

The sustainability of carbon sinks in forests

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The sustainability of carbon sinks in forests

Studying the sensitivity of forest carbon sinks in the Netherlands, Europe and the Amazon to climate and management

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ABSTRACT

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The aim of this study was to assess the sustainability of carbon sinks in managed or unmanaged forests of Europe and the Amazon. First, the functioning and seasonal variability of the carbon sink strength in forest ecosystems was analysed in relation to climate variability. For this, existing global data sets of ecosystem fluxes measured by eddy correlation were analysed. A simple, comprehensive empirical model was derived to represent these flux variabilities. Also, new soil respiration measurements were initiated in the Netherlands and Amazonia and their usefulness to understand the uptake- and emission components of carbon exchange was analysed.

Then, two long-term forest dynamics models were parameterised (FORSPACE and CENTURY) for Dutch *Pinus* and *Fagus* forests, to study the development of forest carbon stocks over a century under different management and climate scenarios.

Finally, using the empirical model as well as the long-term models, scenario predictions were made. It turns out that uptake rates are expected to decrease in a climate with higher temperatures, but that storage capacity for carbon can be expected to be slightly enhanced, especially if also the management intensity is carefully tuned down.

Key-words: permanence, sustainability, carbon sink, forests, Amazon, eddy correlation, modelling, CO₂ fluxes, soil respiration, *Pinus*, *Fagus*

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Preface

The project was made possible through financial support by the 'Climate Programme' of the Dutch Ministry of Agriculture, Nature Conservation and Fisheries, programme P344, theme 1.1. Other sources of support were from the EU FP5 and Brazilian Ministry of Science and Technology. We would like to thank the steering committee, consisting of Gijs van Tol, Frits Mohren and Eveline Trines for valuable discussions and input.

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Summary

The possible role of forests and natural ecosystems as carbon sinks to compensate for carbon emissions is a topic of much discussion in both formal, political debate on how to implement the Kyoto protocol as well as in general in discussions on how the global carbon balance should be managed. One of the debates concentrates on the idea that forests may on one hand be able to store substantial carbon, but on the other hand may present a risk to the atmospheric carbon balance because this sink may easily reverse into a net source of carbon. In assessing sustainability of (re)afforestation, the most important issue is to establish for how long the forest will stay a net sink, and how management or climate may affect this. Secondly, it is important to predict the development of the ecosystem after equilibrium has been reached: will sequestration continue, will the carbon stock stay constant or will it break down over time? For existing forests that are near or at carbon equilibrium, it is important to assess the effects of climate change and management as well.

In this study we have investigated the magnitude of carbon sinks in European and Amazon forests, as well as the contribution of soil respiration to these sinks. Using three different modelling approaches, one empirical and strongly based on data, the other two more theoretical, we investigated the effects of climate change (temperature, rainfall) and variability in different parts of Europe and under different forest management schemes.

Also, new soil respiration measurements were initiated in the Netherlands and in Amazonia and their usefulness to understand the uptake- and emission components of carbon exchange was analysed.

Existing global data sets of ecosystem fluxes measured by eddy correlation were analysed. Overall, seasonal carbon exchange in temperate zones is mainly related to irradiation whereas in the tropics rainfall seems to be the main controlling factor. A simple, comprehensive empirical model, describing these fluxes in terms of solar radiation, temperature and rainfall was derived to represent the variability of the fluxes. This model was then used along with long-term European climate data to simulate variability related to climate variability. Also, the climate data was modified to simulate climate change and the model was used to predict possible future development of existing forest sinks.

Two long-term models of forest dynamics (FORSPACE and CENTURY) were implemented for hypothetical pine and beech stands in the Netherlands. These were then used to simulate a 100-year development of these stands under different climate scenarios (contemporary and elevated temperature) as well as different management schemes (5- or 10- year thinning intervals).

Analysis of the flux data first of all quantified the natural variability in forest carbon sink strength resulting from variability in the climate. This variability is partly related to the winter value of the North-Atlantic Oscillation (NAO) index. Year-to-year variation in sinks seems to be higher in deciduous forests (sometimes over 100% variation) than in conifers (26-50% variation), although the potential gain in deciduous forests is larger. Variability in itself is not a problem for long-term carbon sequestration, but it can pose problems in the quantification of sinks in Kyoto forests during an 8-year commitment period.

The flux data also suggest that higher temperatures in the long run are associated with lower sink strengths in forests (8-19% for coniferous forests and 5-38% for deciduous forests). Although decreased sink strength not always implies reduction of stocks, this observation does call for caution in interpreting the long-term modelling results that suggest that a combination of warmer climate and less intensive thinning can lead to great increases in forest carbon stocks.

Looking at climate change scenarios applied to the long-term forest modelling, it turns out that that storage capacity for carbon can be expected to be slightly enhanced, especially if also the management intensity is carefully tuned down. Giving exact predictions is as yet very difficult, as the two models proved very sensitive to exact choices in assumed management and to the degree of complexity at which aboveground processes are simulated. Also, effects of nutrient stress and variability in rainfall were ignored in these simulations and this is likely to have hidden some important feedbacks and limiting factors.

Taking all long-term predictions together, it seems that we can expect modest mitigation of atmospheric CO₂ increase through forest sinks in a warmer climate if management intensity is carefully tuned down. CO₂ fertilisation is likely to enhance this effect.

1 Introduction

The possible role of forests and natural ecosystems as carbon sinks to compensate for carbon emissions is a topic of much discussion in both formal, political debate on how to implement the Kyoto protocol as well as in general in discussions on how the global carbon balance should be managed. In principle, the potential for *new* forests to store carbon is large and there are several lines of evidence showing that also *existing* forests are accumulating carbon or at least have a potential to do so, but on the other hand, forests present a risk to the carbon cycle in the sense that their disturbance or removal will lead to substantial additional sources of carbon to the atmosphere. This led to proposals to enable credits for afforestation and reforestation, but also for protecting forests or changing their management. As negotiations on the rules of first Kyoto protocol commitment period are now (2003) approaching their conclusion, the arguments are being settled. There are several arguments against much emphasis on forests in the management of the global carbon balance. First, crediting for storage of carbon in forests diminishes the incentive to tackle the real problem: emissions of carbon dioxide through fossil fuel burning. Second, storing extra carbon in terrestrial ecosystems can only temporarily provide a reduction in net carbon emissions, because the storage capacity is likely to saturate when the ecosystems reach (new) equilibrium. However, data from old-growth forest areas such as in the tropics suggest that even mature forests are sequestering carbon. Third, the availability of land for (re)afforestation or demands for land for agriculture vary widely per country and are not necessarily related to the needs for carbon credits. This would lead to intense international negotiations and trading need for verification mechanisms and gives much scope for misuse and fraud. Finally, stocks of carbon stored in ecosystems may not be very stable and present a risk of potentially reversing or even turning into a source of carbon. Forest production depends among others on climatic factors and on management, so changes in climate or socio-economic conditions may affect forest sinks. This last issue is usually discussed under the term 'Permanence' or 'Sustainability of sinks'.

How do we assess permanence and which are the processes of most interest?

In assessing sustainability of (re)afforestation, the most important issue is to establish for how long the forest will stay a net sink, and how management or climate may affect this. Secondly, it is important to predict the development of the ecosystem after a fully developed mature forest has been reached: will sequestration continue, will the carbon stock stay constant or will it break down over time? For existing forests that are near or at carbon equilibrium, it is important to assess the effects of climate change and management as well. In this case, the question is to what extent a new equilibrium will develop following change, and whether this will result in a different annual uptake or release of carbon. In practice both the questions for new forests and for existing ones can be assessed by studying the development of forests towards equilibrium under different conditions.

Apart from these 'continuous' effects there are also more abrupt and more dramatic risks in the maintenance of forest carbon sinks. Fires represent the most abrupt disturbance risk of forests, apart from clearing. Especially if biomass and litter has been accumulating over time as fuel, the risk of losing this carbon to the atmosphere through burning increases. This risk is also related to climate variability: if highly productive, moist periods are followed by severe droughts, fire risks will increase. However, although much carbon is lost during a fire, if climate does not change systematically, forest ecosystems can be expected to regrow rapidly and accumulate large amounts of carbon especially during the first decades following the fire. It has also been observed (Schulze et al., 2000) that in ecosystems in which fires normally recur every generation of trees, the soils slowly accumulate carbon in the form of charcoal, which is of course very stable. Therefore, fire risk alone is in the long run not a serious threat to carbon sinks in forests. The same holds for the occurrence of pests, and, most common, the regular disturbance of clear cutting at the end of a forest rotation. If, however, as a result of disturbances the species composition or soil properties change drastically, the ecosystem can enter a different state with a different carbon balance.

Another potentially dramatic risk was demonstrated by Cox et al., 2000 for the Amazon region. With a global climate model coupled to a (relatively simple) land surface model they predicted that during the 21st century the Amazon forests, after a period of net strong carbon uptake, will start losing carbon progressively, enhancing the greenhouse effect and climate change in a feed-forward loop, leading to almost complete degradation of the forests. The underlying processes in this model were strong responses of productivity to increased periodic droughts, combined with increased respiration with increasing temperatures. Increased incidence of fires in this case would enhance this process. The study raised many questions, including to what extent productivity of rain forests really depends on rainfall and whether decomposition and respiration are limited by reduced soil moisture and reduced productivity.

Aspects of sustainability of sinks addressed in this study

The main question we wanted to address in this study was how sustainable European and Amazon forests are as carbon sinks over time, under different scenarios for climate change as well as under different management regimes.

We have used three different modelling approaches, one empirical and strongly based on data, the other two more theoretical, to investigate the effects of climate change (temperature, rainfall) and variability in different parts of Europe and under different forest management schemes.

Moreover, as at this moment our understanding of carbon sequestration in forests is limited to a great deal by the (dis)ability to separate net fluxes into photosynthesis (uptake of carbon) and soil respiration (release of carbon), soil respiration measurements were initiated at tower flux sites.

2 Methodology

2.1 Approach

The overall approach aimed for has been to combine experimental data on whole-ecosystem carbon exchange and component fluxes with long-term simulation models of forest and soil carbon dynamics to assess the dependence of climate and management on carbon sinks. A schematic of the approach is presented in Figure 1.

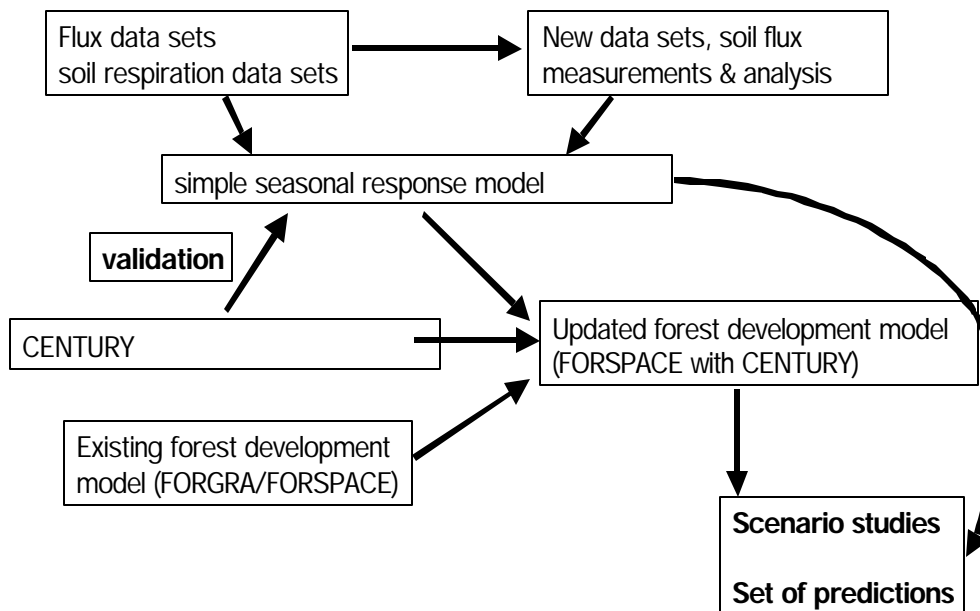


Figure 1 Schematic representation of project approach

2.1.1 Flux data

Since about five years ago, a growing global network of continuous, long-term measurements of whole-ecosystem carbon, water and energy exchange over forests has emerged. This network consists of towers equipped with automated eddy correlation equipment and registration of weather variables (see BOX 1) above these forests. Although these measurements are carried out by different groups within various collaborative consortia, most of these data collections are co-ordinated under the umbrella of FLUXNET (Baldocchi et al., 2001) and made available to the international research community through the internet (<http://daac.ornl.gov/FLUXNET/>). Tower flux data typically consist of half-hourly or hourly values of CO₂, water vapour and sensible heat fluxes, representative for several hectares to km² of underlying surface, supplemented with elaborate weather data including air temperatures, air humidity, radiation, precipitation, wind speed, and soil humidity, covering 24 hours of the days, over up to seven years. The data sets

available typically have been quality controlled and corrected while missing data have been replaced using statistical procedures.

Of course half-hourly data represent excessive time resolution for long-term carbon balance studies such as the present one. Fortunately, data are also available in an aggregated form, as daily totals or monthly totals. In this study, only monthly total data were used, as this seems a logical time resolution for understanding processes on multi-annual time scales that may be controlled by seasonal variation between years. Also, the modelling tools used were designed to run on monthly time scales and in this way a model validation would be possible.

The data analysis and synthesis was carried out in two stages. First, from the full data collection available on the internet only those forest sites were selected that have a minimum of one full year's data. These data as well as the meta-data (the description of site characteristics, variables and periods available) were then offloaded to an off-line comprehensive database, enabling quicker selection of data for further analysis. This represents FLUXNET, including EUROFLUX data. Additionally, similar gap-filled monthly data sets were constructed for several sites in the Amazon forest LBA project. Second, three subsets of these data were selected, and these were used to do an analysis of the main climatic factors that influence Net Ecosystem carbon Exchange, or NEE at seasonal time scales. The largest subset included sites in Europe, the USA and Brazil, over up to five years. This data set was used for a broad-scale assessment of 'what the data are telling us'. Another subset included only Amazon data, and was used to analyse the specific effects of rainfall on NEE in the Amazon. The last subset consisted of a number of European forest data sets, and this set was used for the most elaborate analysis of climate dependence, and to predict effects of climate variability and of long-term climate changes on European forest carbon sinks (BOX 4).

Because NEE represents the total net flux of CO₂ to or from an ecosystem, it does not directly give information on the magnitude of the components represented by assimilation and autotrophic respiration on one hand and decomposition or heterotrophic respiration on the other hand. These two components respond in different ways to the environment and act at different time scales. For understanding observed relationships with climate, to make predictions about future development of the carbon balance and to calibrate and understand models of long-term development, therefore, it is important to analyse these two components separately. Groen 2002 made an attempt to do this, using the nighttime NEE and a temperature-dependent correction to estimate the daytime respiration and assimilation components for four European sites. Although this led to reasonable numbers, it turned out that any separate statistical analysis of climate dependence for these components did not provide new information as the separation procedure carries too many uncertainties as yet. More separate measurement data of soil respiration (next section), or other techniques such as ones using stable isotopes, are needed to produce firmer estimates of the component fluxes.

2.1.2 Soil respiration data

Although it is widely recognised that it is important to measure CO₂ emissions from the soil separately, this is done much less commonly and routinely than flux measurements. Reasons for this include the high spatial variability of emissions, the more laborious and time-consuming methods and the technical problems still associated with this measurement (BOX 1). CO₂ emissions from the soil measured in combination with eddy correlation measurements are even more rare and often not as easily available as the measurements of the net carbon flux. Therefore the priority here is to where possible consolidate existing measurements and in other locations initiate new ones.

We contributed to this objective by:

- reviving bi-weekly manual measurements of mean and spatial variability of soil respiration in the Loobos tower site at the Veluwe
- supporting the installation of a continuous, automated soil respiration chamber system at two sites in the Brazilian Amazon
- supporting the set-up of a series of manual soil respiration measurements at one of the Amazon forest sites, where it is especially important to understand spatial variability

Concurrent with the soil respiration measurements, soil temperature was always measured as well, and with the continuous instruments, soil humidity was also recorded. These data sets were analysed for:

- functional relationships between soil respiration on one side and temperature and soil humidity on the other side
- the proportional importance of soil respiration in the full ecosystem carbon budget
- the variation of soil respiration over time

2.1.3 Long-term modelling

Flux measurements and statistical analysis of measurements can strictly only be used to interpolate exchange over space and time if the surface and climate properties do not change. For near-future predictions over unchanged vegetation, it can be argued that extrapolating observed relationships between carbon exchange and climate variables and using these to predict possibly different exchange in future years with different climate, will not produce bias. For prediction in a more distant future, some kind of model needs to be used that accounts for sensitivities to changed conditions. When assessments of the impact of climate change and management need to be made for the next 50-100 years, under different scenarios, a prediction scheme needs to account for changes in vegetation and soil properties, such as growth, death and rejuvenation, changes in nutrient pools, and even possible shifts in species composition. Such long-term effects are not captured by multi-year flux measurements, and although there is scattered information on the necessary parameters in the literature, predictions here often strongly depend on assumptions.

In this study, the longer-time scale modelling was performed along two, not completely independent lines. To model the below-ground processes of decomposition and mineral recycling, a version of the CENTURY model (Parton et al., 1988, Parton et al., 1994), or code equivalent to this model was used. To model biomass and vegetation development, two different approaches were taken (Table 1). In the first, an existing forest gap dynamics model was used and extended (FORSPACE, see BOX 2). In FORSPACE, biomass development is based upon light interception and mutual shading of trees, death, harvest and rejuvenation. In the other model, the much simpler bulk vegetation development module of CENTURY was used (BOX 3), which simulates growth as a constant factor, modulated by climate along fixed, predefined functions. The parameters in both models were adjusted to match measurements made at the Netherlands carbon flux site at Loobos, Veluwe.

After parameterisation and testing, both models were used to run a number of climate and management scenarios for two species in the Veluwe area, in the centre of the Netherlands.

Table 1. Comparison of main characteristics of the long-term simulation models used

	FORSPACE	CENTURY
Canopy H ₂ O/CO ₂ exchange module	canopy light use efficiency, transpiration of cohorts of identical individual trees	Genetically fixed maximal monthly growth rate modulated by LAI and temperature (NOT IMPLEMENTED: by water and nitrogen availability) Potential transpiration, restricted by water availability
Growth/Allocation module	empirical relationships depending on age	Fixed carbon allocation over leaves, branches, stemwood, coarse roots and fine roots
Tree mortality module	exponential decline of probability of mortality with increase of 5-yr average radial increment (as in SORTI, Pacala, 1993)	Fixed mortality (percentage of pool) of leaves per month and other compartments per year.
Tree germination and establishment module	definition germination and establishment based on light, moisture, nutrients, litter layer	NOT PRESENT
Decomposition module	as in Century (Parton et al., 1987; 1988; 1993; 1994)	Century (Parton et al., 1987; 1988; 1993; 1994; 2001)
Soil water balance module	(NOT USED) 3-layer, individual-tree root systems; + transpiration of herb & grass vegetation; soil-evaporation	1 to multilayer, root biomass used to calculate root uptake potential, transpiration of trees and grassy vegetation; soil evaporation

2.1.4 Scenario studies and parameterisation of the models

The future stability and development of carbon sinks in forests has been predicted using the empirical model and the two long-term process-based models. In the empirical model the variability of sink strengths has been investigated using natural (historical) variability in radiation, temperature and precipitation while future

development has been studied using the same historical climate data, but artificially increasing mean temperature and increasing the seasonal variation in precipitation. Resulting means and variance of annual fluxes have been calculated and the relative changes serve as a measure of sensitivity to climate.

In the process-based models the meteorology input was constant for all years (annual course of monthly values), and scenario studies were carried out for increases in temperature only, because the water balance module for one of the models has not been developed yet. In addition, the process models enabled the analysis of management effects such as different thinning periods. The scenario runs have been carried out for a coniferous species (Scots Pine, *Pinus sylvestris*) and a deciduous species (Beech, *Fagus sylvatica*). For each simulation cumulative biomass over 100 years has been calculated, for different compartments of ecosystem carbon (biomass, soil organic matter, etc.). The relative differences between those values again serve as an index for sensitivity to mean temperature or management. The simulation conditions under the different scenarios are summarised in Table 2.

Table 2. Set-up and scenarios for the three models in this study

Forest type	Model	Temperature control	Temperature change	Management low	Management high	Other effects
Monoculture	FORSPACE 100 yrs, <i>Pinus, Fagus</i>	Fixed annual pattern	Transient increase by 4°C over 100 yr	10 year thinning	5 year thinning	None (i.e. nutrients and moisture saturating)
Monoculture	CENTURY 100 yrs, <i>Pinus, Fagus</i>	Fixed annual pattern	Transient 4°C increase over 100 yr	10 year thinning, proportional to production	5 year thinning, proportional to production	Nutrients and moisture saturating
Monoculture	CENTURY 1928-2000	Real assimilated data (CRU) 1928-2000	Observed temperature change	None	None	
Sweden	Empirical 45 y, coniferous, deciduous	Real assimilated data (CRU) 1950-1995	+2.5°C increase	None explicit	None explicit	Precipitation - 10% during growing season, +10% outside growing season
Spain	Empirical 45 y, coniferous, deciduous	Real assimilated data (CRU) 1950-1995	+2.5°C increase	None explicit	None explicit	Precipitation - 10% during growing season, +10% outside growing season
Poland	Empirical 45 y, coniferous, deciduous	Real assimilated data (CRU) 1950-1995	+2.5°C increase	None explicit	None explicit	Precipitation - 10% during growing season, +10% outside growing season

The two different models were used also to evaluate the level of complexity needed to simulate sensitivity of forests to climate and management (Table 1). Since FORSPACE at this moment does not include dynamic simulation of water nor

nutrient limitation, these factors were set to an ample supply in CENTURY. Thus, as the main growth limiting factors were removed, for CENTURY the potential growth rate was adapted to restrict growth to the same levels as found with FORSPACE. Simulated minimum and maximum temperature were chosen to mimic average temperature in FORSPACE. For the climate warming scenario, a transient increase of 4 °C over a 100 year simulation horizon was added to both minimum and maximum temperatures. Monthly rainfall was set high to increase water availability (960 mm year⁻¹). However, it cannot be totally eliminated that water shortage might have occurred in the CENTURY simulation during in summer in the soil, considering the coarse soil texture (80% sand). Atmospheric nitrogen deposition was set at 60 kg N ha⁻¹ year⁻¹ to ensure ample supply of nitrogen.

Carbon allocation, leaf and wood lignin and turn-over were partly derived from literature (Smit, 2000; Sanger et al., 1996; Sanger et al., 1998) and partly calibrated on the FORSPACE data for Pine. For Beech, those data were available from another source (Bauer et al., 1997; Scarascia-Mugnozza et al., 2000; Dyckmans et al., 2002; Cortez et al., 1996) and as these fitted quite reasonably with the FORSPACE data, they were used with only minor adjustments. Both for Pine and Beech parameters describing the relation between temperature and relative production were taken from the CENTURY standard parameter set (Parton et al., 2001).

CENTURY simulates tree removal (thinning) as a set percentage of biomass for above-ground tree parts. We used the same percentages as derived from FORSPACE results and rounded them to the nearest 5% to simulate similar management. Large wood mass was removed from the system, while branches and leaves were input into the litter compartment. Roots from these harvested trees died off and became below ground litter. As harvesting was scheduled in winter, this did not increase input of leaves to litter for a deciduous species like beech.

Initial values for most parameters were chosen to describe a “null” start on drifting sand dunes as much as possible, i.e. a sandy soil very poor in organic material, as was the true state of the Veluwe area in 1928 when the Loobos forest was planted.

2.1.5 Simulation of NEE at Loobos

At this site an attempt was made to validate the CENTURY model with measured NEE data from the tower site at Loobos, the Veluwe. Simulation was started for 1928, running until 2000. Actual weather data were used for the Netherlands from 1928-1995 and from the site itself from 1996-2000, which were the validation years.

The area has a sandy soil (95% sand) with extremely little clay content, and was initially very poor in organic matter, as the forest was planted on drifting sand dunes. In CENTURY soil nitrogen deposition is not variable with time, and it was set at 40 kg N ha⁻¹.year⁻¹, which is the actual value. This is certain to be a too high value for the first 30-40 year of the simulation and is about 20 kg N ha⁻¹.year⁻¹ less than measured at this site in the 80's. However, this value was considered most

representative of the last 5 years, which were the only from which NEE measurements were available.

Both tree and grass (under)growth was simulated. Tree species at this site is 100% *Pinus sylvestris*, and undergrowth was considered to consist entirely of *Deschampsia flexuosa*. Parameters for *Pinus sylvestris* were derived from literature or were estimated using site specific data (Smit, 2000; unpublished data). No management was simulated. Tree growth was simulated year round, using a temperature response to decrease or stop growth in winter. This corresponds with the observation that even in winter, some photosynthesis is measured (E. Moors, pers. communication).

Parameters for *Deschampsia flexuosa* were derived from literature or calibrated using literature data from a site located nearby with a similar vegetation (Smit, 2000). For parameters that could not be estimated in this way default values from the CENTURY tutorial manual were used (Parton et al., 2001).

Competition for nutrients between trees and grass vegetation, and effects of shading on *Deschampsia flexuosa* were calibrated using site and literature data (Smit, 2000; unpublished data).

Eddy correlation

Eddy correlation is a direct measurement technique aimed at assessing the total exchange of carbon, water or energy between the land surface and the atmosphere at the 'patch' scale, usually through the deployment of automated sensitive instruments at the top of a tower extending well above the surface (Aubinet et al., 2000). The basic principle of eddy correlation is that the average net transport of energy or matter through a horizontal plane above a surface is estimated by measuring rapid fluctuations of vertical air motion, together with concurrent scalar air properties (momentum, temperature or gas concentrations). The product of these in principle leads to the net transport through the upper cross-section of an imaginary control volume containing the vegetation of interest. Over tall vegetation, it is also necessary to measure the concentration changes underneath the sensor, to account for exchange between vegetation and canopy air that did not (yet) cross the sensor level. The method, however, assumes that we can close the mass balance of the volume, implying horizontal homogeneity, horizontal terrain and flow, and absence of advective fluxes through the sides of the volume. In many cases, this assumption does not hold, for example during calm night conditions when substantial emission fluxes can be missed by the method, and an assessment is needed of how sensitive measured fluxes are to deviations from basic assumptions (Kruijt et al., 2003). In practice there are still substantial discrepancies between eddy correlation results and those from repeated inventory studies of biomass and other organic material in ecosystems (Schelhaas et al., 2002).

If assumptions are sufficiently met, the method estimates the carbon exchange between surface and atmosphere for an area of several hectares to square kilometres upwind of the sensor, depending on measurement height. This exchange includes the activity of all components of the ecosystem: autotrophic and heterotrophic soil respiration as well as photosynthesis and respiration of above-ground biomass. This is an advantage since no complex scaling-up procedure is required, but for the same reason a disadvantage, as component processes are not resolved and their role in ecosystem functioning cannot be assessed separately.

Soil respiration

Measurements of soil respiration have been made using chambers. The basic principle is that after a closed chamber is placed on the soil, the CO₂ concentration inside starts to rise at a rate proportional to the soil CO₂ emission rate. To enable measurement of this concentration over time, the air inside is sampled continuously and led to an infrared gas analyser (IRGA), and then brought back to the chamber to minimise pressure differences between the inside of the chamber and outside. Although simple in principle, the method is fraught with difficulties. For example, it is essential that air is mixed well enough inside a chamber, but pressure differences should be avoided as these will lead to leakage flows. The soil surface should not be disturbed but at the same time the chamber should be placed on the soil firmly enough to seal the bottom of the chamber from the outside air. The disturbance of the environment (temperature, rainfall, pressure) inside should be minimal. Finally the spatial variability of soil respiration is usually very high, requiring measurements at many points.

To address some of the above issues as well as possible, measurements have been made either with 1) a portable system which was moved from point to point along a pre-set transect (in Loobos, Veluwe), only covering the soil for short periods, and 2) with a continuously measuring, automatic system consisting of four chambers with a lid that is normally open, and only closes for short periods when a measurement is made (Manaus and Rodonia, Amazon).

BOX 2 FORSPACE

FORSPACE, an acronym for *forest dynamics in spatially changing environments*, is a spatially explicit model that simulates forest dynamics at the scale up to several 1000's of hectares. Gap-dynamics are an important aspect that determines the growth of individual trees and the succession of plant species in time. The forest dynamics as described in FORSPACE are based on the dynamics of the vegetation on grids with a size of 20x20 m, indicated hereafter as plots. However, to be able to represent an entire landscape, FORSPACE does not track individual trees or shrubs but cohorts of identical individuals by species. Different cohorts of each species in the herb-, shrub- and tree layer represent the vertical structure of a forest. A cohort can shift to a higher layer (e.g. from shrub layer to tree layer) if it reaches the limit of its own layer and a cohort of individuals of the same species does not occur in the next higher layer. For herbs and grasses, the concept of individuals cannot be maintained, hence for these plant species the number of square metres that are occupied in the herb layer are simulated. A full description of processes driving the dynamics of the vegetation can be found in Kramer et al 2001, <http://www.alterra.nl/publ-prod/rapporten/download/AlterraRapport216.pdf>) Groen et al., 2000 and (Kramer, accepted)

Vegetation dynamics

The variables that describe the plant population are the number of plants per plot, their individual weight and their structural properties, including tree height; diameter and base of the crown; and diameter of the stem at breast height (dbh). These variables are calculated for each species and for each layer. New plants appear as a result of germinating seeds. Seeds germinate if species-specific conditions with respect to available light, cover of the vegetation, and depth of litter layers are met.

Events that may lead to mortality are fire, insufficient photosynthesis (for woody species), competition, reaching the maximum age, and, for species in the herb layer, trampling. Mortality due to insufficient growth is described in the model by evaluating the rate of increase in the diameter at breast height. If the average dbh value falls below a minimum value, a fraction of trees in that cohort dies. For seedlings and saplings of woody species in the herb layer, mortality due to competition is based on the self-thinning rule, or $-3/2$ power 'law'. For herbs, a fixed fraction per year dies due to competition. Age related mortality of trees and shrubs increases linearly when plants approach their maximum age. New biomass is formed through photosynthesis. Photosynthesis is described by converting intercepted light into net primary production (NPP) by means of radiation use efficiency (CRue; g DM MJ⁻¹; Table 3). The amount of intercepted light depends on the leaf area index of the canopy i.e. the ratio of the surface area of the foliage to the area delineated by a vertical projection of the canopy onto the ground. The surface area of the foliage is calculated from the biomass of the foliage and the surface area per unit biomass. The total amount of absorbed radiation is then accumulated by species for each layer, and the NPP is calculated. The increase in weight is then calculated for each organ (foliage, branches, sapwood, heartwood, roots (=fine roots)), and depends on the amount of NPP allocated and the turnover rate of that organ. If leaf biomass approaches zero priority is given to attaining an optimal foliage density in the canopy, determined by the maximum leaf area index of the species and the volume of the crown. The rate of height increment of trees and shrubs in the herb and shrub layer increases linearly until the maximum height of this layer is reached. Once in the tree layer, the rate of height increment decreases linearly until the maximum height is reached. The maximum height of trees and the radiation use efficiency (CRue), and thus the rate of growth, are related to the site conditions. The CRue is calibrated with separate model runs for mono cultures of adult trees of each species. The allocation parameters were estimated based on an extensive database of the biomass of the components of woody species collected by Van Hees (pers. comm.). The seed production parameters are the same as those used in the FORGRA model (Jorritsma et al., 1999). For the herbs, the parameter values are based on the work of Nabuurs 1996) or estimated from the data collected for the Dutch Forest Reserve Programme. The characterisation of the environmental conditions allowing germination and establishment of plant species is based on expert judgement

(R.J. Bijlsma, pers. comm). Only thinning at variable intervals were applied as management in the simulations of this study. The intensity of thinning depends on the deviation between the actual and the normal basal area. The normal basal area was derived growth and yield tables (Jansen et al., 1996).

The approach presented in van der Meer et al., 2002 was used to simulate the effects of climate change on functioning of tree species. These include the effects of increasing atmospheric CO₂-concentration and temperature on growth, phenology and seed production.

Soil organic matter

To describe the carbon dynamics in the soil, the Century-model (Parton et al., 1988, Parton et al., 1994) was linked to Forspace. However, for the model simulations shown neither the nitrogen- nor the water-submodule were operational.

Above-ground input of litter is based on the turnover of foliage and branches, whereas below-ground litter input originates from the turnover of roots. Additionally, if there is any thinning or harvesting being simulated, the foliage, branches and roots are input to their respective litter pools.

Table 3. Change of radiation use efficiency (RUE) and leaf unfolding (LU) (expressed in change on RUE in May to attain equivalent of change in day of budburst per degree increase in temperature (T) (based on Van der Meer, 2002)

	dRUE/dT	dLU/dT
<i>Fagus</i>	0.150	0.066
<i>Pinus</i>	0.165	0.033

BOX 3 CENTURY

CENTURY is a dynamic terrestrial ecosystem model, which has been developed, tested and used over the past fifteen years to simulate the major pathways of carbon and nitrogen cycling (Parton et al., 1987, Parton et al., 1988, Parton et al., 1994; Kelly et al., 1997). CENTURY includes the effects of climate, human management and soil properties on plant productivity and decomposition processes with a monthly time step. Different plant production submodels exist for grasslands/crops, forests, and savanna's. Plant production submodels are linked to a common multiple compartment organic matter submodel. Both are described in more detail below. Water availability and flow through the system is simulated using a simplified water budget model which is mostly determined by soil texture and depth.

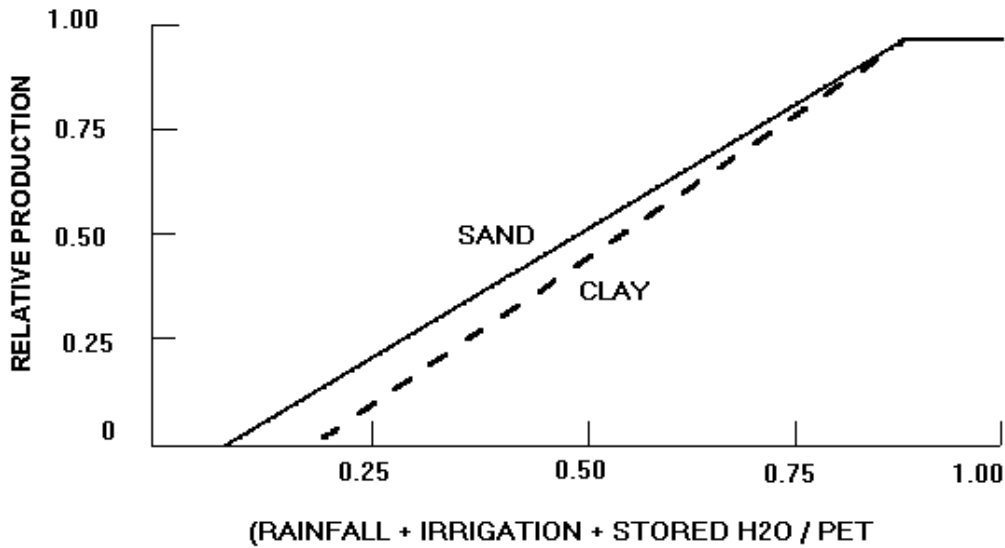
Plant production submodel

In this study only the forest submodel has been used for the scenario studies. The combination of trees and grasses in the savanna submodel gives the opportunity to explicitly simulate undergrowth in a forest along with the tree compartment. and this was used for the Loobos simulation. Monthly net production in a forest system is the product of a fixed/genetically determined maximum (gross) production rate and factors (0-1) describing the effect of moisture, soil temperature, nutrient availability and live LAI (e.g. Fig. 2). Net production is allocated to leaves, fine branches, stemwood, coarse and fine roots according to a fixed pattern, which may differ between young and old forests but shows no annual course. However, in deciduous trees, 80% of all assimilates in the first month of growth is allocated to leaves.

The grass/crop submodel is not described in detail here but simulates monthly net production analogous to the forest submodel.

Both in coniferous and deciduous trees leaf mortality rate is set per month, while in deciduous trees an additional leaf mortality rate is specified for the senescence month. Death rates of all other tree compartments are specified as fixed fractions of live pools. Nutrient concentrations of tree

components may be set as fixed or allowed to float between maximum and minimum values. During leaf senescence, a fixed percentage of nutrients is retranslocated to other tree parts.



CENTURY relation between productivity and temperature

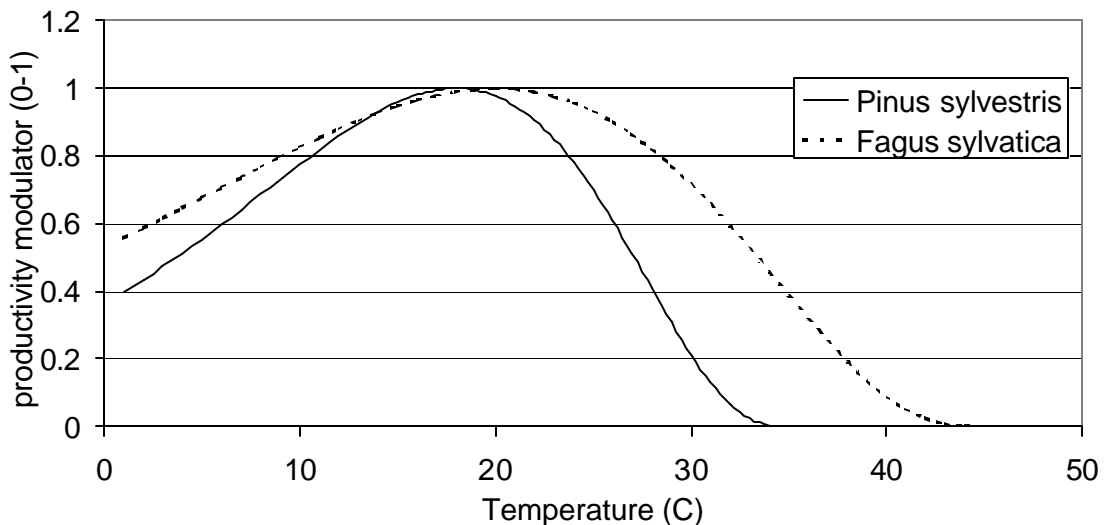


Figure 2 Examples of functional dependence of productivity on environmental factors in CENTURY

Organic matter production submodel

The soil organic matter submodel is based on multiple compartments of SOM describing different SOM fractions. The model receives organic matter as above- and belowground dead material from the forest production submodel, and partitions these into above- and belowground structural and metabolic litter pools as a function of the lignin to N ratio of the material. The structural pool contains all lignin. Further pools are above- and below-ground active SOM, equivalent to the microbial biomass and its product (Metherell, 1993), and slow and passive SOM. Microbial decomposition processes determine flows between different pools with associated CO₂ loss as a result of respiration. CO₂ loss associated with decomposition of the active pool increases with increasing soil sand content (Metherell, 1993; Parton et al., 2001). Effects of temperature, soil moisture (drought as well as anaerobic conditions), soil texture, and carbon reduce maximum

potential decomposition rates to nutrient ratio's. Nutrient pools in soil organic matter are analogous to carbon pools. Carbon to nitrogen ratios can float within more or less narrow ranges for different pools. The flows of nitrogen between pools follow the flows of carbon. Mineralisation to or immobilisation from the inorganic nitrogen pool occurs as necessary to maintain the carbon to nitrogen ratios of the different pools. If the immobilisation demand for nitrogen cannot be met, the decomposition rate is reduced.

BOX 4 Empirical model of monthly NEE

In order to construct an empirical model three steps have been taken. First, a hypothetical equation that describes the multiple effect of relevant quantities was constructed from the combination of theory and data analysis. After the parameterisation of this equation, the equation was calibrated against EUROFLUX data and finally the obtained set of equations was used to model NEE in time and space.

Parameterisation

Statistical relationships were derived between monthly mean flux data and selected meteorological quantities. These are monthly cumulative incoming short wave radiation (R), monthly mean air temperature (T) and, initially, monthly cumulative precipitation (P). After analysis of the precipitation influences, however, a clearer relationship was established between NEE and average P of the current and preceding month. The underlying assumptions leading to the empirical model used are as follows:

- *radiation*: The theoretical influence of radiation is an exponentially saturating function. However, at monthly scale the amount of incoming radiation will not reach the point where radiative saturation will occur, certainly in non-tropical latitudes. Any increase in monthly incoming radiation is likely to increase monthly carbon uptake in a near-linear way.
- *Temperature*: Although temperature is well correlated with incoming radiation, its influence on carbon exchange is quite different. An increase in temperature will result in a faster occurrence of chemical reactions. Temperature is in this way highly correlated with respiration, both autotrophic and heterotrophic. The functional dependence of respiration on temperature is assumed to be exponential.
- *Precipitation*: A three dimensional plot with incoming short wave radiation on the second independent axis suggested that precipitation acts as a limiting factor on the NEE dependence on radiation. This relationship is confirmed by similar data analysis of carbon fluxes in the tropics (see elsewhere in this report). The hypothetical equation when temperature and radiation are not limiting is an exponentially decreasing one.

The combined effect of these three dependencies can be summarised in the following bulk equation:

$$C_{NEE,tot} = (a * R + b * e^{c*T}) * (1 - e^{-d*P}) \quad \text{(equation 1).}$$

With:

$C_{NEE,tot}$: Monthly net ecosystem exchange of carbon	[g C m ⁻² mo ⁻¹];
T	: Monthly (24h-) mean air temperature	[°C];
R	: Monthly total incoming sort wave radiation	[MJ m ⁻² mo ⁻¹];
P	: Two-monthly mean cumulative precipitation	[mm mo ⁻¹];
a	: empirical monthly radiation use efficiency	[g C MJ ⁻¹]
b	: empirical monthly base respiration	[g C m ⁻² mo ⁻¹]
c,d	: Empirical exponential parameters	[°C ⁻¹ ; mm ⁻¹]

This equation has been fitted against data from 8 Euroflux sites between 1996 and 2000. During this process, a distinction has been made between coniferous and deciduous forests.

Extrapolation of the empirical model in time and space

To use the fitted model to simulate variation over time for any forest in Europe, the empirical equations were embedded in a calculation scheme which enables calculation of monthly flux for all points on a 0.5 by 0.5 degree Latitude-Longitude grid over Europe, for any year between 1950 and 1998. The dominant forest type in each grid cell was provided from the PELCOM (Mücher et al., 2001) data base and interpolated historical monthly weather data were taken from the CRU (New et al., 1999) data base. As these weather data contain temperature, precipitation and cloud cover but not incident radiation, the latter variable was estimated using cloud cover and an algorithm taken from lecture notes by De Bruin (Wageningen University Meteorology and Air Quality department, 1998). More details can be found in Groen 2002.

The model was used in this study for estimating the extent of variability in NEE as a result of climate variability over the period 1950-1998, as well as to perform a speculative climate change scenario study, assuming changes in mean temperature and in the distribution of precipitation (see Table 2).

3 Results and discussion

3.1 Observed relationships between climate and carbon exchange

3.1.1 Description of data sets

3.1.1.1 The FLUXNET dataset

An aggregated database was set up containing metadata on 112 sites worldwide and monthly carbon flux data of 65 site-years (21sites). Figure 3 gives an overview of these sites. Figure 4 shows the distribution of forest ages in the sites represented here and the magnitude of monthly fluxes measured there. The outer envelope of this plot suggests that most forests studied are between 50 and 100 years of age and that at these ages uptake is maximum. From this one of the restrictions of using FLUXNET data emerges: these data represent mainly forests which are at or around the maximum carbon accumulation phase of their development. When all these data are plotted together against monthly climate variables, a number of gross relationships emerge (Fig 5). First of all, these show a strikingly good, linear relationship between monthly total NEE and incoming radiation. Scatter is quite large but it should be realised that these data include very different forests and climate zones. These figures suggest a general pattern with a linear relationship with radiation, reflecting the seasonal variation in carbon uptake, with 'scatter' related to limiting factors such as water availability and variation in counter-acting processes such as respiration, controlled by temperature. Of course there are more differences between forests, related to soil water properties, nutrients and vegetation density. Given these differences it is even more surprising that carbon fluxes in most forests seem to vary along similar lines and within similar limits. One other aspect is interesting: the relationship with incoming radiation is not exactly linear, with a smaller slope at low monthly radiation than at high radiation. This is curious because light response curves of plants and ecosystems at shorter time scales always show *maximum* slopes at low light, with saturation at high light. The explanation of this discrepancy is not entirely clear. But one likely reason is that in these graphs deciduous and coniferous forests have been plotted together. Although the evergreen coniferous forests can respond to variations in radiation year-round, the deciduous forests will not increase carbon uptake during dark winter months. In contrast, in such months an increase in radiation will usually be correlated with an increase in temperature, leading to higher *emissions* of carbon. In the more detailed statistical analysis presented in the next sections this analysis is substantiated further.

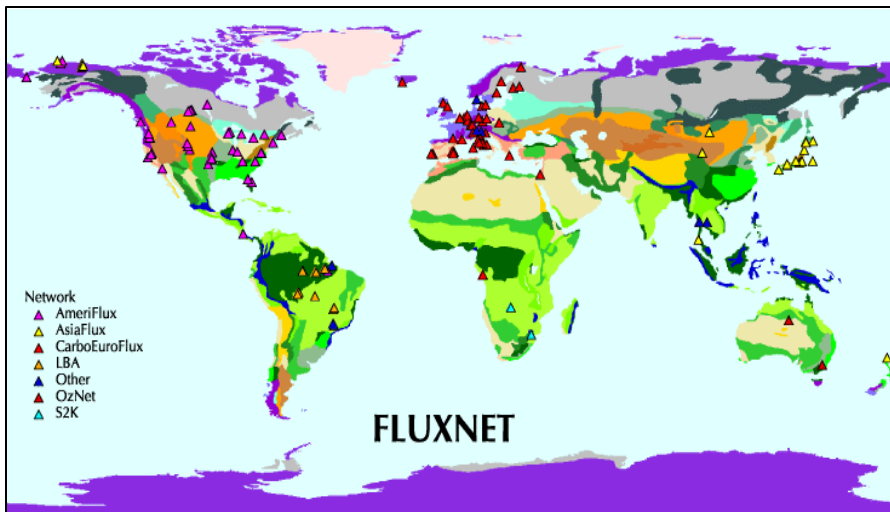


Figure 3 map showing the location of FLUXNET flux tower sites

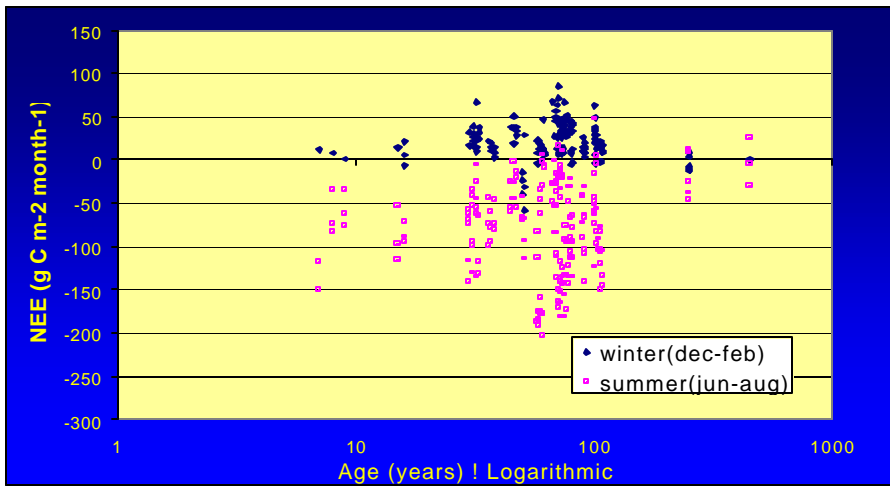


Figure 4 - Monthly total NEE in relation to forest age for 21 selected FLUXNET sites

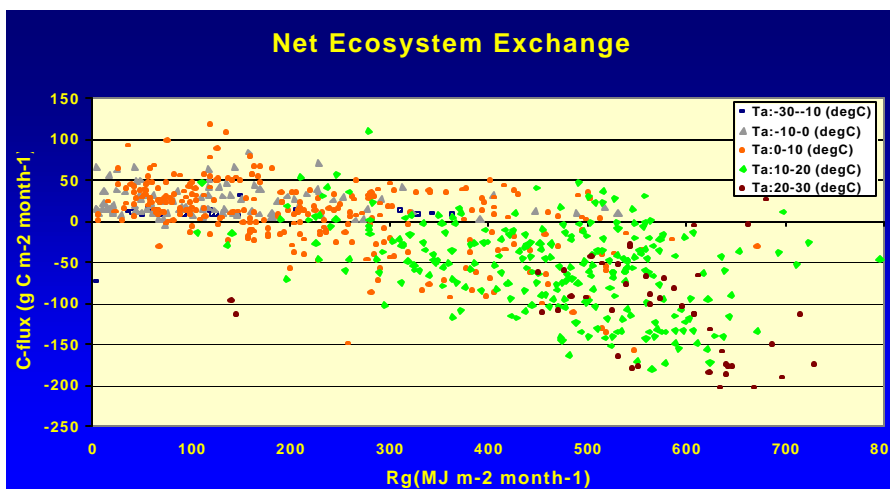


Figure 5 dependence of monthly total NEE on monthly total radiation and monthly temperature for 21 FLUXNET sites

3.1.1.2 The LBA dataset

Figure 6 gives an overview of the carbon flux data collected in the first two years of five long-term flux measurement forest sites in the Brazilian Amazon. It is immediately clear from those data that seasonal variation is much less than in temperate sites, due to less seasonality in the climate, but that nevertheless there are differences between dry and wet seasons in fluxes. In Fig 7 an analysis is presented of the dependence of these fluxes on monthly radiation and monthly rainfall. Interestingly, in this case there is no relationship of NEE with incoming radiation at this monthly time scale, while there is a broad, but clear relationship with monthly rainfall for most of the sites. Again, this reflects the seasonal variation in the Amazon, where the major factor defining seasons is rainfall and not radiation. For three of the sites (Central, Eastern and SW Amazon), geographically widely apart, this relationship is similar both in an absolute and in a relative sense. Another forest site located between the Central and Eastern sites (Tapajos km83) is an exception. In this case there is, at best, a weak *negative* relationship with rainfall: uptake is small at high rainfall months. According to the researchers at this site this is because respiration and decomposition are suppressed during the dry season, so that photosynthesis prevails, whereas during the wet season decomposition of litter that fell during the dry season is high. This forest is growing on very deep soils and the dry season is very distinct here. Presumably the trees have deep roots and are well adapted to the deep water table during the dry season. The overall conclusion from the Amazon data is, that there are important similarities in *response* to the environment between sites wide apart, but that there are also important differences.

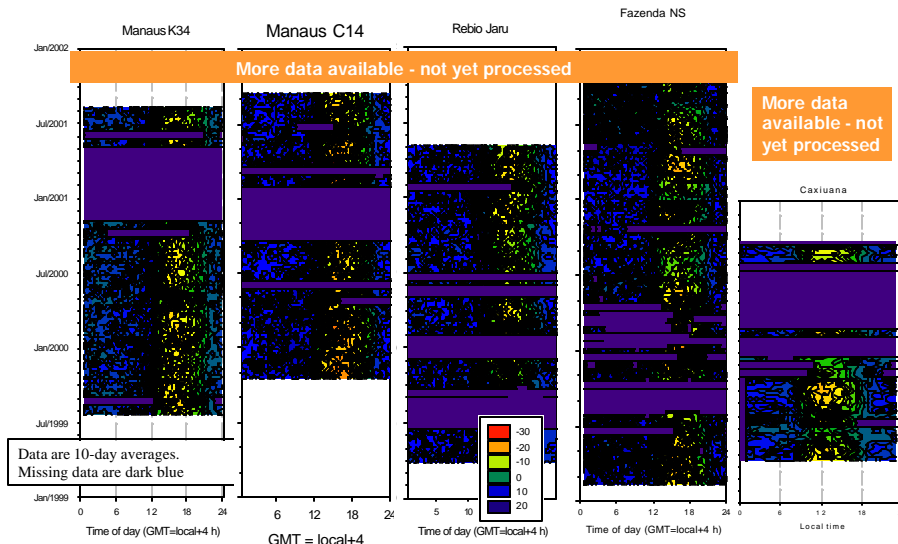


Figure 6 - Representation of Amazon CO_2 flux data for five sites over 3 years. Ten-day average values are plotted as contour values for each hour of the day along the horizontal axis and against date along the vertical axis. The Fazenda site is grassland in SW Amazonia, the other sites are rain forest

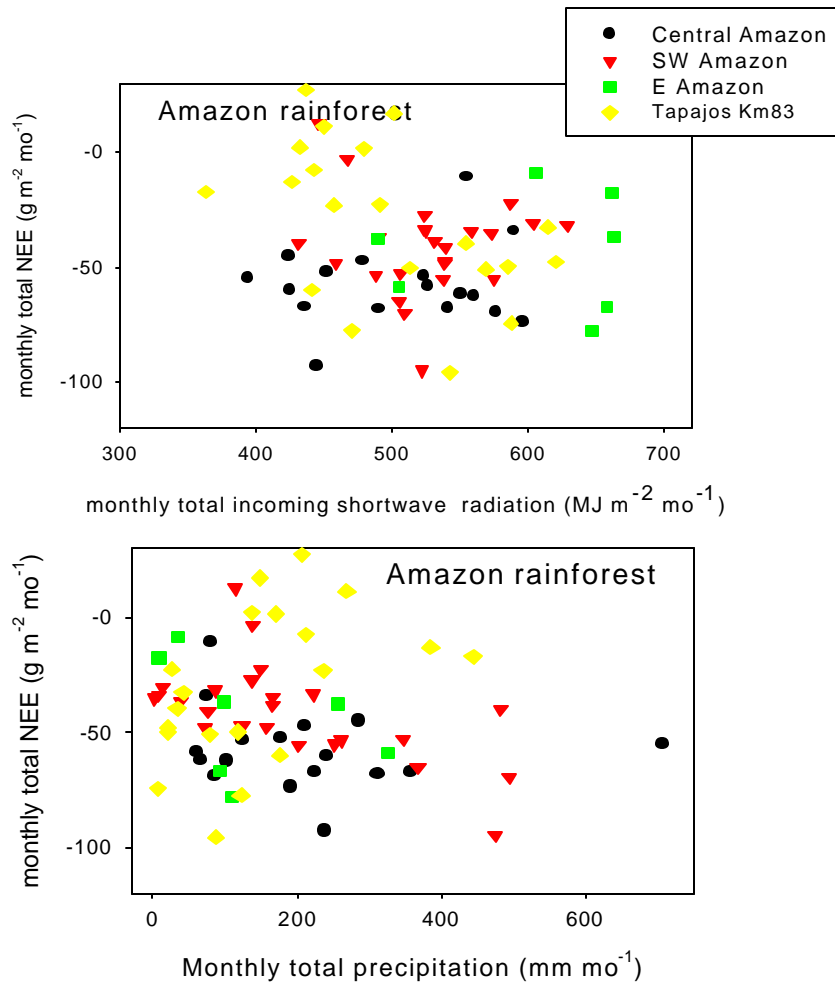


Figure 7 - Dependence of monthly total NEE on radiation and precipitation in in four Amazon flux tower sites

3.1.1.3 The Euroflux dataset analysed in more detail

Figure 8 shows the multi-year time series of measured (and gap-filled) monthly carbon exchange for 8 sites in the Euroflux network. The data from these sites have been analysed in more detail and the results have been used for assessments of uncertainty and sustainability of forest carbon sink strength in relation to climate.

Fitting a model

The parameters a , b , c and d in the empirical model in Equation 1 have been determined for the selected Euroflux sites. A first regression on all data explained 67% of the data variance ($R^2 = 0.67$, see Table 4). As it was very likely that seasonal difference in vegetation properties could not be described by simply one set of parameters, division into ‘summer’ (here, i.e. growing season, assumed from March till September) and ‘winter’ (here, i.e. not-growing season, assumed from October till February) was therefore a logical step. However, this resulted in only 1% improvement. The alternative, division into coniferous and deciduous forests, gave much more improvement in modelling carbon exchange: 74% of variance was explained. Because of the difference in physiology of deciduous trees in growing and not-growing season, it was likely that combinations of the above divisions (summer/winter and coniferous/deciduous) would give the best results. In Table 4, the obtained values of the empirical constants a , b , c and d are presented. Explained variances of 77% and 80% were obtained for coniferous and deciduous forests, respectively.

Table 4. Results of the performed calibration. Notes:

(1): summer and winter separately

(2): coniferous and deciduous separately

(3): combination of division (1) and (2); these values are being used for further modelling

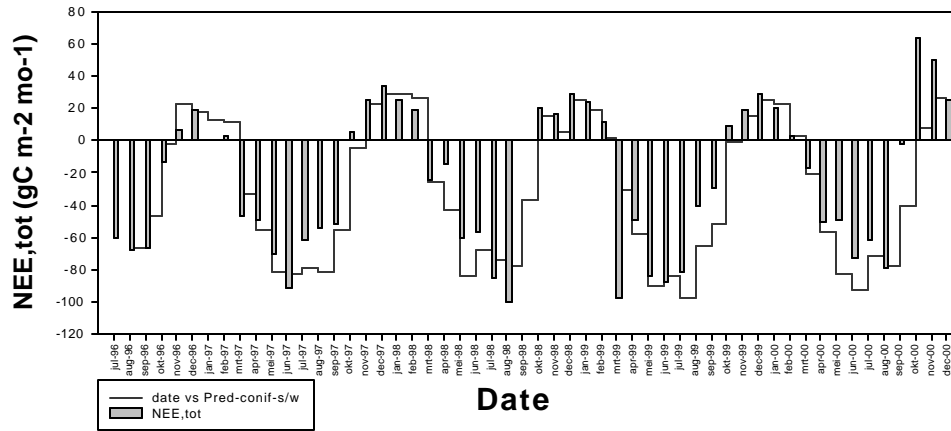
Regression:		Deciduous				Coniferous			
NEE,tot	yearly, R^2 :					0.67 (0.68 ⁽¹⁾)			
NEE,tot	yearly, R^2 :					0.74 ⁽²⁾			
Combined ⁽³⁾ :		a	b	c	d	a	b	c	d
NEE,tot	Summer:	-0.493	174.49	-0.0096	3.18E6	-0.160	24.95	-0.181	0.194
	Winter:	-0.181	44.37	0.0565	-	-0.298	35.18	0.0403	-
R^2 :		0.80				0.77			

It has to be taken into account that the output of a statistical regression is a numerical approximation of the four dimensional data plot of NEE against the independent variables, therefore, an explanation of the fitted parameter values is hard to give. Note the large value of parameter d for deciduous forests in summer. This implies that the model cannot infer any seasonal water stress for European deciduous forests and even short periods (few days) of excessive droughts hardly seem to affect seasonal carbon flux. During wintertime, there was no sensible result when precipitation was taken into account. Therefore, this part of equation 1 has been omitted completely for winter periods.

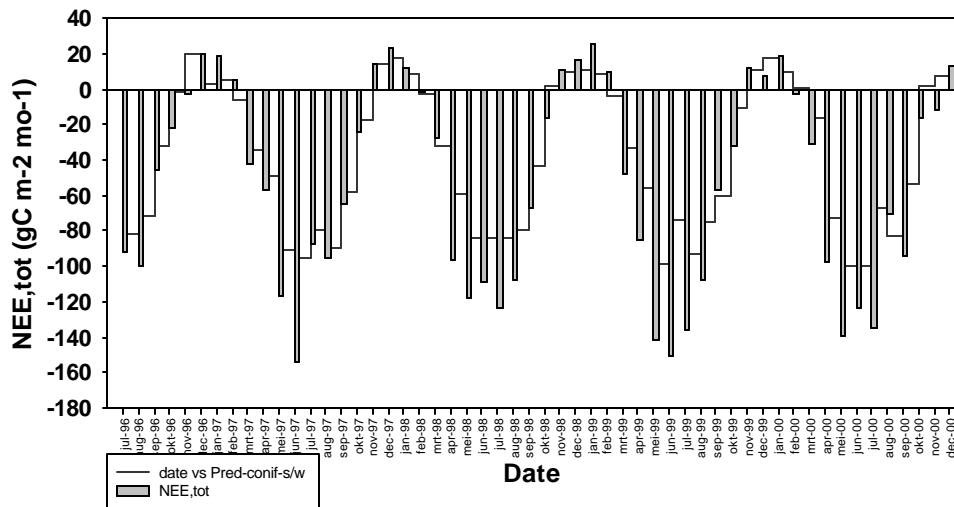
Subsequently, a comparison between modelled and measured values was made. Figure 8 illustrates the fit of some of the regressions. Modelled and measured NEE

are plotted against monthly incoming short wave radiation in figure 9 and we see a remarkable difference between radiation influence on carbon exchange in deciduous and coniferous forests. This difference is expected, because of the expected inequality of vegetation properties. Deciduous forests only respire outside the growing season due to the absence of leaves, while coniferous forests in wintertime utilise most of the light available. For the coniferous forests, the modelled line is now more as expected: a steeper slope at low radiation, while for deciduous forests the predictions at low radiation clearly reflect the winter season when light is not used for photosynthesis. With the assumptions and limitations in mind, the model gave a quite satisfying output.

Loobos, Netherlands (1996-2000)



Tharandt, Germany (1996-2000)



Hesse, France (1996-2000)

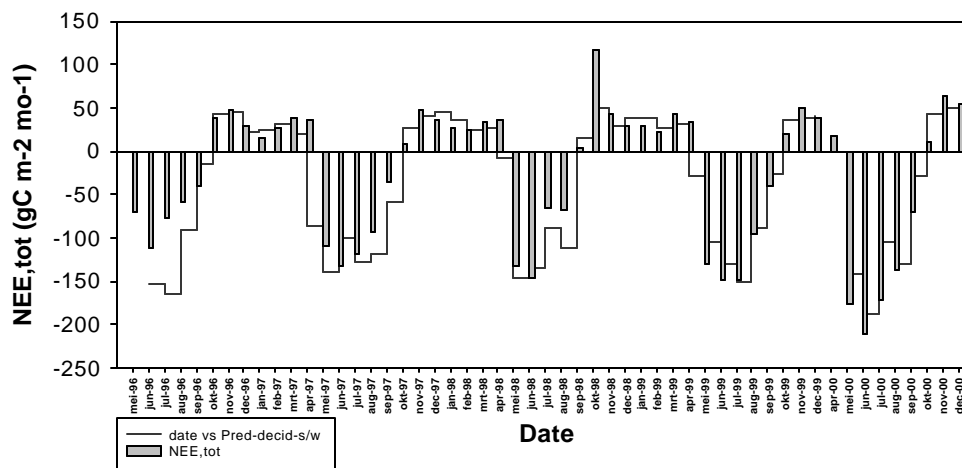


Figure 8: Comparison of time series of the measured NEE with the modelled NEE for three tower sites

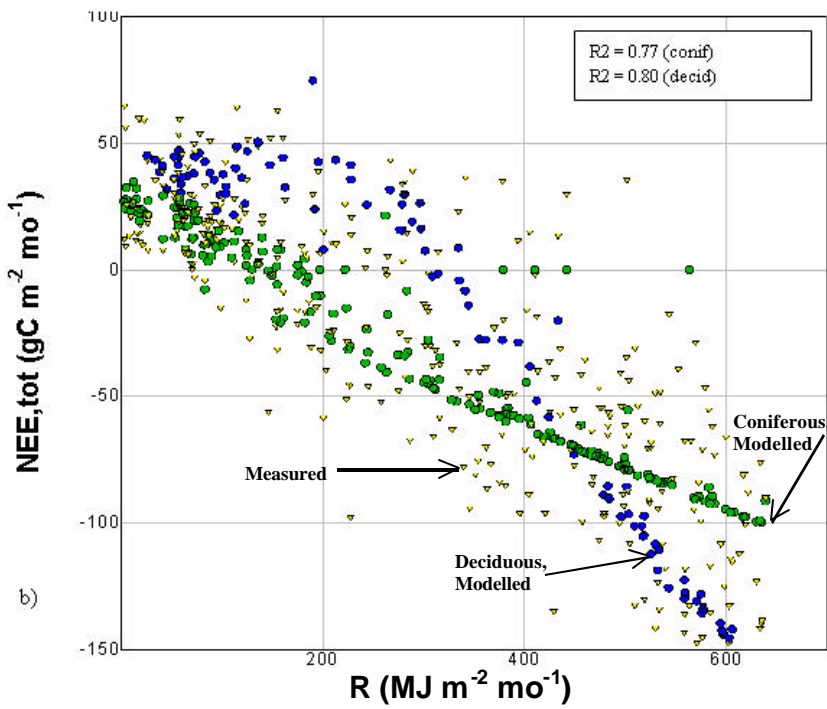
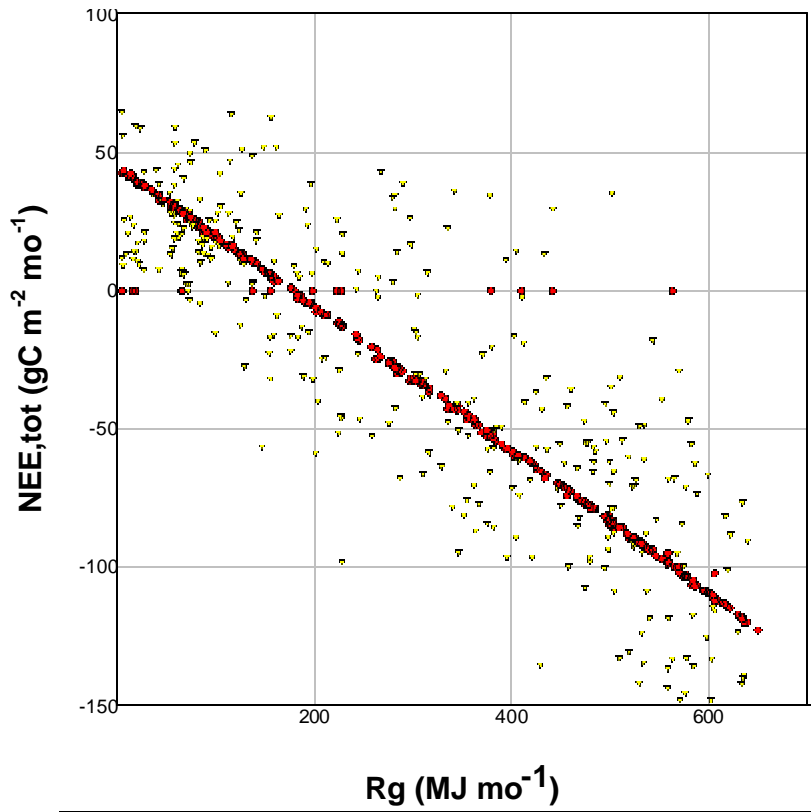


Figure 9: Modelled and measured NEE vs. incoming radiation. Small yellow triangles are measured values. Modelled values derived without any distinction (red circles) in 9a, and with distinction both in vegetation type and in season in 9b (green: coniferous, blue: deciduous)

Sensitivities of carbon exchange to climate

Using the empirical regression model, time series of 45 years (1950-1995) for six grid points were made for NEE. Figure 10 shows these series of annual (Jan-Dec) NEE and assimilation. The amplitude of NEE of the coniferous forests varies from 1.6 to 1.8 tons CO₂ per hectare per year, corresponding with 26% to 50% of total sink strength. However, the figure shows that the time series of deciduous forests contains fluctuations up to 4 tons CO₂ per hectare per year. For both deciduous and coniferous forests, the most extreme peaks are mainly caused by large annual anomalies of incoming radiation. Secondly, the deciduous forests show much more in phase fluctuations relative to the coniferous forests. NEE of the deciduous forests in France and Poland is alternating from annual uptake to annual release of CO₂, almost each year, although assimilation of the French deciduous forest is far more than the Polish one. This could implicate that apart from the seasonal changes in physiology, also deciduous forests are more vulnerable to annual weather fluctuations than coniferous forests.

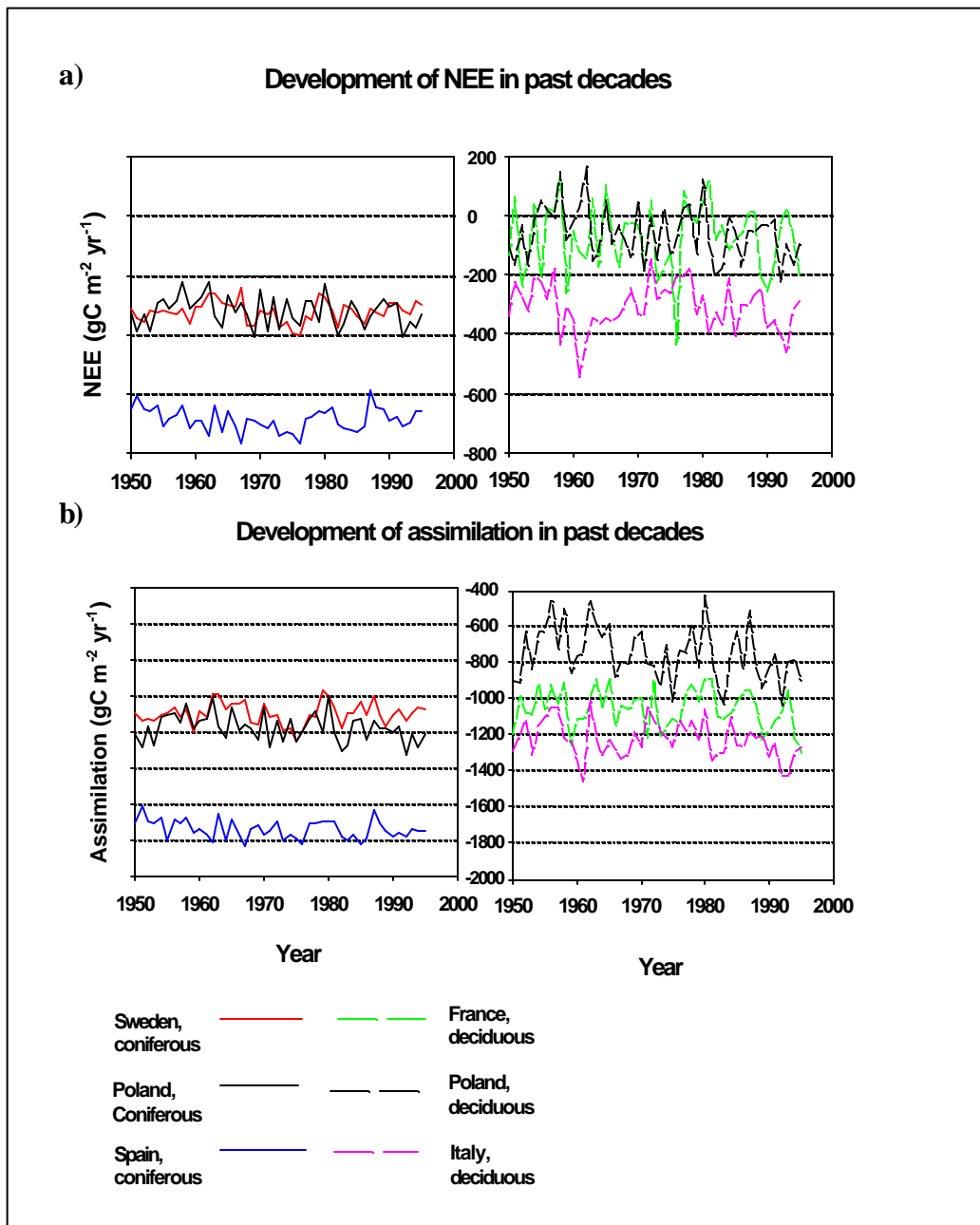


Figure 10 Time series of modelled NEE (a) and assimilation (b) for three coniferous and three deciduous gridpoints (PELCOM)

The model sensitivity of carbon exchange to annual anomalies of weather parameters is shown in figure 11. The figure shows a very clear relationship between annual NEE and the deviation of annual cumulated incoming radiation. Note the large anomalies of radiation. Radiation disturbances seem to affect deciduous forests more than coniferous ones ($|DNEE_{cum} / DR_{cum,anom.}|_{decid} > |DNEE_{cum} / DR_{cum,anom.}|_{conifer}$). Although annual temperature is likely to be related to radiation, the dependence of NEE on temperature is much more scattering than the dependence on radiation. Secondly, annual carbon exchange dependent on

temperature seems to be spatially distributed in a different way. For instance, French and Polish deciduous forests tend to be more positively related to temperature (i.e. more carbon uptake when the average temperature is higher) than the Italian forest. Furthermore, the modelled numbers suggest that coniferous forests in Poland and Sweden have hardly any correlation between temperature anomalies and NEE, while the Spanish forest are even negatively affected by temperature increases.

This temperature effect, and differences between locations in Europe are likely to be related to the correlation between radiation and temperature. Radiation generally higher during warmer growing seasons in northern Europe, while in southern Europe, high radiation and high temperatures are often associated with reduced soil humidity.

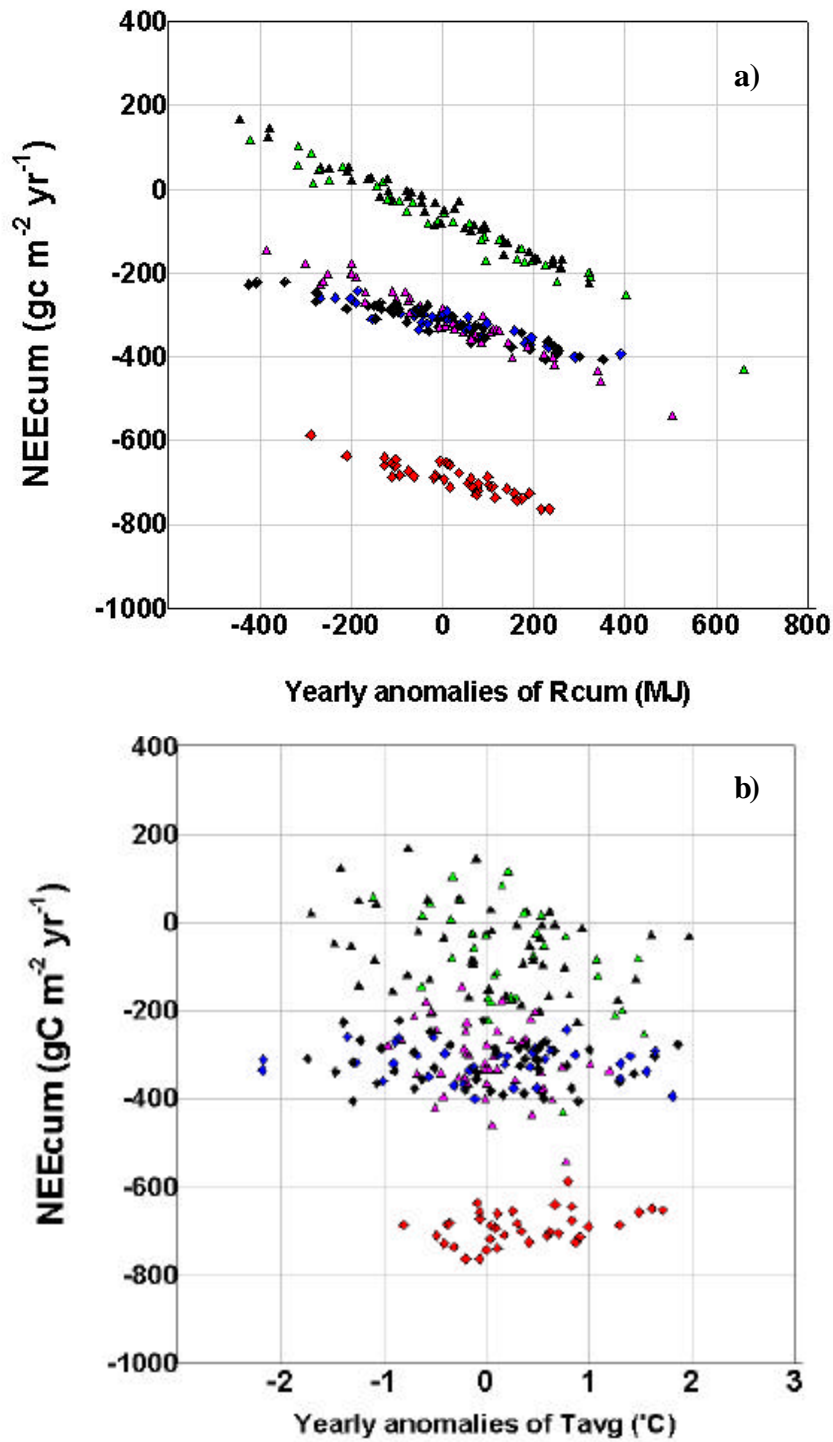


Figure 11 Annual cumulated modelled NEE plotted against annual anomalies of incoming radiation (a) and temperature (b). Triangles represent deciduous forests (green: France, black: Poland and purple: Italy) and diamonds coniferous (blue: Sweden, black: Poland and red: Spain)

Climate variability: relationships with the NAO

One of the most important indices of climate variability in Europe is the North Atlantic Oscillation (NAO-) index, as a measure of the intensity of western circulations. We used this index to represent the climatic conditions during the period between January 1973 and December 1995 to study in more detail the variability in the European carbon sink, calculated using the empirical model as in the previous section. The NAO-indices for growing and non-growing season have been plotted against corresponding seasonal fluxes in figure 12. These fluxes are the seasonal cumulatives of monthly *area averages* of NEE (from now on denoted as NEE) of *all* forests located in a northern band (59.75 – 74.25 °N) of Europe and the same for a southern band (30.75 - 47.75 °N); these bands are illustrated in figure 12 as well (inset). Very interesting is the difference between the northern and the southern band in the way forests are behaving during high and low NAO-indices. The contrasting appearance of the NAO seems to be reflected in the model output. The lines are linear regressions made to give emphasis to the different tendencies. It can be seen that in all situations seasonal (three-monthly) carbon exchange varies with 30 to 50 grams per square meter (corresponds with 0.3 to 0.5 tons ha⁻¹). In the northern band a high NAO will affect the annual exchange with about 0.6 tons ha⁻¹ decrease in uptake. The NAO produces more temperate summers (more humid and lower maximum temperatures) and winters (more humid and higher minimum temperatures). As incoming radiation has a major influence on carbon uptake, it is likely that the increased northwards humidity transport involves more cloudiness, affecting photosynthesis. Furthermore these temperate conditions perhaps are increasing respiration. Separate measurements of respiration and assimilation could clarify these issues.

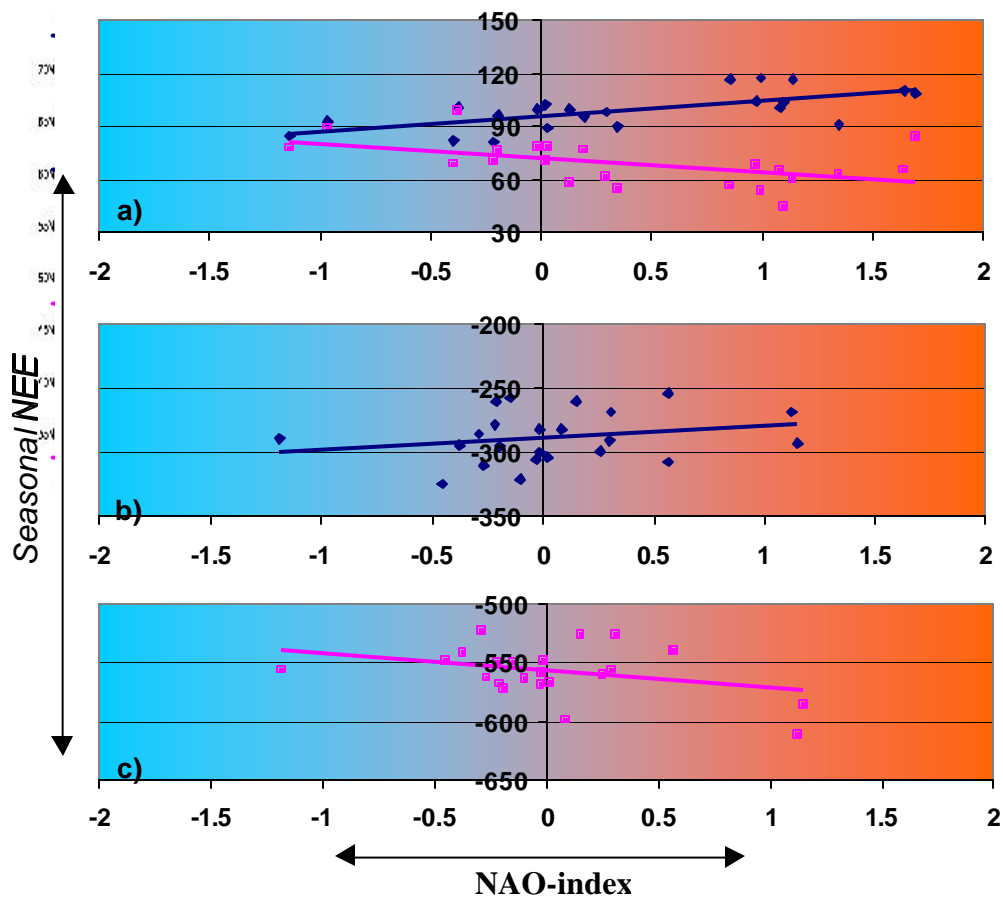


Figure 12 top: Correlation between the NAO-index and the area averaged NEE (**NEE**) in the period from January 1973 till December 1995, outside the growing season (5 months, a), and during the growing season (7 months, b and c). Blue dots and lines represent the northern band; pink ones south (fig 12 bottom). Units of **NEE** are $gC\ m^{-2}$. The lines are linear regressions, but not further quantified.

Figure 12 bottom: Visualisation of the northern and the southern band of which NEE of all the situated forests is averaged (**NEE**). Green pixels indicate coniferous forest while yellow pixels indicate deciduous forest

Forests in Southern Europe seem to take advantage of high NAO conditions. Annual uptake can be increased with about 1.0 ton ha⁻¹. Before, it was shown by figure 11 that the annual NEE of the Spanish coniferous-forested grid cell decreased when mean temperature increased. So the cooling effect on Southern Europe of a high NAO tends to stimulate carbon uptake or it reduces carbon emission. Beside the cooling effect, also the relative drought during high NAO years could play a role in hampering respiration. Note that the model has a low NEE dependence on precipitation and therefore the changing (drier) humidity circumstances have little influence. More measurements in time and space are indispensable to verify or clarify this issue.

Climate change projections using the empirical model

Climate and weather effects are mainly manifesting themselves in temperature and humidity. Associated weather patterns could affect cloud cover and therefore the radiation balance. We speculated on the possible effects of future climate forcing on carbon sinks using the empirical fits to the flux data. For the six grid cells that were studied in the previous section, the likely climate change impact on carbon exchange is calculated in terms of decrease or increase in NEE. A scenario has been constructed, with the help of IPCC forecasts. It is assumed that in the year 2100 mean air temperature will have risen by 2.5°C relative to 1990. At the same time, the more widely varying prediction of humidity is used to assume a decrease of precipitation in summer (i.e. growing season) and increase in winter (outside growing season) by 10%. The possibility of climate change involving disturbances of local incoming radiation (e.g. caused by altered humidity transport) is very hard to define. It is likely that the spatial distribution of cloudiness will still be dependent on the same factors as present ones, and that for example the state of the NAO index still has a large influence on this. Therefore, it is assumed that the distribution of cloudiness and thus of incoming radiation will be unchanged. This scenario was implemented in the model and for the second time, time series have been calculated (Table 2).

The proposed climate change seems to be quite drastic if this would happen instantaneously. This is however only partly the case, because for the recalculation of the time series the CRU-data from 1950 till 1995 are used and hence, the time series can be considered as series from 2055 till 2100. In 1950, the mean temperature was about 0.9° Celsius lower than in 2000. So the actual proposed temperature change relative to 1990 corresponds with about 1.6° Celsius in 2055, which is quite less drastic. Thus, the period from 1950 till 1995 is assumed to be happening again 105 years later while undergoing the above-described climate change. Annual weather variability will be maintained, independently of the imposed climate change. A final remark on the scenario is that the climate change is equally distributed over the whole area of Europe, without taking account of the spatial differences in climate change occurrence.

The results are shown in Table 5. The 1950 – 1995 mean annual values of NEE and assimilation are given for comparison. Sequentially, the mean, minimum and maximum annual departures from the old mean flux caused by the climate change

are given and finally these departures are expressed in relative changes (%). The remarkable difference between the departures in NEE and assimilation is that in all cases NEE decreased while assimilation increased. This implies that respiration must be enormously increased. This is however to be expected when temperature is higher and perhaps, winters more temperate.

If absolute change is considered, we note that coniferous forests are much more affected than deciduous forests. The average NEE departures of coniferous forests are predicted to be 2.3 till 6.6 times higher (more positive flux: less annual net uptake by vegetation) than NEE departures of deciduous forests. The mean sink strength of coniferous forests was predicted to decrease with 8.8% to 19.2%, corresponding to about 0.5 to 0.7 tons carbon per hectare per year. According to this empirical model, deciduous forests will lose 4.5% to 38.6% of their sink strength, corresponding with 0.1 to 0.3 tons carbon per hectare per year. The spread in sink change may be explained by spatial differences in sensitivity, adaptation and vulnerability.

Table 5. Simulated impacts of climate change on carbon exchange in the period '2055' till '2100', using the empirical model. The proposed climate change is specified in Table 2

Location	Sweden	Spain	Poland	France	Italy	Poland
Longit., Latit. (degrees)	12°E, 59°N	4°W, 41°N	23°E, 53°N	1°E, 47°N	12°E, 44°N	24°E, 53°N
Tree group	<i>Coniferous</i>	<i>Coniferous</i>	<i>Coniferous</i>	<i>Deciduous</i>	<i>Deciduous</i>	<i>Deciduous</i>
C-flux ($g\ C\ m^{-2}\ yr^{-1}$)	ΔNEE	ΔNEE	ΔNEE	ΔNEE	ΔNEE	ΔNEE
Mean flux 1950 – 1995	-321.5	-684.7	-321.0	-77.4	-309.9	-58.7
Avg. departure	58.0	68.1	63.5	24.4	18.7	9.6
Min. departure	53.4	64.7	60.0	19.2	14.6	5.4
Max. departure	61.7	71.9	67.1	29.8	21.8	15.7
% change: min, max	-16.6, -19.2	-9.4, -10.5	-18.7, -20.9	-24.9, -38.6	-4.5, -6.8	-7.0, -20.3

3.2 Inter-seasonal soil respiration measurements.

3.2.1 Loobos measurements

At the Loobos site a 50 m transect was present of 22 fixed sampling points consisting of PVC rings inserted into the soil several years ago. The transect runs across the forest, extending into a clearing and covering small-scale dune topography. The rings fit the SRC1 soil respiration chamber linked to the EGM-2 infra-red gas analyser (PP systems inc., UK), and this combination was used to measure the respiration rate at each point on a two-weekly basis from mid 2001 till late 2002. Measurements were usually done during mid-morning as part of the routine servicing of the eddy correlation site. All measurements were accompanied by a concurrent measurement of the temperature in the mineral soil just underneath the litter layer.

The histogram in figure 13 gives an impression of the overall mean and spread of respiration values measured. Apart from the spread being large, the distribution is strongly skewed, making it difficult to judge whether high values are erroneous outliers or not. Our judgement was that occasional values of up to about $15\ \mu\text{mol}\ m^{-2}\ s^{-1}$ are possible.

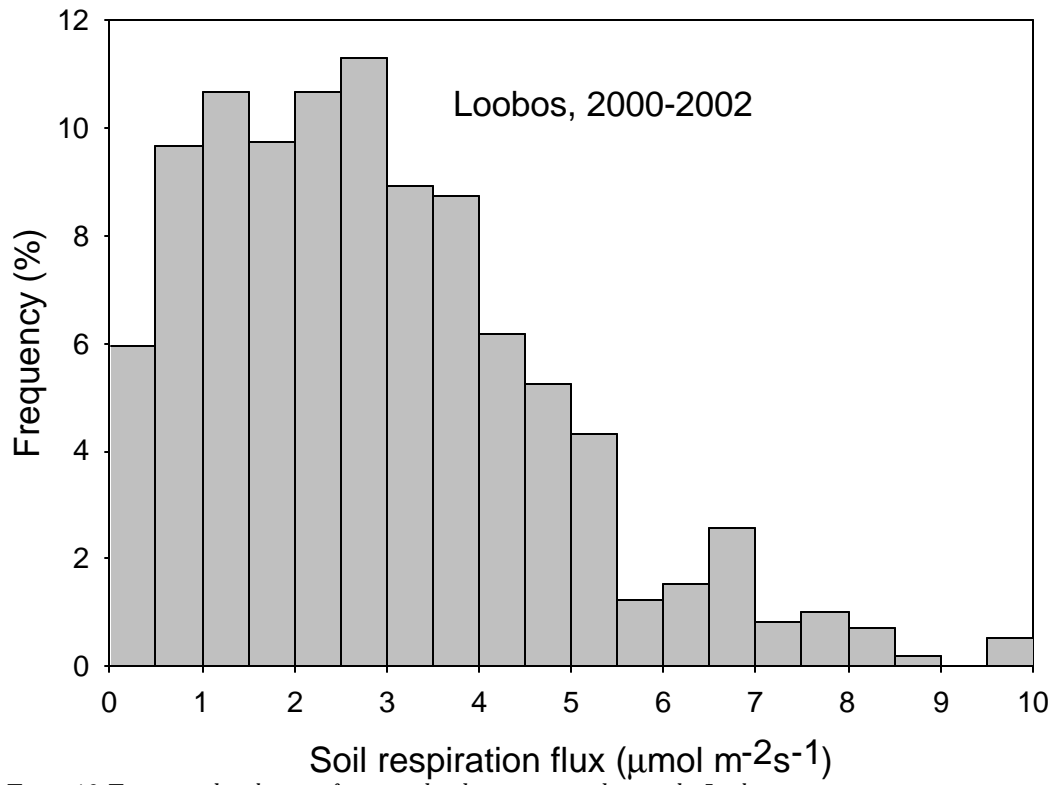


Figure 13 Frequency distribution of measured soil respiration values at the Loobos site

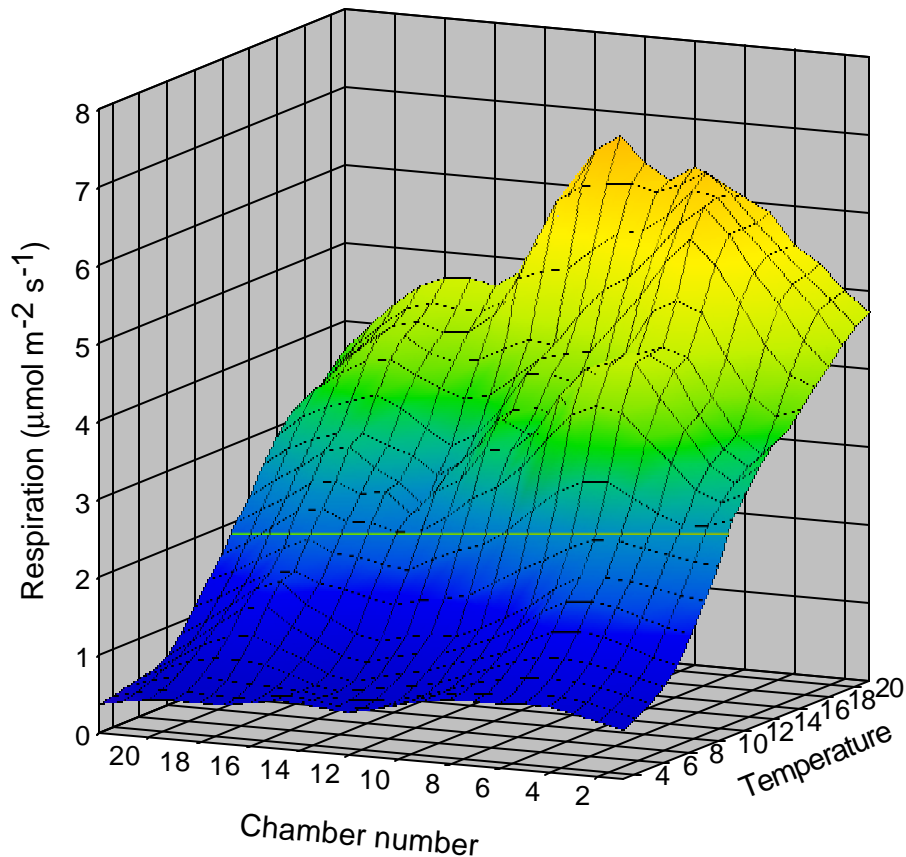


Figure 14 surface fitted to variability of soil respiration at Loobos with temperature and point along the transect

Figure 14 summarises the variability of fluxes with varying temperature and with distance along the transect. The three-dimensional surface has been fitted through all points. Along the whole transect, there is a clear dependence on temperature, where respiration increases if temperature increases, as expected. However, for the higher sample point numbers, this dependence seems limited at higher temperatures. As these points are mainly located in the clearing we can hypothesise that this is an effect of drought limitation occurring more quickly at higher temperatures in the exposed open area. These soils are very sandy, and deeply drained. Unfortunately we did not measure soil humidity along with the respiration and it is clearly a recommendation for future work to do this.

When all respiration values are plotted against concurrently measured soil temperatures, the plot shows a clear positive relationship but with much scatter. The question is whether this relationship represents a basic temperature dependence of the process or merely reflects a seasonal variation in respiration, caused by a combination of factors such as litterfall, humidity and also temperature. We do not show this relationship here, but if we try to stratify the data according to time of the year, the spread is too large and number of points too small to derive meaningful relationships with temperature.

It is interesting to investigate the relative importance of soil respiration in the net carbon budget, and to use the measurements to evaluate other methods to estimate respiration from NEE measurements alone. To do so it is necessary to calculate average respiration at similar time and spatial scales as the NEE measurements from the tower. We attempted to interpolate the two-weekly respiration data over time and estimate monthly totals, comparable with monthly totals of NEE. Here, intermediate values were estimated from the half-hourly air temperatures measured at the lowest tower level, using the observed relationship for measured values (figure 15). The resulting monthly totals are plotted in figure 16 along with measured NEE and a monthly respiration value estimated from a previously derived empirical function of NEE and specific humidity deficit of the canopy air (Dolman et al., 2002). Also shown are the simple averages of soil respiration and measured NEE, integrated to monthly totals, and the estimated monthly ecosystem assimilation rate (NEE minus NEE-based respiration estimate).

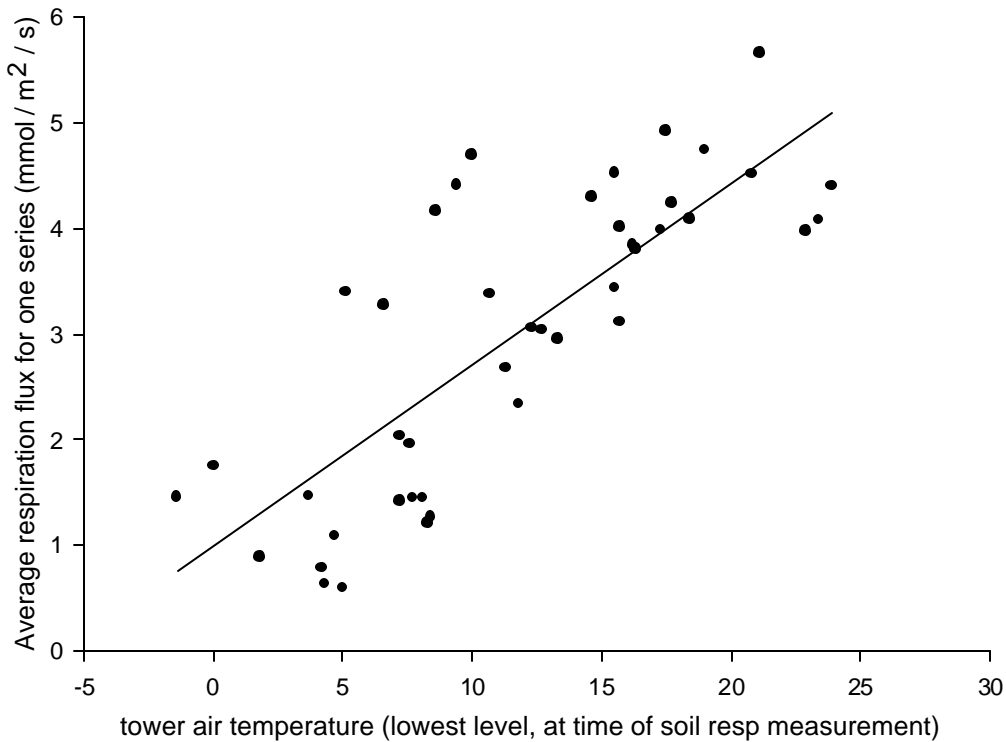


Figure 15 relationship of spatially averaged soil respiration with temperature at the lowest tower level

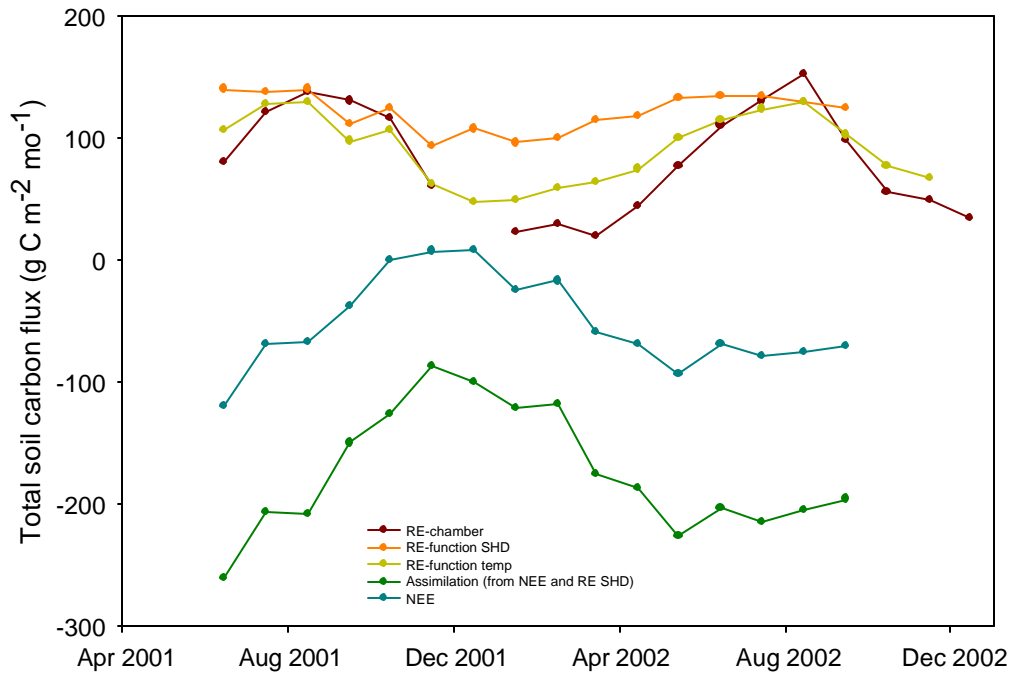


Figure 16 Seasonal variation of measured, interpolated and estimated components of the carbon balance at Loobos

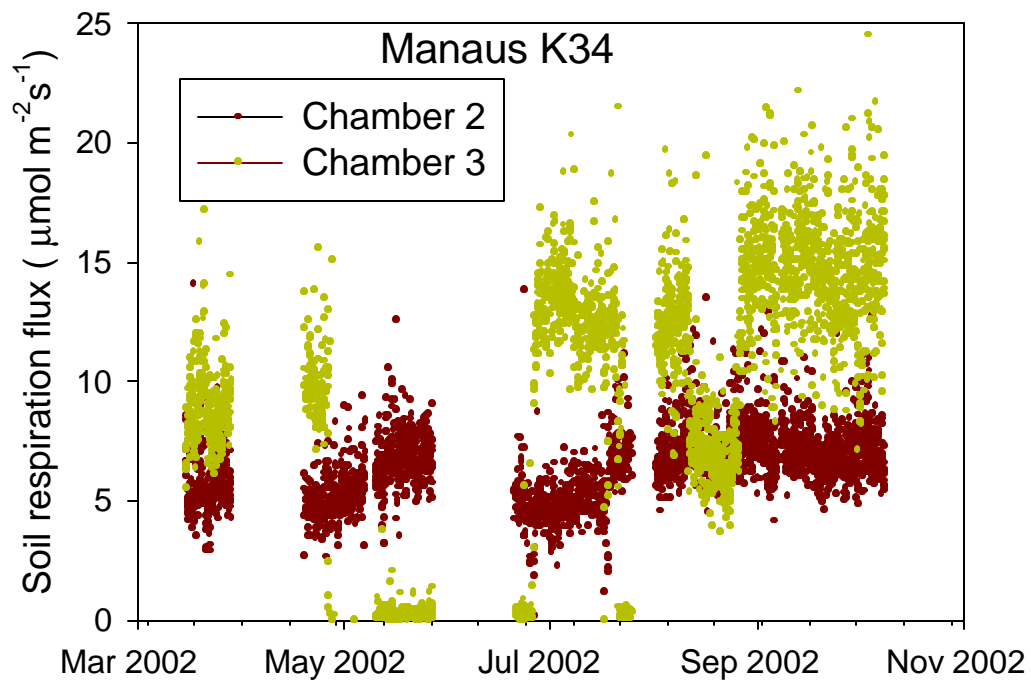


Figure 17 Overview of data from the continuous soil respiration system at Manaus K34

From figure 16 we can see that respiration is higher in summer than in winter, as expected. It also shows that during summer all estimates are very close. A problem clearly occurs during winter. During this period the previous estimates using air humidity deficit are much higher than the others are, while the straight averages seem to underestimate. It is very likely that the humidity deficit function is not equally applicable in all seasons. At the same time it seems reasonable to interpolate measured soil fluxes using a temperature dependence, although we use a relationship with annual temperature variation, which does not necessarily apply to diurnal variation. Finally, soil respiration is only part of total ecosystem respiration. Therefore, this analysis suggests that during summer, the regression method from Dolman et al. (2002) *underestimates* ecosystem respiration, underestimating the seasonal variation in respiration and hence also the variation in assimilation. Overall, this exercise illustrates that, even when direct soil respiration measurements are available, estimating the components of the ecosystem carbon balance carries large uncertainties.

3.2.2 Measurements in the Brazilian Amazon

In the Brazilian Amazon, several field measurement series have been set up. At the K34 site north of Manaus, central Amazon, a newly designed continuous system was installed in early 2002. The system measured fluxes at four nearby points on a half-hourly basis, day and night, and this has delivered data from March 2002 onwards, except for a few breakdown periods (fig. 17). Unfortunately, only one of the four chambers produced data that appear reliable throughout (values around $6 \mu\text{mol m}^{-2}\text{s}^{-1}$). The other chambers probably started working correctly, but have each suffered from various types of problems, such as mechanical wear of the automatic lid (two chambers), leaks (two chambers) and unrealistically high values, above $15 \mu\text{mol m}^{-2}\text{s}^{-1}$ (one chamber). Whether these high values are in fact correct still has not been established. We have so far not been able to trace an instrumental or software problem, and independent testing is almost impossible. At other points, using other systems, high values have also sometimes been found and spatial variation is notoriously large. Ignoring these data, figure 18 shows that the respiration rate at chamber 2 is correlated with both soil temperature and soil humidity. Both relationships carry substantial scatter, but the temperature relationship is clearly monotonously increasing while the relationship with soil humidity suggests that there is an optimal soil moisture of about 35 vol% at which respiration is maximum. Beyond this probably excess water and anaerobic conditions limit decomposition processes.

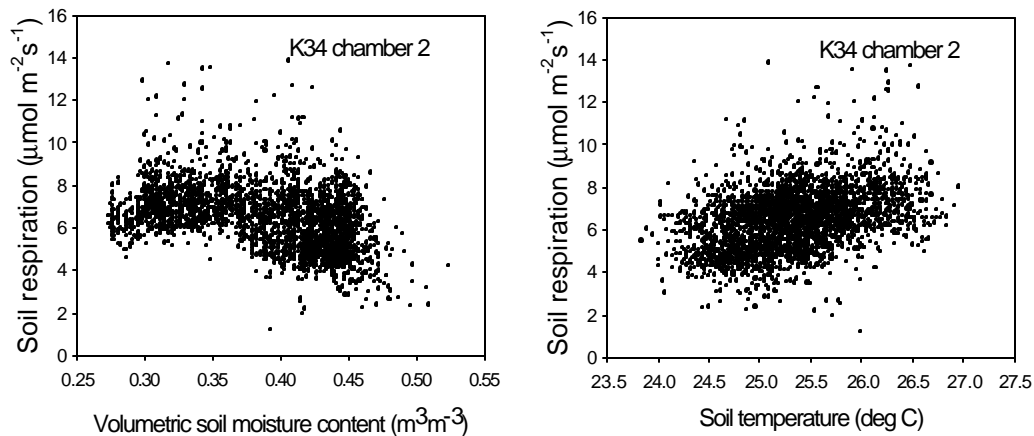


Figure 18 Relationship of measured soil respiration at Manaus (chamber 2) with soil temperature and soil humidity

Apart from the continuous system at K34, new measurement work was also initiated at the same site as well as in another region, in the SW of the Amazon. In K34, we started measuring weekly transects using a mobile soil respiration system similar to the one used in Loobos, only at k34 the transect is over a 800 m toposequence from the plateau area (where the eddy correlation tower is) to a regularly flooded valley bottom about 50 m lower in altitude. The toposequence also represents variation in soil texture, vegetation productivity and nutrition, and of course humidity. Initial problems to overcome here were the large heterogeneity of the soil surface and large variability in fluxes, but from 2003 on a Brazilian MSc student will carry out this project.

In Rondonia the new measurements consist of a new continuous respiration system, based on the Alterra design but modified and built by the group of Dr. Humberto Rocha at the University of Sao Paulo. The system is now ready and during a field visit in September 2002 a site was selected in a forest fragment near the city of Ji-Parana (figure 19). During early 2003 the system has been installed and is now working. No data have been analysed so far.

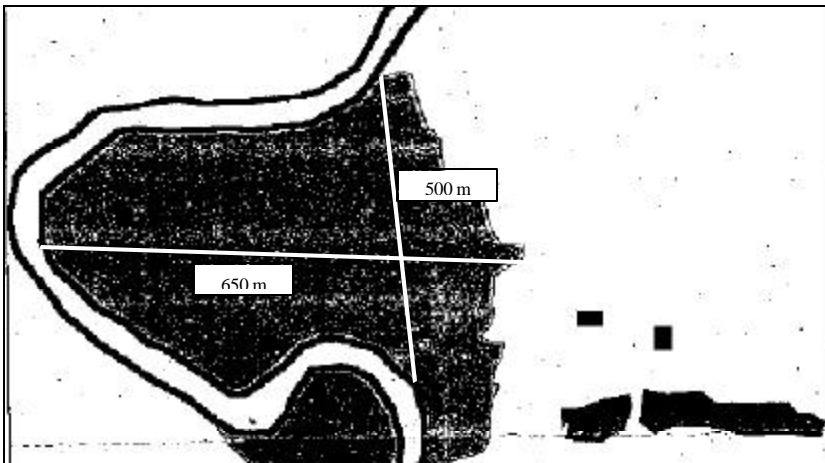
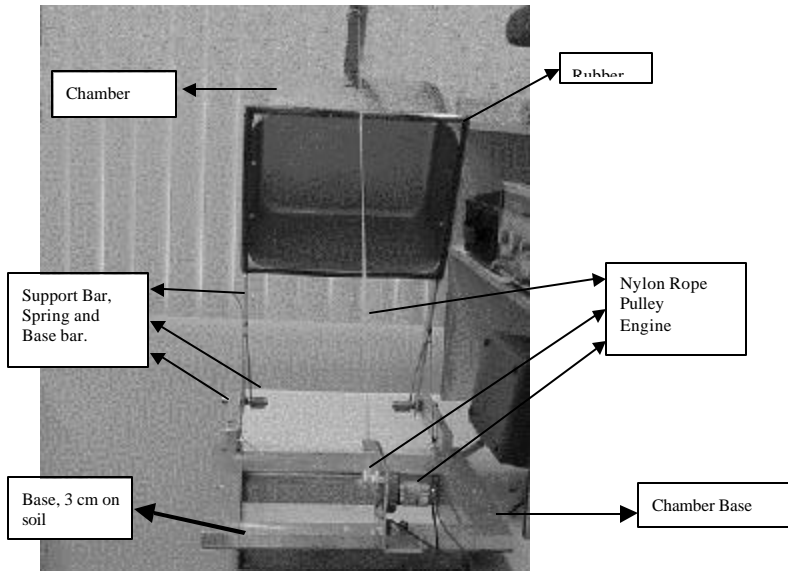


Figure 19 Photograph of newly designed system built at USP Brazil (top), and map of forest fragment near Ji-Parana, RO, Brazil (Fazenda Itapirama ,10°55.6'S, 62°01.266'W), with site location for continuous soil respiration measurements (right)

3.3 Modelling the sensitivity to climate change and management of the carbon balance of natural forests: a case study of a forested area in the Veluwe, Netherlands.

3.3.1 Forspace

The development of carbon stored during 100 years of growth starting from seedlings in the various carbon compartments of a pine (*Pinus sylvestris*) and a beech (*Fagus sylvatica*) forest were simulated under the different scenarios (Table 2), using the model FORSPACE.

Figure 20 illustrates the development of the carbon pools. The graphs show the effect of the scenarios on the overall increase in carbon content from bare soil to 100 year old forest. There are quite distinct effects of either temperature increase or thinning regime, and these effects differ substantially between the two species. Where the temperature effect dominates the simulated sensitivity in *Fagus*, the thinning regime is most important in *Pinus*. The fact that the Soil Organic Matter (SOM) component in the *Pinus* forest is simulated to decline after peaking at about 40 years suggests that the management regime chosen is not sustainable. This is not the case. The yield and thinning regime of the stand is representative of real forests on poor sandy soils, and the FORSPACE model simulates biomass to be more and more locked up in a decreasing number of trees with increasing basal area. Cutting trees thus has an increasingly larger impact on the leaf area and mass of a stand, as fewer trees occupy a larger area. For this situation of ideally managed stands of beech and pine natural mortality of trees was not included. Above- and belowground litter production is strongly affected by management as foliage, branches and roots are assumed to remain in the forest after each thinning. This periodic input of litter is much larger than the continuous input due to turnover of foliage, branches and fine roots. As thinning intensity decreases with stand age, so does above- and below ground litter production. For *Pinus*, with the shorter rotation this decrease of litter production by thinning is attained earlier than *Fagus*. Additionally, below-ground biomass and thus litter production of *Pinus* decreases due to simulated changes in allocation of carbohydrates. Both effects results in the decrease in soil organic matter for *Pinus*.

In *Fagus*, where no similar decrease in root biomass is found, soil organic matter slowly but steadily increases for about 80 years after a period of rapid accumulation during the first 20 years. The similarity in patterns between below-ground biomass and soil organic matter accumulation suggests that root turnover is the primary source of soil carbon (most clearly in *Pinus*, figure 20). This corresponds with results from Rasse et al., 2001 who found that fine root turnover is the major source of C to Belgian forest soils under both *Pinus sylvestris* and *Fagus sylvatica*.

The strong and rapid reaction of soil organic matter to decreases in litter input suggests a high turn-over rate of a substantial fraction of carbon in the soil. Indeed the values for total soil carbon are lower than measured field values (35 000 to 60 000 kg C ha⁻¹ for *Pinus sylvestris* on comparable poor sandy soils (Emmer and Sevink

1994; Van Oene et al., 1999; De Kovel et al., 2000); 94 000 to 228 000 kg C ha⁻¹ for *Fagus sylvatica* on different soil types (Scarascia-Mugnozza et al., 2000). The high decomposition rate is probably a result of model simplification, as for this simulation soil decomposition is not affected by drought or nutrient limitation.

The relative effects of different scenarios are fairly constant (in a relative sense) over time (Fig 20). Therefore, the effects of the different scenarios on the final pool sizes, after 100 years simulation, have been summarised in Table 6. For *Fagus*, a longer thinning interval only has a zero or small positive effect on the development of all components of the carbon stock, except on harvested material. The overall effect on total carbon in *Fagus* is a 5% increase, but if harvest is included then the effect is minimal. In the *Pinus* simulations the effect of doubling the thinning interval is simulated to have a 30% increase effect on all components, except on harvest. If harvest is included in total carbon gain, the effect of decreasing the thinning intensity is about 20%.

In the climate warming scenario, for *Fagus* the build-up of carbon stocks is increased in all components including harvest, except for the above-ground biomass because the management is based on the harvest of the annual growth. Increases in production with increasing temperature in FORSPACE are associated with a combination of higher Radiation Use Efficiency (RUE) and longer duration of the growing season (van der Meer et al., 2002). All extra above-ground production is harvested (harvest is doubled!) in this scenario. Because of the dominant proportion in above-ground biomass, the effect of temperature rise on total stand carbon is only 4%, but if harvest is included the effect rises to 36%. The effect of temperature increase in *Pinus* is rather different, as mentioned before. All components except below-ground biomass and harvest *decrease* in this case. This is related to the fact that the response of leaf unfolding of *Fagus* to increasing temperature is twice that of *Pinus* (van der Meer et al., 2002). Overall the effect of higher temperatures on *Pinus* stand carbon is a 5% decrease, but including harvest an 11% *increase* in carbon yield is predicted in the warmer climate.

The combined effects of less intense thinning and higher temperatures is always positive. Where responses are weak or negative for either single change, the combined effects are now clearly positive. Where single effects were already positive, the combined effects are very large, up to more than doubling the carbon storage.

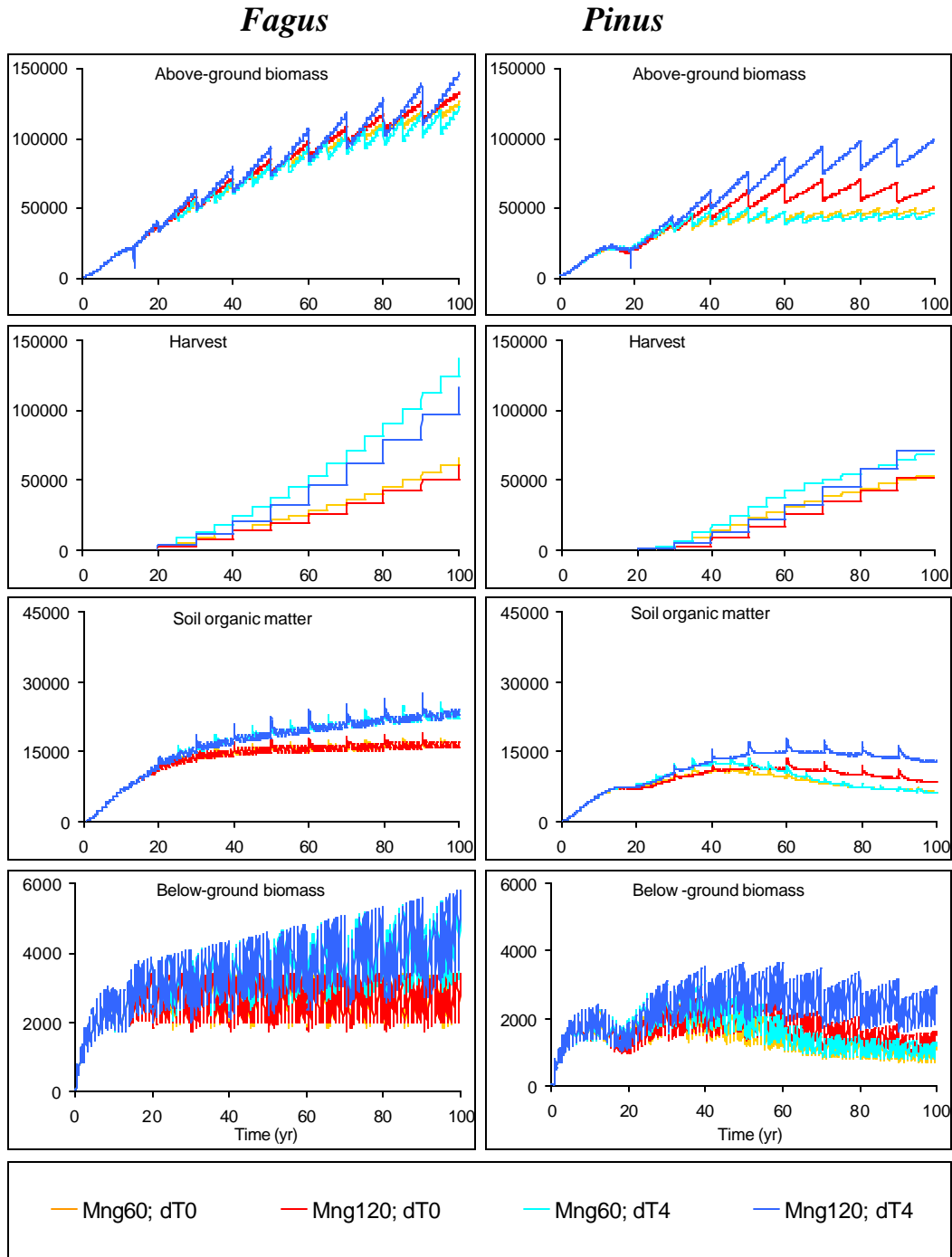


Figure 20 Development of carbon pools for a beech (*Fagus sylvatica*, left) and a pine (*Pinus sylvestris*, right) forest, using FORSPACE. Vertical axes represent kg C ha^{-1} and horizontal axes show time in years. Mng60 and Mng120 represent management intervals of 60 months (5 years) and 120 months (10 years), respectively, while dT0 and dT4 stand for temperature increases of 0 and 4 degrees. See also table 2

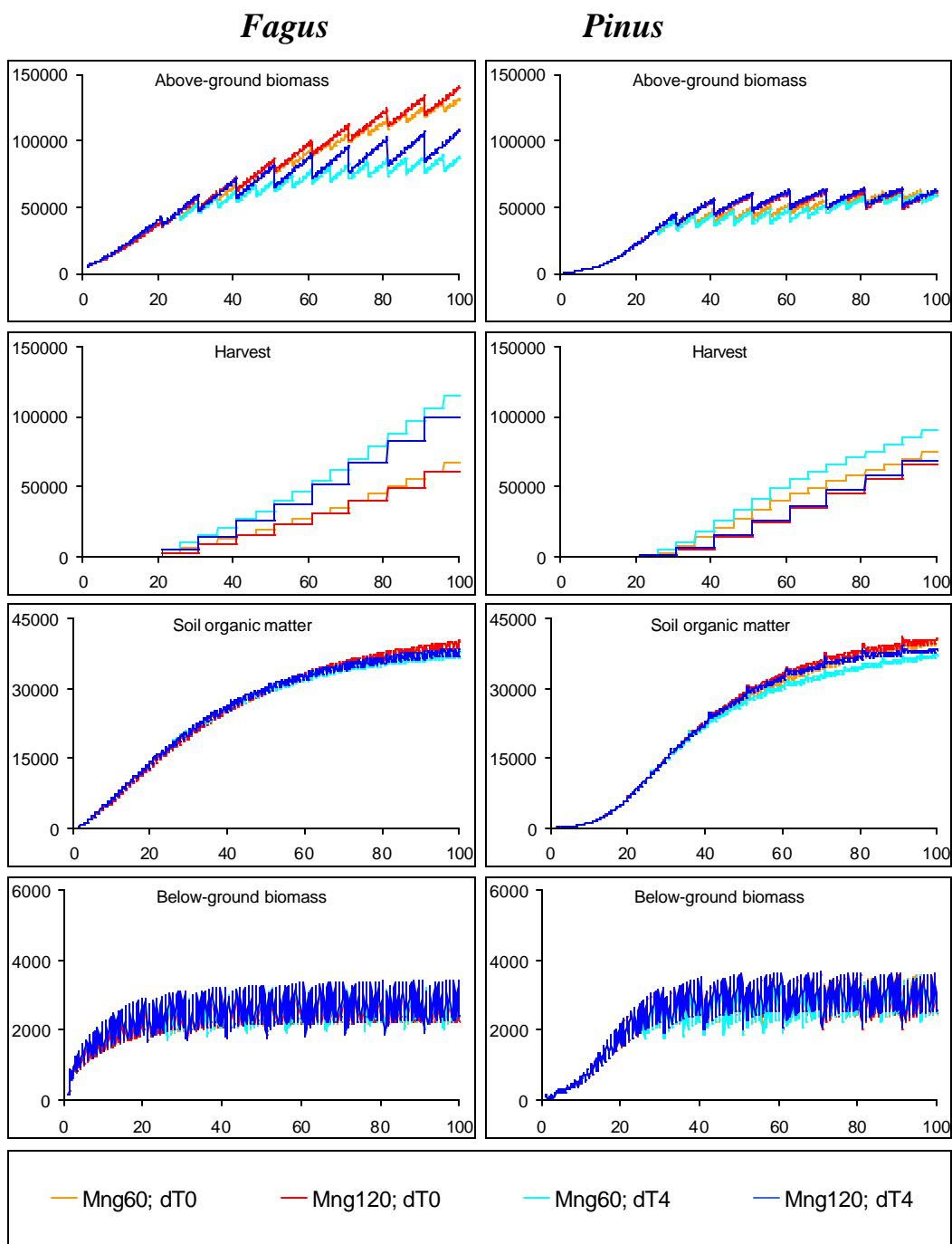


Figure 21 Development of carbon pools for a beech (*Fagus sylvatica*, left) and a pine (*Pinus sylvestris*, right) forest, using CENTURY. Vertical axes represent kg C ha^{-1} and horizontal axes show time in years. Mng60 and Mng120 represent management intervals of 60 months (5 years) and 120 months (10 years), respectively, while dT0 and dT4 stand for temperature increases of 0 and 4 degrees. See also table 2

Table 6. Predicted relative sensitivity of *Fagus* and *Pinus* forest by FORSPACE and CENTURY to management (thinning every 5 or 10 years) and climate change (reference or 4C transient increase)

Fagus	Model	Effect of management		Effect of Temperature	
		dT=0	dT=4	M=5	M=10
Aboveground biomass	FORSPACE	1.06	1.20	0.97	1.11
	CENTURY	1.01	1.01	1.08	1.08
Belowground Biomass	FORSPACE	1.00	1.05	1.63	1.72
	CENTURY	0.96	0.96	1.08	1.08
Soil Organic Matter	FORSPACE	1.00	1.03	1.38	1.42
	CENTURY	1.00	1.00	0.98	0.98
Total forest Carbon	FORSPACE	1.05	1.17	1.04	1.15
	CENTURY	1.01	1.01	1.05	1.05
Harvest	FORSPACE	0.92	0.85	2.08	1.93
	CENTURY	0.99	0.99	1.07	1.07
Total Carbon	FORSPACE	1.01	1.02	1.36	1.37
	CENTURY	1.00	1.00	1.06	1.06

Pinus	Model	Effect of management		Effect of temperature	
		dT=0	dT=4	M=5	M=10
Aboveground biomass	FORSPACE	1.32	2.14	0.94	1.52
	CENTURY	0.87	0.86	1.02	1.02
Belowground Biomass	FORSPACE	1.37	2.26	1.10	1.82
	CENTURY	0.87	0.87	1.01	1.01
Soil Organic Matter	FORSPACE	1.33	2.07	0.99	1.54
	CENTURY	1.03	1.03	0.95	0.95
Total forest Carbon	FORSPACE	1.32	2.13	0.95	1.53
	CENTURY	0.88	0.87	1.01	1.01
Harvest	FORSPACE	1.07	1.19	1.27	1.42
	CENTURY	0.97	0.97	1.03	1.02
Total Carbon	FORSPACE	1.19	1.60	1.11	1.48
	CENTURY	0.93	0.93	1.02	1.02

3.3.2 CENTURY

First, the CENTURY model, parameterised for the Loobos site, was run using measured meteorological input data for the years 1996-2000, and compared with monthly totals of measured CO₂ fluxes. The agreement is good on average, although month-to-month variation differs. This is likely to be the result of the treatment of rainfall and soil water in CENTURY, where the water balance is updated only on a monthly time scale.

The scenario studies in CENTURY sharply contrast with the runs using FORSPACE. Figure 21 shows the time development over 100 years of simulation and Table 6 shows the totals and relative effects of management and temperature after 100 years. Overall effects simulated with CENTURY are much smaller than with FORSPACE. In *Fagus* the effect of management is simulated to be very small. In *Pinus* the effect of management intensity is opposite to that in the FORSPACE

simulations, as biomass as well as harvests decrease by about 15% with doubling thinning intervals and SOM is unaffected. In the *Pinus* simulation the inadequacy of simulating tree biomass without water and nutrient feedbacks in CENTURY was most urgently felt as this resulted in an almost linear growth curve over time, similar to *Fagus*. Decrease in growth rate with age was acquired by allowing a fixed relative death rate for the stem wood, thus artificially increasing turn-over rate of stemwood. With longer management intervals, the average biomass integrated over time increases and thus also absolute wood mortality integrated over time. As there is no feedback of woody biomass on tree removal rate in CENTURY, this is not compensated by changes in the management. Thus an initial increase in biomass with longer management intervals after about 30 years has disappeared by the time that the stand is about 70 years old, and eventually results in less in biomass than in the more intensely managed stand.

The simulated effects of temperature are very small or non-existent in the CENTURY simulations. For *Fagus*, biomass is predicted to increase by 7% with temperature but SOM decreases slightly for both species. The effects of thinning interval and temperature are independent in the CENTURY simulations. No significant interaction effects were evident.

3.4 Model comparison

The simulations of the two long-term models differ substantially. The lack of effects of thinning regimes in CENTURY is likely to be related to the fact that in CENTURY leaf area and leaf mass are not spatially explicitly simulated, and thus thinning does lead to lower leaf mass but not necessarily to gaps in the canopy. As there is a saturation function between leaf area and stem mass, at high biomass a thinning operation does not negatively affect production. In general this illustrates the importance of explicitly accounting for the dependence of productivity on biomass and leaf area, and, because this leaf area is affected by thinning, it is also important to realistically specify thinning volumes. This is the strength of FORSPACE.

However, the SOM response in FORSPACE is likely to be related to the length of the rotation, but is also probably too fast because nutrient and moisture effects were ignored. The strong decrease in SOM in the *Pinus* stand simulated by FORSPACE also illustrates the importance of root dynamics on carbon storage in an ecosystem. Though unimportant as a carbon sink per se, due to low biomass, the high input rate of carbon in the soil through root turn-over makes allocation to roots a decisive factor in carbon sequestration. In FORSPACE this depends on age phenology, while in CENTURY carbohydrate allocation to roots in trees is a fixed proportion of monthly production. This makes the soil organic matter in FORSPACE thus more sensitive to indirect effects through changes in allocation. The strength of CENTURY is clearly in the soil.

The low response of plant growth in CENTURY to an increase in temperature is probably related to the saturation of the ecosystem with water and nutrients. Whereas an increasing temperature in FORSPACE immediately and directly stimulates plant growth by increasing radiation use efficiency, in CENTURY there is an optimum function between temperature and a productivity modifier. The parameters for this function are not well known and default values have been taken for temperate hardwood and temperate coniferous. However, this function now dominates the response of plant growth to temperature, whereas in a “normal” simulation temperature affects plant growth to a major extent indirectly, through effects on evapotranspiration (and thus water availability) and C and N mineralisation (and thus nutrient availability) (e.g. Peng and Apps 1999)

4 Conclusions

In this study we evaluated the information contained in eddy flux and soil chamber flux data, and assessed, using three different modelling approaches, how sensitive European forest carbon sinks may be to climate change and management.

Flux data analysis

The simulated time series, using the empirical model, showed that the annual net carbon uptake by European coniferous forests fluctuate with 26 to 50% and deciduous with more than 100%, implying a higher sensitivity of deciduous forests. Secondly, the NAO index plays an important role in the temporal development of terrestrial carbon cycle by controlling the prevailing weather and climate conditions. High winter NAO conditions can affect carbon sequestration with about 0.6 tons per hectare per year in Northern Europe, while at the same time forests located in Southern Europe increase their carbon uptake with about 1.0 tons ha⁻¹yr⁻¹, relative to low NAO years. The impact of future climate change was projected by the use of a scenario with a temperature change of +2.5°C and a precipitation change of -10% in summer and +10% in winter. These predictions say that the mean sink strength of coniferous forests will decrease with 8.8% to 19.2%, corresponding to about 0.5 to 0.7 tons of carbon per hectare per year, while deciduous forests are predicted to lose 4.5% to 38.6% of their sink strength, corresponding to 0.1 to 0.3 tons of carbon per hectare per year.

Soil respiration measurements

Although many measurements are still in their set-up phase and meaningful conclusions can only be drawn after sufficiently long time series have been formed, the conclusions drawn from one and a half years data in the Loobos forest point to one of the major problems in interpreting eddy correlation data: it is still very difficult to separate ecosystem respiration and assimilation (or Gross Primary Productivity - GPP), and hence it is still difficult to understand the component processes underlying NEE.

Long-term modelling

Although results of the long-term model simulations under the various scenarios differ widely, we can distill at least a few qualitative conclusions. If we assume that FORSPACE gives a better representation of above-ground processes than CENTURY then we may conclude that individual effects of changing forest management or increased temperatures on biomass and harvest can be positive or negative depending on species, yield and thinning strategy. Combined, however, the results suggest that in a warmer climate it is wise to increase thinning intervals as this may greatly increase the overall biomass carbon sequestration and stocks in temperate forests. As CENTURY is considered to better represent SOM dynamics, we should combine these results with the SOM predictions of this model. The effects of management on SOM are unanimously neutral in CENTURY whereas SOM always decreases with increasing temperatures. Thus, the positive combined

effects on biomass predicted by FORSPACE are likely to be offset by decreased SOM.

This study also shows that reliable quantitative predictions of long-term forest carbon dynamics cannot be made unless the models used account for changes in canopy structure and light interception, thinning and harvest practice, changes in allocation patterns, as well as include proper representations of nutrient cycling and water limitations in soil and biomass.

The simulations of forest management in FORSPACE also reveal that long-living, well managed and undisturbed forests are not necessarily the optimal storage locations for soil carbon, because litter input to the soil decreases as thinning intensity gets less. This varies per species and yield class. It seems that different management practices may have to be designed to optimise for this, as concentrating carbon storage in stemwood may be a less safe option for long-term carbon storage than storage as soil carbon. This emphasises the need for careful conservation and build-up of soil carbon, for example by de-intensifying forest management and avoiding soil disturbance during planting and harvesting.

5 Recommendations

Analysis of the flux data first of all quantified the natural variability in forest carbon sink strength resulting from variability in the climate. Year-to-year variation in sinks seems to be higher in deciduous forests than in conifers, although the potential gain in deciduous forests is larger. Variability in itself is not a problem for long-term carbon sequestration, but it can pose problems in the quantification of sinks in Kyoto forests during an 8-year commitment period. Under the treaty, higher uncertainties lead to discounts. Therefore, there is a clear need to either increase the length of future commitment periods or better understand the sensitivity to climate variability. For this understanding it is crucial to be able to distinguish photosynthetic and respiratory responses of trees from the purely respiratory responses of (heterotrophic) processes in decomposition in litter and soils. Therefore methods to separate these in overall ecosystem fluxes, such as soil respiration chamber methods, need to be developed further.

The flux data also suggest that higher temperatures on the long run are associated with lower sink strengths in forests. Although decreased sink strength not always implies reduction of stocks, this observation does call for caution in interpreting the long-term modelling results that suggest that a combination of warmer climate and less intensive thinning can lead to great increases in forest carbon stocks. Taking all long-term predictions together, it seems that we can expect modest mitigation of atmospheric CO₂ increase through forest sinks in a warmer climate if management intensity is carefully tuned down. CO₂ fertilisation is likely to enhance this effect.

The present study with all its shortcomings strongly emphasises the importance of developing fairly detailed forest carbon dynamics models. This includes carrying out the experimental work to acquire process knowledge, model parameters and validation data. The requirement in currently negotiated Kyoto agreements to separate direct (anthropogenic) and indirect (natural) effects further strengthens this recommendation to explicitly understand the effects of forest management.

Finally a general note on the issue of 'permanence of carbon sinks' in forests. On reflection, even though harvests, fires and pests can occur any time in forest stands, it seems unlikely that carbon stocks in forested lands can be permanently reversed given proper management. After disturbance or harvest and given some time, the stock will generally grow back. Only after severe and permanent changes in climate or land use, or after long periods of mismanagement leading to soil exhaustion or erosion the sink potential of an area can be permanently destroyed. Therefore, as long as it is recognised that the mitigation impact of forest sinks on global climate change can only be limited and temporal, the risks to the climate in such activities are also not very high, except for when forests degrade *as a result of* fairly drastic climate change.

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