lower soil layer
runoff_tuner_NEW	Calibration parameter to drainage runoff from lower soil layer
wpool_NEW	The new water pool (mm)
wcont[soil layer]	Soil water (fraction of water holding capacity)
awc[soil layer]	Available water holding capacity of each soil layer (mm)
perc_base	Coefficient in percolation calculation
influx	Inward water flux to soil (mm)
perc_frac	Fraction of wcont that percolates
BASEFLOW_FRAC	Parameter in baseflow runoff calculation

Surface runoff – runoff_surf

```
if (wcont[0]>1.0) {
            runoff_surf=(wcont[0]-1.0)*awc[0];
            wcont[0]=1.0;
}
```

```
if (wcont[0]>runoff_surf_roof_NEW) {
            runoff_surf=runoff_surf_tuner_NEW*(wcont[0]-runoff_surf_roof_NEW)*awc[0];
            wcont[0]-=runoff_surf/awc[0];
}
```

Percolation – perc

```
perc=min(perc_base*pow(wcont[s-1],perc_exp),influx);
```

```
perc=min(perc_tuner_NEW*perc_base*pow(wcont[s-1],perc_exp),influx);
```

Quick-fix: So that wcont[1] does not exceed saturation

```
// Comment: s=1

wcont[s-1]-=perc_frac;
wcont[s]+=perc_frac*awc[s-1]/awc[s];
```

```
if (perc_frac*awc[s-1]<=(wmax_NEW-wcont[s])*awc[s]){
            wcont[s-1]-=perc_frac;
            wcont[s]+=perc_frac*awc[s-1]/awc[s];
}
else {
            wcont[s-1]-=(wmax_NEW-wcont[s])*awc[s]/awc[s-1];
            wcont[s]=wmax_NEW;
}
```

Drainage runoff – runoff_drain

```
// Comment: s=1

if (wcont[s]>1.0) {
            runoff_drain+=(wcont[s]-1.0)*awc[s];
            wcont[s]=1.0;
}
```

```
if (wcont[s]>wmax_NEW) {
            runoff_drain+=runoff_tuner_NEW*(wcont[s]-wmax_NEW)*awc[s];
            wcont[s]-=runoff_drain/awc[s];
}
```

New water above ground pool – wpool_NEW

```
if (wcont[1]>wmax_NEW){
        wcont[0]+=(wcont[1]-wmax_NEW)*awc[1]/awc[0];
        wcont[1]= wmax_NEW;
}
if (wcont[0]>wmax_NEW){
        patch.soil.wpool_NEW+=(wcont[0]-wmax_NEW)*awc[0];
        wcont[0]=wmax_NEW;
}
if (patch.soil.wpool_NEW>200.0){
        patch.soil.wpool_NEW=200.0;
}

if (patch.soil.wpool_NEW>0.0 && wcont[0]+wcont[1]<2*wmax_NEW){
        double wpool_num_NEW;
        wpool_num_NEW =patch.soil.wpool_NEW/100;
        while (patch.soil.wpool_NEW-wpool_num_NEW>0.0
                        && (wcont[0]<wmax_NEW || wcont[1]< wmax_NEW)){
                if (wcont[0]<wmax_NEW){
                        wcont[0]+=wpool_num_NEW/awc[0];
                        patch.soil.wpool_NEW-=wpool_num_NEW;
                }
                if (wcont[1]< wmax_NEW){
                        wcont[1]+=wpool_num_NEW/awc[1];
                        patch.soil.wpool_NEW-=wpool_num_NEW;
                }
        }
        if (wcont[0]>wmax_NEW){
                patch.soil.wpool_NEW+=(wcont[0]-wmax_NEW)*awc[0];
                wcont[0]= wmax_NEW;
        }
        if (wcont[1]>wmax_NEW){
                patch.soil.wpool_NEW+=(wcont[1]-wmax_NEW)*awc[1];
                wcont[1]=wmax_NEW;
        }
}
```

Quick-fix: So that wcont[1]>=wcont[0]

```
if (wcont[0]>wcont[1]){
        double half_water_NEW=(wcont[0]*awc[0]+wcont[1]*awc[1])/(awc[0]+awc[1]);
        wcont[0]=half_water_NEW;
        wcont[1]=half_water_NEW;
}
```

Table 2. Hydrology parameter values for the different scenarios. The natural scenario and the detrended temperature scenario had the same values as the clear-cut & thinning scenario. The values for the drainage scenario are for the period before/after the drainage in 1890.

	LPJ-GUESS original	Clear-cut & thinning	Drainage	Minimum peatland	Maximum peatland
runoff_surf_roof_NEW	1	1.5	2.9167/1.5	2.9167	2.9167
runoff_surf_tuner_NEW	1	0.07	0.0197/0.07	0.07	0.07
perc_tuner_NEW	1	0.05	0.05/0.05	0.05	0.05
runoff_tuner_NEW	1	0.2	0.0563/0.2	0.072	0.034
perc_base	4.5	4	1/4	1	1
BASEFLOW_FRAC	0.5	0.2	0.0563/0.2	0.072	0.034

Appendix 2

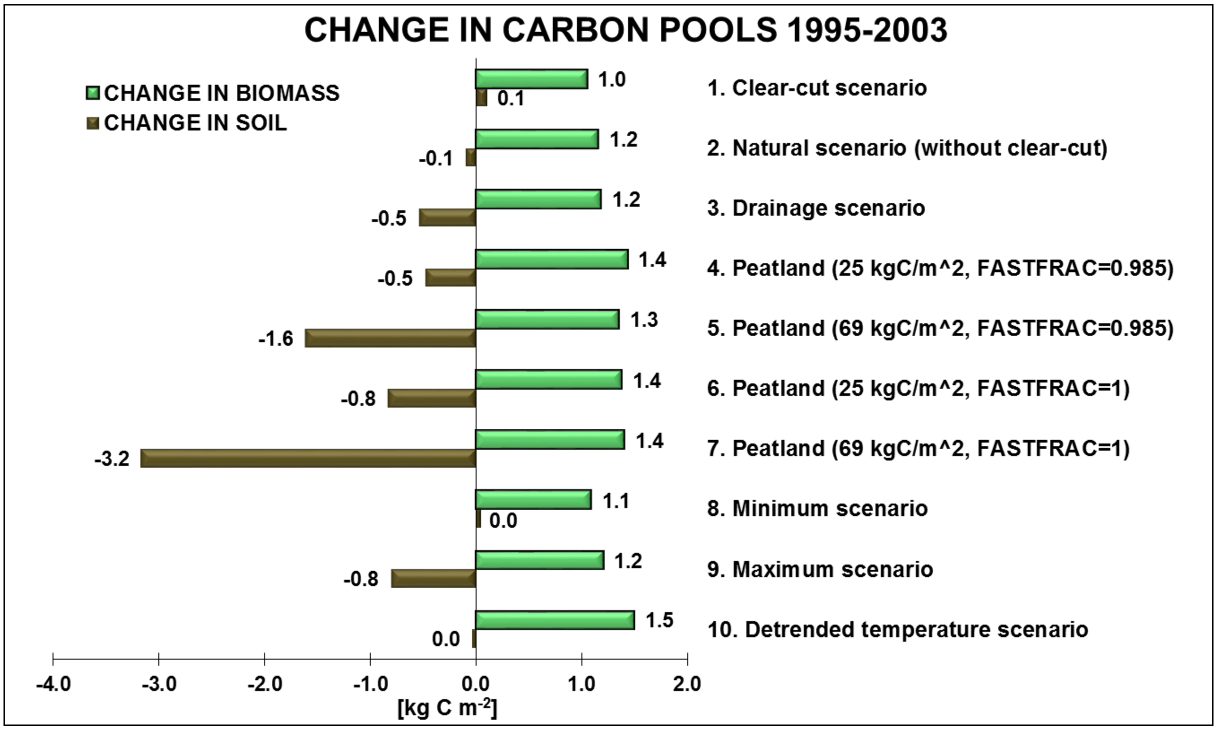

Fig. 1 Change in carbon pools (compartments) 1995-2003 (measurement period). Rounding of the values can in some cases have caused a small difference compared to the accumulated *NEE*.

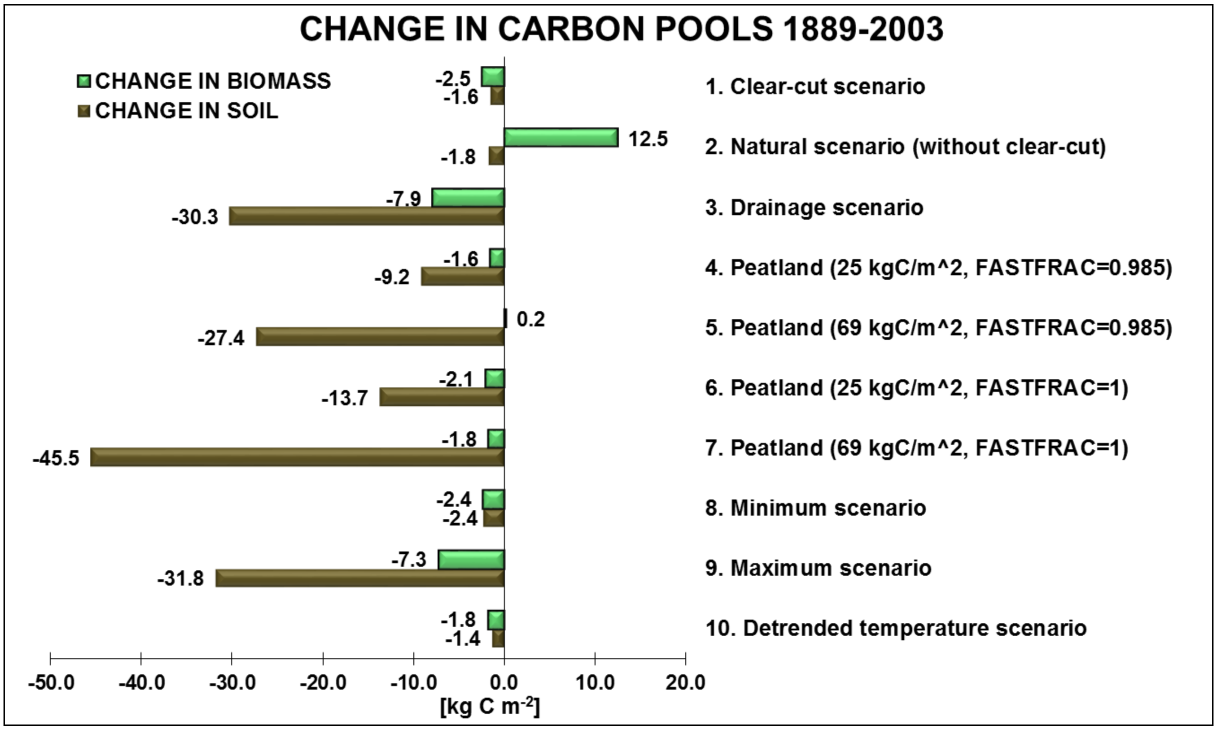

Fig. 2 Change in carbon pools (compartments) 1889-2003 (just before drainage to the end of the simulation).