Converging estimates of the forest carbon sink

This project was carried out through funds made available under the 'Climate Programme' of the Agricultural Research Department (DLO).

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a comparison of the carbon sink of Scots pine forest in The Netherlands as presented by the eddy covariance and the forest inventory method

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ABSTRACT

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The aim of this study was to compare estimates of the Net Ecosystem Exchange by two different methods for a small pine forest in the Netherlands. The inventory based carbon budgetting method estimated the average NEE for 1997 - 2001 at 202 g C m^{-2} yr^{-1}, with a confidence interval of 138 - 271 g C m^{-2} yr^{-1}. The estimate obtained by the eddy covariance method was 295 g C m^{-2} yr^{-1} on average for the same period, with a confidence interval of 224 – 366 g C m^{-2} yr^{-1}. Uncertainties in both methods are assessed, and recommendations are given for future research.

Keywords: eddy covariance method, forest inventory, carbon budgetting, uncertainty estimates, monitoring system

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Preface

This project was carried out through funds made available under the 'Climate Programme' of the Agricultural Research Department (DLO). We like to thank the forest manager of the Loobos site, Mr. A. Boone, for his co-operation, and the members of the steering committee: Prof. Frits Mohren, Ir. Gijs van Tol, and Drs. Eveline Trines for their valuable comments and feedback.

Summary

According to the recent accords of Marrakesh, Annex I countries are committed to annually report the national terrestrial biospheric sources and sinks of greenhouse gases in a "transparent and verifiable manner", and in addition those parts that will fall under the Kyoto Protocol. At the moment, the required transparency in monitoring and reporting seems to be far away. Several methods exist to quantify terrestrial carbon sources and sinks, each with its individual strengths and weaknesses, and each applicable to different temporal or spatial scales. The different methods result in a broad range of estimates for the role of forests in the carbon cycle. A key problem is that the various methods have to use different scaling techniques to transform information obtained at one spatial and temporal scale to another, in order to make comparable estimates. Part of the discrepancy between the estimations by different methods on a European scale may be caused by such transformation of information in space and time. In order to minimise the effect of these transformations, we focussed in this study on a small area of pine forest (about 300 ha), in the central parts of the Netherlands, where the different methods could be applied without such transformations. The aim of this study was to compare two different methods for the quantification of carbon fluxes over forests: the inventory based method and the eddy covariance method.

The inventory based carbon budgeting method measures (indirectly) carbon pools at two different points in time and derives NEP and NBP from changes in these pools. The eddy covariance measurement uses micro-meteorological principles to directly measure the exchange between the land-surface and the atmosphere (i.e. NEE).

Through the inventory based carbon budgeting method, (measurement of stem wood volume and coarse woody debris) combined with literature estimates and visual assessment of soil and ground vegetation, an estimate of the NEE over the period 1997 - 2001 of 202 g C m^{-2} yr^{-1} was obtained, with a confidence interval of 138 - 271 g C m^{-2} yr^{-1}. The estimate obtained by the eddy covariance method was 295 g C m^{-2} yr^{-1} on average for the same period, with a confidence interval of 224 - 366 g C m^{-2} yr^{-1}.

In this project where the comparison of methods for annual sink estimates was brought back to exactly the same vegetation type, the same years, and the same scale, the eddy covariance method gave an estimate 46% higher than the inventory conversion method. The time frame of 5 years may be enough to take care of the inter-annual variability of both methods and thus limit the uncertainties due to the different time scales of both methods. As there were 36 plots used for the inventory based method, it is believed that the above ground carbon pools are representative for the area corresponding to the flux-footprint. However, this is not necessarily the case for the below ground carbon pools that were estimated from literature, thus there is still some uncertainty left in the spatial representation of both methods. The pools that were not directly measured and thus giving the highest uncertainty, are the

below ground carbon stocks. In other studies inter-annual variability of NEE was mostly attributed to the variability in soil respiration. As below ground and above ground carbon pools may have the same magnitude, this may well explain most of the differences found between both approaches. To a lesser extent these differences may also be attributed to processes not taken into account in the present study, such as the seepage of carbon by hydrological pathways, carbon fluxes by VOC's or grazing.

Future actions to improve the accuracy of the inventory method could consist of reducing uncertainties regarding the non-tree vegetation and the soil compartment, as well as to improve the models for tree biomass other than stems, and those for branch biomass in relation to branch diameter. For the micro-meteorological method the uncertainty could be reduced by improving our knowledge on among others the effects of nocturnal drainage flow and the influence of low frequency eddies on the total flux.

Overall, the results showed large uncertainty in net sink estimates when carried out by two independent methods. This indicates that it is not straightforward to design a sound National System for monitoring and reporting of the total land area greenhouse gas fluxes and their verification. A major effort is needed to arrive at an operational and reliable National System in 2005.

1 Introduction

1.1 Background to the study: towards an integrated and verifiable carbon monitoring and reporting system

Articles 3.3 and 3.4 of the Kyoto protocol allow for Annex I nations to partially offset their emissions of CO_2 by carbon accumulated due to specific activities in the Land use, Land use change and Forestry sector. The details of this were set out in the Marrakesh accords recently (UNFCCC 2002). According to these accords the Annex I countries are committed to annually report the national terrestrial biospheric sources and sinks of greenhouse gases in a "transparent and verifiable manner", and in addition those parts that will fall under the Kyoto Protocol.

At the moment, the required transparency in monitoring and reporting seems to be far away. Several methods exist to quantify terrestrial carbon sources and sinks, each with its individual strengths and weaknesses, and each applicable to different temporal or spatial scales. The different methods result in a broad range of estimates for the role of forests in the global carbon cycle, and more specific for the European forests carbon sink as well. The latter is illustrated in Figure 1.1 where the results of a variety of methods is presented. For example, the figure shows a factor 5 difference between the estimates obtained by Schulze et al. (2000) and Nabuurs et al. (1997) for the tree compartment. A key problem is that the various methods have to use different scaling techniques to transform information obtained at one spatial and temporal scale to another, in order to make comparable estimates.

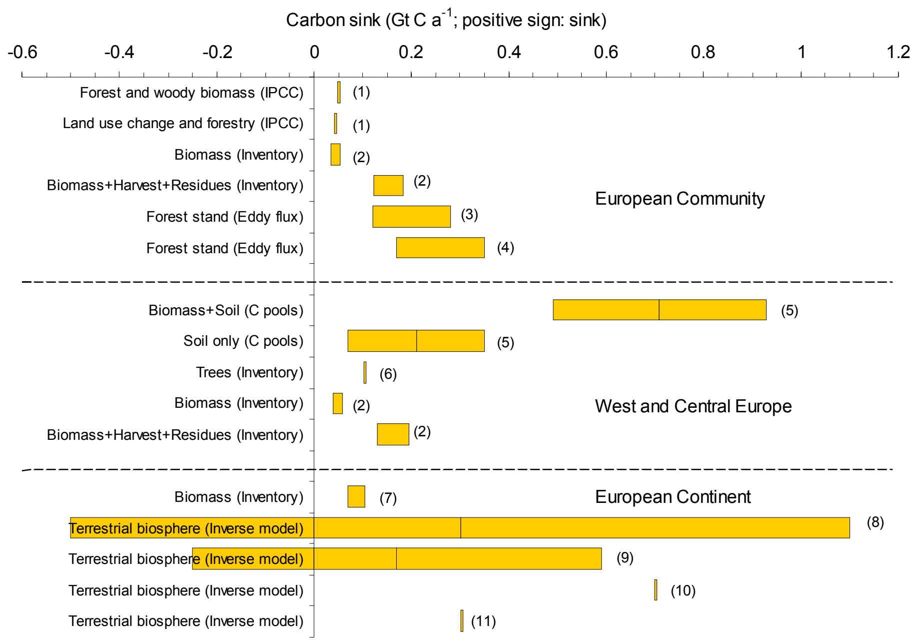

Figure 1.1 Estimates of the carbon sink in European forests, based on various methods and for different European regions ((1) Paivinen et al. 1999; (2) Kauppi and Tomppo 1993; (3) Martin et al. 1998; (5) Schulze et al. 2000; (6) Nabuurs et al. 1997; (7) Kauppi et al. 1992; (8) Bousquet et al. 1999; (9) Kaminski et al. 1999; (11) Ciais et al. 1995)

1.2 Aim

The aim of this study is to compare two different methods for the quantification of carbon fluxes over forests. Part of the discrepancy between the estimations by different methods on a European scale may be caused by the transformation of information in space and time. In order to minimise the effect of such transformations, we will focus in this study on a small area of forest (about 300 ha), where the different methods can be applied without such transformations. The resulting estimates will better represent the differences caused by the application of the methods itself, rather than by its transformations. This will lead to a better insight in the comparability of the different methods, causes of differences, and explain part of the differences found for the larger scale. Insight in the causes of the differences will also be valuable in the design of a "transparent and verifiable" monitoring and reporting system that must be developed in order to meet the Kyoto Protocol's requirements.

1.3 The carbon cycle

A managed forest ecosystem consists of three main carbon stocks. The living biomass (mainly tree biomass), soils and wood products. Carbon is exchanged between these pools and the atmosphere through various processes (Figure 1.2). In the photosynthesis process, plants take up CO_2 from the air and convert it into carbohydrates. This results in the Gross Primary Production (GPP). Part of these carbohydrates is used for maintenance of the plant, the autotrophic respiration. The difference between the uptake in photosynthesis and the release in autotrophic respiration is called the Net Primary Production (NPP). This NPP results in expansion of the biomass amount (growth). Due to mortality in different biomass compartments, dead organic matter is added to the litter layer and the soil layer. Part of this litter will decompose and a small fraction will be converted into soil organic matter, which slowly releases carbon to the atmosphere as well. Carbon release from the soil and litter layer is called the heterotrophic respiration. The difference of uptake in Net Primary Production and the emission due to heterotrophic respiration is called the Net Ecosystem Production (NEP) or Net Ecosystem Exchange (NEE). In a managed forest ecosystem, part of the biomass is harvested for wood products. The remaining (long-term) build-up of growing stock in the forest is called the Net Biome Production (NBP).

After harvest, part of the affected biomass is left in the forest, like branches and leaves, which become part of the litter layer. The stemwood is used in products, where the carbon is stored for shorter or longer term, depending on the life span of the product. Eventually the wood product will be discarded, burned for energy or it will decay in a landfill, releasing the carbon back to the atmosphere. The difference between the input in the product pool and the output via decay or burning is the Net Product Exchange (NPE). The total of Net Biome Production and Net Product Exchange is the Net Sector Exchange (NSE), which determines if the sector as a whole is a carbon source or a sink.

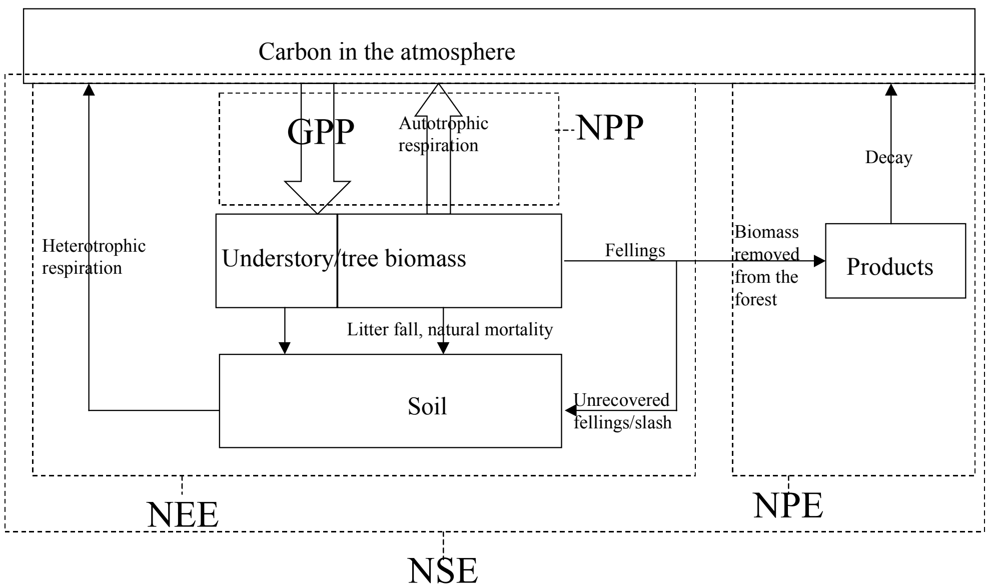

Figure 1.2 The full forest sector carbon cycle (Note: the size of the boxes does not represent the absolute size of the carbon stock). GPP=Gross Primary Production, NPP=Net Primary Production, NEE=Net Ecosystem Exchange, NPE=Net Product Exchange, NSE=Net Sector Exchange.

2 Methods and data

2.1 Study set-up

This study is based on a comparison of two different methods to estimate the annual carbon exchange of a small area of forest in The Netherlands. The first method is the eddy covariance method, which is based on direct measurements of the carbon exchange with the atmosphere (NEE). The second method is based on the conversion of forest inventory results, further referred to as inventory based carbon budgeting. Each of these methods has its strengths and weaknesses. Advantages of the eddy covariance method are that it measures the NEE of the whole ecosystem directly, and at a high time resolution. Disadvantages are that the contribution of different compartments to the total NEE cannot be separated, and that the extraction of carbon due to harvest is not taken into account. Moreover, the eddy covariance method can only be applied in homogeneous stands, with continuous forest cover of at least 1 km in prevailing wind directions. An additional disadvantage is that the eddy covariance method can only estimate fluxes and no stocks. The advantage of inventory based carbon budgeting is that it is based on a well-established technique, relatively simple, and that it is representative for large areas. Almost all European countries carry out forest inventories, so with relatively minor effort these can be converted to carbon estimates. A disadvantage of the inventory based carbon budgeting is that it covers only the tree part of the forest ecosystem. Understory vegetation and the soil compartment are usually not included in the inventory. Especially the soil compartment can contain a considerable carbon stock.

2.2 Site description

Our study object is located in Loobos, part of the forest range "Kootwijk", in the Veluwe area, in the centre of the Netherlands (see Figure 2.1). Before planting started on this site at the beginning of the 20^{th} century, the landscape consisted of drifting sand, caused by overexploitation of the heathlands in the past. The first aim of the State Forest Service with afforestating this area was to prevent the sand from being blown away and thus protecting the cultivated fields and villages in the surroundings. The second aim was to produce wood from these bare lands in the long term (Jager Gerlings 1907). The landscape consisted of sand dunes where surviving parts of vegetation caught the drifting sand, and of blown-out areas where the sand to the groundwater table was gone. This landscape was very dynamic, with the hills changing shape and place all the time.

The area was planted with Scots pine at a planting distance of 0.8 meter (local archives). Usually the young plants were planted very deep in the soil. When this was done carefully, usually most plants survived (Jager Gerlings 1907). However, due to the unfavourable conditions the initial growth was poor. According to Graaff (1999), a stand had reached a height of only 40 - 60 cm 15 years after planting. The growth of the pines on the hilltops was much better than in the lower areas, because the sand was less compact and more humus was present, due to old profiles that were covered under the sand.

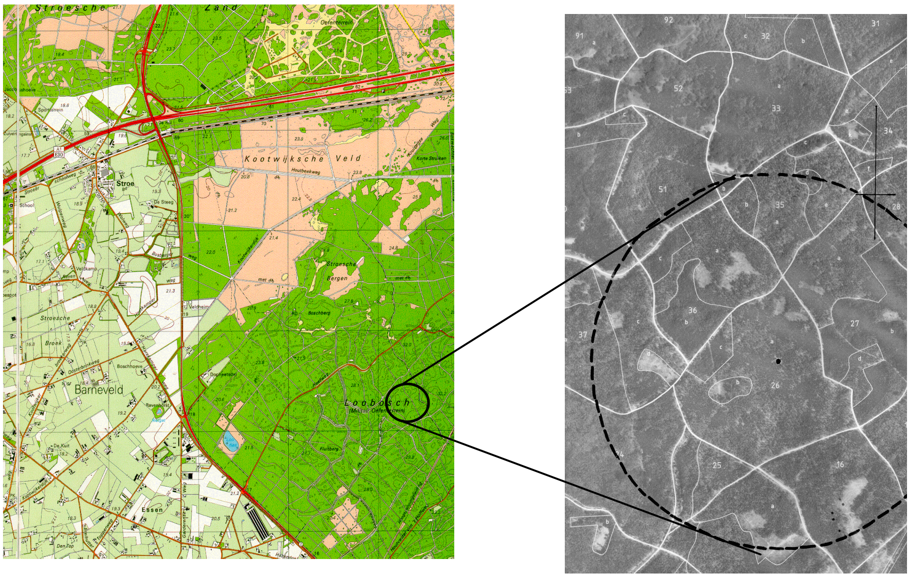

Figure 2.1 Location of the site. Left the topographic map, right an aerial photograph of the area, taken in 1987, with the dot representing the location of the eddy covariance tower and the circle indicating the distance (500 m) where under unstable conditions 70 - 80% of the flux originates as measured by the flux tower.

The management after stand closure consisted probably of very light and very regular thinnings. According to Kuiperi (1937) a lot of stands were too dense because there were hardly possibilities to sell the thinned trees. After afforestation the input of litter by the trees and ground vegetation increased the amount of humus, having a positive feedback on the growth of the trees.

Currently the landscape consists of vast areas of 70 - 100 year old Scots pine, with the old sand dunes still recognisable. The maximum height differences in the topography are about 10 metres. On the dunes the stem densities and average diameters are usually higher, resulting in higher basal areas and volumes than in the blown out areas. The stands are quite open, mostly without a shrub layer, although currently oak and birch regeneration starts to occur on some places. The ground is covered with a dense layer of grass, mostly *Deschampsia flexuosa* (L.) Trin. Also on some places heather (*Calluna vulgari* (L.) Hull) is present.

The stand where the eddy covariance tower is located (stand 26a), consists of Scots pine with an area of about 16 ha. It was planted in 1906 (germination year 1904) with a planting distance of 0.8 x 0.8 m (local administration). In 1974 and 1985 the stand was inventoried and described in the administration (Table 2.1). Further, in 1981 - 1984 the Fourth Dutch Forest Statistics was carried out. During this inventory round all forest stands in the Netherlands were visited and several characteristics visually estimated (Table 2.1). These sources give us an idea what the stand looked like at those moments, but the numbers are probably not very accurate, since they were not measured but estimated. Especially the estimates of the increment seem to be quite low. Moreover, it is not known what is exactly reported, mean height or dominant height, average diameter or the diameter of the average tree.

In 1997 a small inventory was done in this stand, close to the flux tower (Sabaté, unpublished; Table 2.1). It consisted of four plots of 314 m^2 each, two on top of the dunes and two in the blown out areas. Besides the usual measurements on diameter and height also additional measurements were carried out, to be able to estimate the amount of above ground biomass. Further a core was taken from each tree as well, and the tree ring widths were measured. In 1999, all trees on an area of one hectare around the flux tower were counted in order to estimate the stem number (Moors, unpublished data).

Table 2.1 Characteristics of the stand at different times. Source: for 1906, 1974 and 1985 local administration, 1981 - 1984 Fourth Dutch Forest Statistics (Staatsbosbeheer 1988), 1997 Sabaté (unpublished data), 1999 Moors (unpublished data).

Year	Density	Diameter	Basal area	Dominant height	Growing stock volume	Current annual increment
	N ha^{-1}	cm	m^2 ha^{-1}	m	m^3 ha^{-1}	m^3 ha^{-1} a^{-1}
1906	15625					
1974	1234	14	19	11	100	1.7
1981 - 1984		15		13	130	
1985	589	18	15	13	97	1.4
1997	478	24.6 *	24.4	16.4	183	
1999	403					

* Note: this is the arithmetic average, it is not certain if this represents the same as the other inventories.

Most of the surrounding stands are of the same age and tree species, while some have been planted after a fire in 1929. Small parts of these stands have been cut in the past and are replanted, mostly with Scots pine and sometimes with other species like oak, but these are only small patches of the total footprint area.

This site was chosen for eddy covariance measurements because of the relative homogeneity of the stand. Further the stand is representative for a lot of forests in The Netherlands regarding tree species, age and stand history.

2.3 Methodologies for monitoring forest carbon dynamics

2.3.1 Eddy covariance measurements

At this site, fluxes of latent and sensible heat and momentum were obtained by the eddy covariance method from scaffolding towers since early 1995. In 1996 the system was extended to measure also the flux of CO_2. The fetch is at least 1.5 kilometres in all directions. For this site Elbers et al. (1996) calculated that most of the flux originates from 500 m around the tower, with the maximum flux contribution at 120 m for neutral atmospheric conditions.

The eddy covariance system consists of a 3-D sonic anemometer (Solent 1012 R2), a Krypton hygrometer (Campbell, Inc., USA) and a LiCOR 6262 infrared gas analyser linked to a notebook computer. In 2001 the R2 sonic anemometer and the closed path gas analyser were replaced by a Solent Windmaster Pro in combination with an open path LiCOR 7200. The computer calculates on-line variances and co-variances at half-hourly intervals using a moving average filter with a time constant of 200 s. Measurements were taken at 10 Hz. All raw data were saved on a removable hard disk and collected every week. Corrections for signal loss due to sensor separation, path length, finite instrument response time and tube length were calculated following Moore (1986), Moncrieff et al. (1996) and Aubinet et al. (2000). The reference frame of the co-variances was rotated for every half hourly flux measurement to align the fluxes perpendicular to the mean streamline. For further details on the methodological aspects of the measurements see Aubinet et al. (2000).

At five levels (2.5, 5.0, 8.4, 23.5 & 26.0 m, after 1998 this was changed to 0.4, 2.5, 5.0, 8.4 & 26.0 m) in and above the canopy measurements were made of the CO_2 concentration using a single channel CIRAS infrared gas analyser (PP Systems, UK). These measurements were taken at each level for five minutes. The profiles thus obtained were time-differenced and vertically integrated to estimate the total CO_2 storage. The CIRAS data is used for off-line calibration of the LiCOR system.

An automated weather station took measurements of incoming and reflected solar (Kipp and Zonen CM21) and long wave (Kipp en Zonen, CG1) radiation, soil heat flux (TNO-WS 31 and Hukseflux SH1), windspeed (Vector A101ML), wind direction (W200P) and temperature and relative humidity (Vaisala HMP35A). Note that no measurements of net radiation were taken, as the separate components of the energy balance, short-wave and long-wave radiation were determined independently. The incoming long-wave instrument was cooled by a fan to minimise temperature differences between the housing and the environment.

Rainfall was measured above the canopy and in the open field with automated tipping bucket rain gauges. Power was supplied by 12 V batteries connected to solar panels and a wind generator. A diesel generator was used as backup and installed downwind at about 100 m of the tower. No effect of the exhaust fumes on the CO_2 signal could be found in the tower CO_2 profile measurements.

2.3.2 Inventory based carbon budgeting

In order to monitor the state of their forest, almost all European countries regularly carry out a forest inventory. In a forest inventory, a small sample of the total population of trees is measured, in order to make estimates for the total population. Usually easily measurable features are assessed, like the diameter and height of the tree, which is then converted to the desired parameter like volume, using regression methods. Traditionally, in forest inventories the focus has been on characteristics important for wood production like forest area, standing stemwood volume and stemwood volume increment, although currently increasing attention is paid to other values, like nature conservation and recreational aspects.

2.3.2.1 Inventory set-up

In order to obtain an inventory based estimate of the carbon flux comparable to the eddy covariance measurements, a systematic forest inventory in the stands surrounding the tower was carried out in a circle with a radius of 1 km. Within this circle, 36 circular plots on a regular grid basis were assessed (Figure 2.2). The plot sizes were variable, so that each plot included at least 20 trees with a minimum diameter at breast height of 5 cm. On each plot all individual stems (dead or alive) with a minimum diameter at breast height of 5 cm were assessed, as well as branches on the forest floor with a diameter exceeding 5 cm. From each individual the following characteristics were recorded: tree species, diameter and status (dominant, dominated, seed tree, dead standing, dead lying, lying crown/branch, stem parts, or stump), and how long they had been in that status: before 1996, between 1996 - 1999 or after 1999. On each plot, the first living tree north from the centre was taken as sample tree. From each sample tree the height was measured and a core was taken. In the laboratory the individual tree ring widths over the period 1991 - 2001 were measured on a digital positiometer with an accuracy of 0.01 mm. Apart from the tree characteristics some stand characteristics were recorded: planting year, dominant height, crown coverage, stand phase and vitality. Site characteristics were also assessed: exposition, thickness of litter and humus layer, coverage of shrubs, plants, mosses, grasses, and soil type.

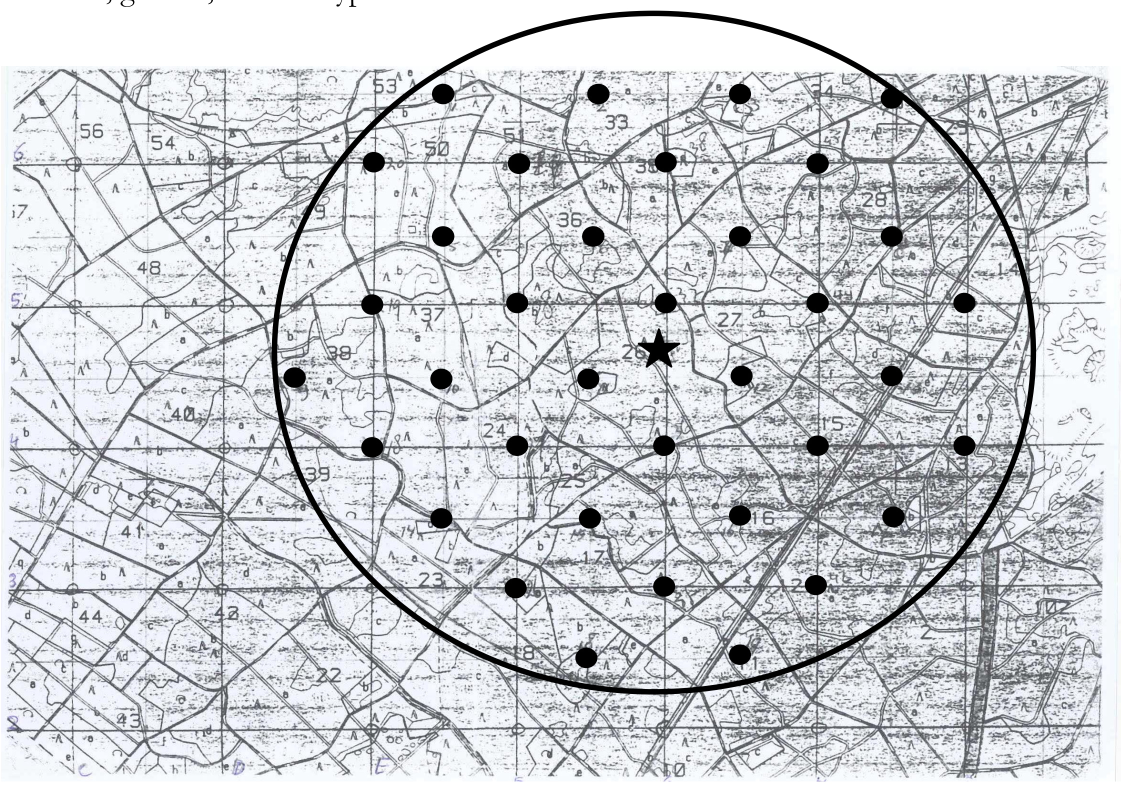

Figure 2.2 Sampling design of the inventory. The star indicates the position of the tower; the dots represent the sample plots of variable size. The circle has a radius of 1 km.

2.3.2.2 Data processing

The results of the inventory were converted to estimates of the current standing wood volume, wood volume increment over the period 1991 - 2001, current carbon stock, and carbon fluxes over the period 1991 - 2001. The carbon stock and flux estimates are for the tree compartment only. Wood volume and carbon stocks were estimated from the height and diameter measurements. Historic wood increment consists of 1) increment of current trees, and 2) increment of harvested trees. Carbon fluxes in the tree compartment are caused by: 1) increment of current trees, 2) increment of harvested trees, and 3) decomposition of dead woody material. For all conversions of biomass into carbon, a carbon content of 50% was assumed.

Wood volume

For the conversion of tree diameter to individual tree volume, the following equation was used:

$$v = c_1 * dbh^{(c_2 + c_3 * status)} * hdom^{c_4} \quad \text{(Equation 2.1)}$$

with

v:	individual tree volume
dbh:	diameter at breast height (mm);
hdom:	dominant height (m);
status:	tree status (dominant, dominated or seed tree)
c_1, c_2, c_3, c_4:	parameters (see Table 2.2).

Table 2.2 Parameter values for Equation 2.1.

Tree species	c_1	c_2	c_3 (dominant)	c_3 (dominated)	c_3 (seed tree)	c_4
Scots pine	0.002077654	1.952764402	-0.000086651	-0.111105354	0.001095496	0.485608777
Other pines	0.000426129	2.066225947	-0.001926657	-0.079562443	0.003695010	0.806369066
Douglas fir	0.000959160	2.092560524	0.000297255	-0.044900701	0.000000000	0.488243442
Larch	0.000352168	2.128418280	0.003292718	-0.105416795	-0.002606697	0.762839251
Norway spruce	0.000532384	2.164126647	0.004108377	-0.046700176	-0.010258196	0.548798076
Other conifers	0.000104117	2.440267129	0.000493907	-0.049384485	0.000000000	0.548288283
Oak	0.000958533	2.040672356	0.001965013	-0.021019214	-0.043546125	0.563664372
Beech	0.000214914	2.258957614	0.001411006	-0.011206382	-0.009566947	0.602910746
Poplar	0.000950700	1.895629295	0.001650837	-0.092088227	-0.007736944	0.839214604
Other broadleaves	0.000424022	2.215713231	-0.000555255	-0.012444031	0.024439070	0.472847330

These equations are developed within the "Meetnet Functievervulling", a system to monitor the different functions of the forest (Daamen and Dirkse 2002). Because of the small size of our sample population (36 trees), we chose to use this equation, which is based on a much larger sample. Standing wood volume per hectare is then calculated by:

$$V = \sum_{1}^{n} v_i / A \qquad \text{(Equation 2.2)}$$

with

V: total wood volume on current plot
v_i: individual tree volume of tree i
n: number of trees of current plot
A: area of current plot

Carbon stock

The carbon stock per tree was estimated using the allometric equations from Vaessen (2001). Vaessen derived allometric relations for Scots pine, based on a literature review of measurements throughout Europe. In these equations, tree diameters are used to estimate biomass in the compartments roots, stem, branches and foliage.

$$Bf = e^{-3.2134} \times dbh^{1.6561}$$
$$Bb = e^{-3.435} \times dbh^{2.0632}$$
$$Bs = e^{-2.7928} \times dbh^{2.458}$$
$$Br = e^{-3.489} \times dbh^{2.3169} \qquad \text{(Equation 2.3 - 2.6)}$$

with

Bf : biomass in the foliage (kg dry matter)
Bb : biomass in the branches (kg dry matter)
Bs : biomass in the stem (kg dry matter)
Br : biomass in the roots (kg dry matter)

The total carbon stock per tree is the total of these compartments, and the carbon stock per hectare can be calculated in the same way as the wood volume per hectare (Equation 2.2).

Wood increment of current trees

For the sample trees, the historic diameters were reconstructed using the following equation:

$$d_k = d_{2002} - 2 * \sum_{k=l}^{2001} w_l \qquad \text{(Equation 2.7)}$$

with

d_k: diameter in year k
w_l: tree ring width in year l (average of all plots)

From the measurements on current dominant height and current diameter, a relationship of dominant height to diameter was derived. From this relationship, the corresponding heights for the yearly diameters were estimated. For each year, the volume was then estimated with Equation 2.1. The annual (individual tree) increment is then simply the difference between subsequent estimates of tree volume. These individual tree increments were then extrapolated to all trees, using a regression of individual tree increment on plot characteristics.

Total biomass increment of current trees
If we combine Equation 2.1, Equations 2.3 - 2.6, and the diameter to height relationship, we can derive a direct relationship between biomass and volume:

$$\Delta biomass = 0.70708 * increment \qquad \text{(Equation 2.8)}$$

with
Δbiomass : change in whole tree biomass (ton dry matter ha^{-1} yr^{-1})
increment : increment (m^3 ha^{-1} yr^{-1})

Increment of harvested trees
Trees that were harvested within the period of consideration have contributed to the wood increment and the carbon accumulation until their year of removal. It was assumed that dbh was 90% of the stub diameter. The wood and biomass increment for the removed trees was calculated in the same way as for the current trees, but only until the estimated year of harvest.

Decomposition of dead woody material
In the inventory, the dbh of each dead tree, lying or standing, and the diameter of stem parts, was measured. With Equations 2.3 - 2.6, the total biomass at the moment of dying was calculated. For stumps, the root biomass at the moment of dying was calculated, by inserting the stump diameter in Equation 2.6. From the biomass measurements in Kootwijk by Sabaté (unpublished) the following relationship between branch diameter and branch biomass was derived:

$$Bb = -0.01834 - 0.126 * bd + 0.207 * bd^2 \qquad \text{(Equation 2.9)}$$

with
Bb : branch biomass (kg dry matter)
bd : branch diameter (cm)
This equation was used to estimate the woody branch biomass at the moment of dying.

According to Olson (cited in Alban and Pator (1993)), decomposition of woody biomass can be described according to the following function, describing the decrease in wood density:

$$Dt = Dd * e^{(-k*t)} \qquad \text{(Equation 2.10)}$$

with
Dt : density of wood t years after dying
Dd : density of wood at the moment of dying
k : decomposition speed
t : years after dying

Estimates for parameter k are based on van Hees and Clerkx (1999) and are as following:

Pinus species	0.08
Douglas fir, oak	0.06
Birch	0.12
Norway spruce:	0.11

Branches decay twice as fast as stems (Alban and Pator 1993), therefore k is doubled in case of branches.

From the inventory, an estimate is available in which period the branch or stem died (before 1996, 1996 - 1999, after 1999). If the death moment is estimated to be before 1996, it is assumed that the dead biomass became available equally divided over the years 1982 - 1995. Biomass that died in the period 1996 - 1999 is equally divided over those years, and biomass that died after 1999 was divided over 2000 and 2001.
For each piece of dead biomass, the decrease in density was calculated for each year, using equation 2.10 and the original dry matter weight. The difference between consecutive years is the emission of C due to decomposition.

Reliability estimate
In order to quantify the reliability of the inventory based carbon budgeting method, we estimated the confidence interval. Within the carbon budgeting method, many steps are needed to estimate the NEE, all adding uncertainty. It would be very elaborate to quantify the uncertainty associated with each step separately. Therefore we tried to find an easier way to estimate the confidence interval. From the results it is apparent that the total NEE is dominated by the increment of the current trees. The increment of harvested trees and the decay of woody material each contribute only very little to the total flux, and have opposite effects. Therefore, if we take a conservative uncertainty estimator for the contribution of the increment of the current trees, uncertainty for the other components will be covered as well. A simple estimator for the increment of the current trees is:

$$B = \frac{b}{v} * V \qquad \text{(Equation 2.11)}$$

with
B: volume increment 1991 - 2001 of the current trees
b: average volume increment 1991 - 2001 of the sample trees
v: average volume of the sample trees
V: average standing volume of the current trees

The variance of B is:

$$\operatorname{var}(B) = (\frac{\bar{b}}{v})^2 * \operatorname{var} V + \bar{V}^2 * \operatorname{var}(\frac{\bar{b}}{v}) + 2 * \operatorname{cov}(\frac{b}{v}, V) \qquad \text{(Equation 2.12)}$$

The increment for an individual year within the period 1991 - 2001 can be expressed as:

$$B_t = p_t * B \qquad \text{(Equation 2.13)}$$

with

B_t: increment in year t

p_t: share of increment in year t relative to the total increment in 1991 - 2001

The variance of B_t is then:

$$\text{var}(B_t) = p_t^{\ 2} * \text{var}\, B + b^2 * \text{var}(p_t) + 2 * \text{cov}(p_t, B) \qquad \text{(Equation 2.14)}$$

3 Results of the individual methodologies

3.1 Eddy covariance measurements

The average NEE over the period 1995 - 2001, according to the eddy covariance measurements, is 336 g C m^{-2} yr^{-1} (Figure 3.1). The NEE in individual years varies from 275 g C m^{-2} yr^{-1} in 2000 to 442 g C m^{-2} yr^{-1} in 1996. Note that the direct CO_2 measurements started only in 1996, so the data for 1995 and 1996 (partly) are inferred from the measurements on latent heat fluxes. For a further comparison we will focus on the period 1997 - 2001, since the inferred measurements for 1995 and 1996 have a larger associated uncertainty than the measured values of the period 1997 - 2001. The average NEE over the period 1997 - 2001, according to the eddy covariance measurements, is 297 g C m^{-2} yr^{-1}.

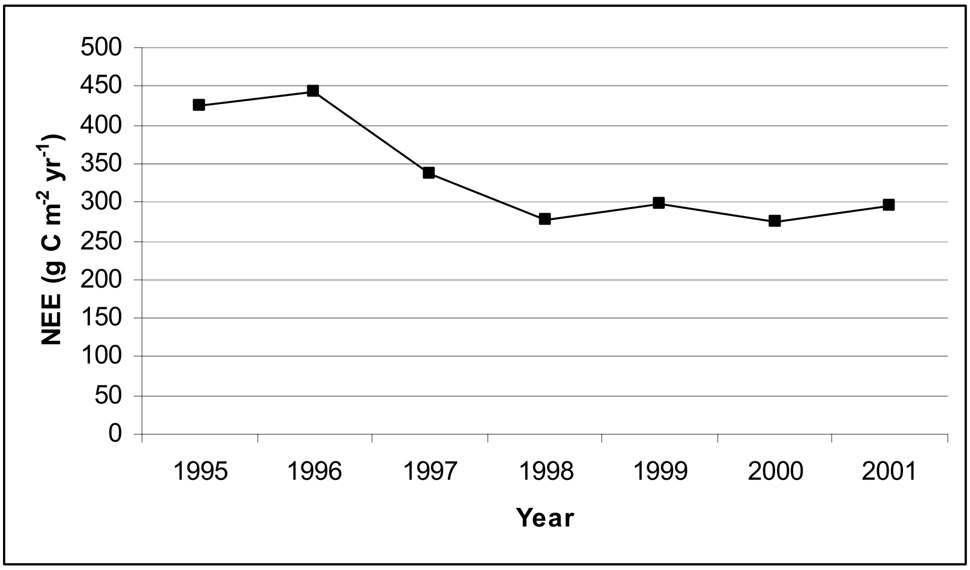

Figure 3.1 NEE according to eddy covariance measurements for the period 1995 - 2001

3.2 Inventory based carbon budgeting

The inventory based carbon budgeting method determines the net carbon flux for three parts of the forest ecosystem: increment of current trees, increment of harvested trees and decomposition of woody material. The net carbon uptake is largely determined by the increment of the current trees (Figure 3.2). The uptake of carbon of the harvested trees is at a comparable level as the release of carbon due to decomposition of dead woody material, but both are of a much smaller size than the uptake in the current trees. The average uptake of all living trees over the period 1997 - 2001 was 168 g C m^{-2} yr^{-1}. The release due to decomposition of dead woody material was 10 g C m^{-2} yr^{-1}, resulting in a net uptake in the tree compartment of 158 g C m^{-2} yr^{-1}. The 95% confidence limits for individual years are ±35 - 37%, while for the period 1997 - 2001 it is ±32%, resulting in an interval of 107 - 209 g C m^{-2} yr^{-1} for the tree part and the dead woody biomass.

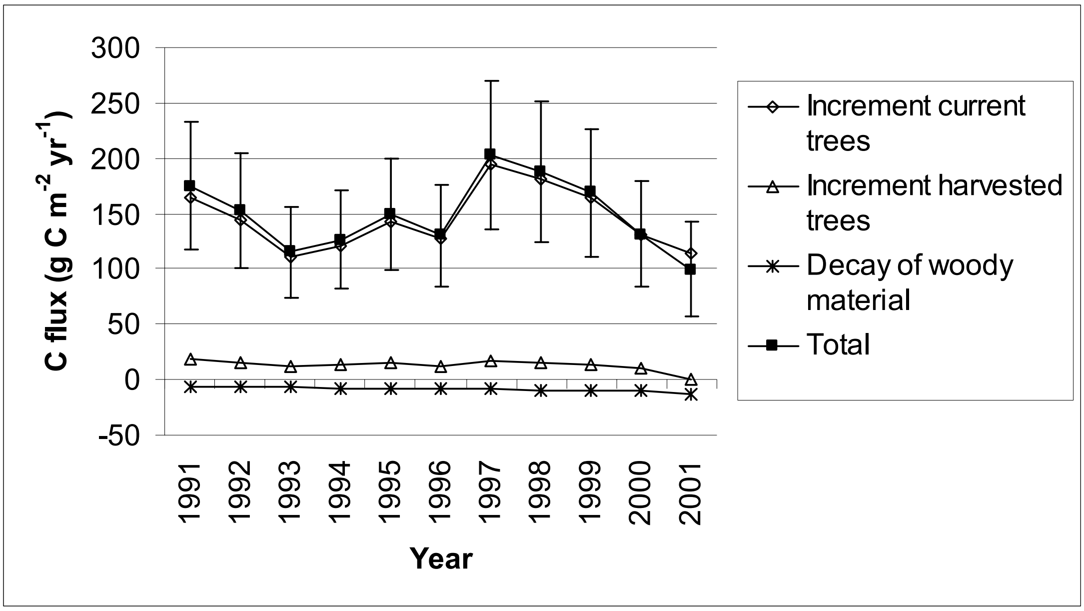

Figure 3.2 Net carbon fluxes as calculated from the inventory due to gains and losses in the tree compartment, as calculated from the inventory. Negative values denote release of carbon to the atmosphere, positive values denote uptake of carbon.

A disadvantage of the forest inventory based carbon budgeting is that it only covers the tree compartment and, in our case, the dead woody biomass. Carbon dynamics in the soil (litter and soil organic matter), products, and in the herb and shrub layer were not included. In order to obtain an inventory based estimate comparable to the eddy covariance measurements, we estimated net carbon fluxes for the soil compartment and herb and shrub layer, using published results for comparable forest sites.

Emmer (1995) investigated the development of the humus profile (litter plus soil organic carbon) in a time sequence of Scots pine afforestations on drift sand in the Netherlands. He developed a model that describes the development of the accumulation of organic matter in different horizons in the humus profile (Figure 3.3). Given the age of our stand and a carbon content of 50% according to Emmer, the estimated average rate of carbon accumulation is 21 g C m^{-2} yr^{-1} for the period 1997 - 2001, according to the model. However, this model is not validated, and shows at the range of interest a clear decreasing trend in accumulation speed. A more conservative estimate is to take the average accumulation speed between the measured organic matter stocks at 59 and 95 years old, resulting in an estimate of 35 g C m^{-2} yr^{-1}. An estimate of the maximum accumulation speed is obtained when we assume that the carbon stock at 95 years has developed linearly since afforestation, in which case we obtain an estimate of 53 g C m^{-2} yr^{-1}. Therefore, an average estimate for the soil accumulation of 35 g C m^{-2} yr^{-1}, with an interval of 21 - 53 g C m^{-2} yr^{-1} was used. This agrees well with an overview by Paul et al. (2002), who found average sequestration rates in soil plus litter for afforestations in the range of 35 - 46 g C m^{-2}

yr^{-1}, on a range of different soil types and climate conditions. According to Figure 3.3, a 95 year old forest stand would then store about 10 kg dry organic matter per m^{-2} in the litter layer plus soil organic carbon pool, equivalent to about 5 kg C m^{-2}. This organic matter stock agrees very well with other values found in literature for comparable sites (Nabuurs and Mohren 1993; Broekmeyer and Maas 1994).

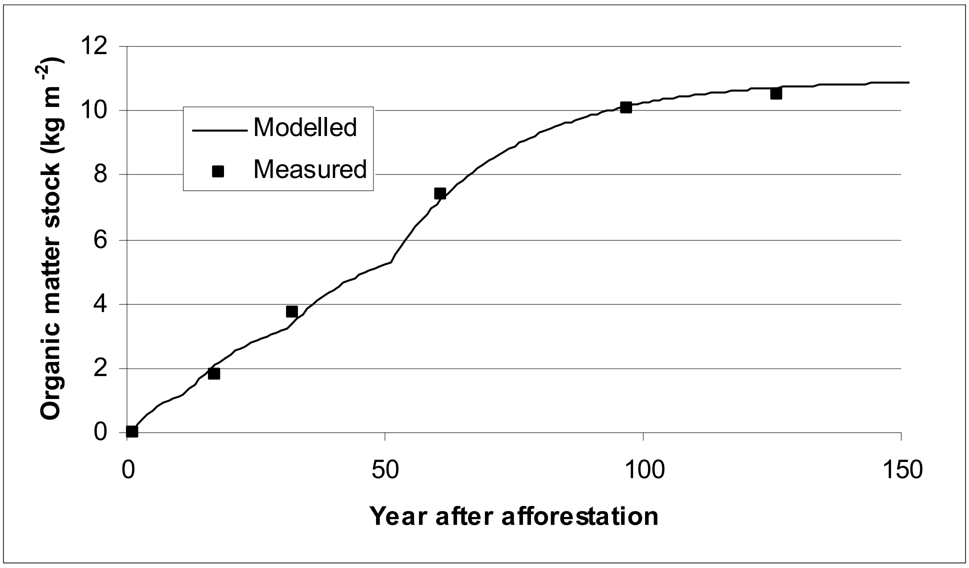

Figure 3.3 Modelled development of organic matter in the humus profile according to Emmer (1995)

Moszynska (1991) studied the production and biomass of the herb layer (mostly a thick layer of Deschampsia flexuosa) under primary Scots pine stands of various ages on blown-out areas, comparable to our site. Under 75 year old Scots pine she found a dry matter biomass of 4766 kg ha^{-1} and under 120 year old Scots pine 13659 kg ha^{-1}. If we assume a linear increase in biomass and a carbon content of 47.5% (Moszynska 1991), we obtain an average accumulation rate of 9.4 g C m^{-2} yr^{-1} for the period 1995 - 2001. A shrub layer is hardly present in the study area, therefore we neglect its contribution to the total NEE.

If we combine all abovementioned results, we find an estimate of the total NEE for the period 1997 - 2001 of 202 g C m^{-2} yr^{-1}, with a (95%) confidence interval of 138 - 271 g C m^{-2} yr^{-1}.

3.3 Comparison

When comparing the estimates of the NEE over the period 1997 - 2001 (Figure 3.4), it is obvious that the two different methods yield consistently different results. Over the period 1997 - 2001, the eddy covariance method estimates an average uptake of 295 g C m^{-2} yr^{-1}, while the inventory based carbon budgeting method estimates 202 g C m^{-2} yr^{-1}, including literature estimates for soil and non-tree vegetation. The confidence interval for the inventory based method is 138 - 271 g C m^{-2} yr^{-1}, and for the eddy covariance method 224 - 366 g C m^{-2} yr^{-1}.

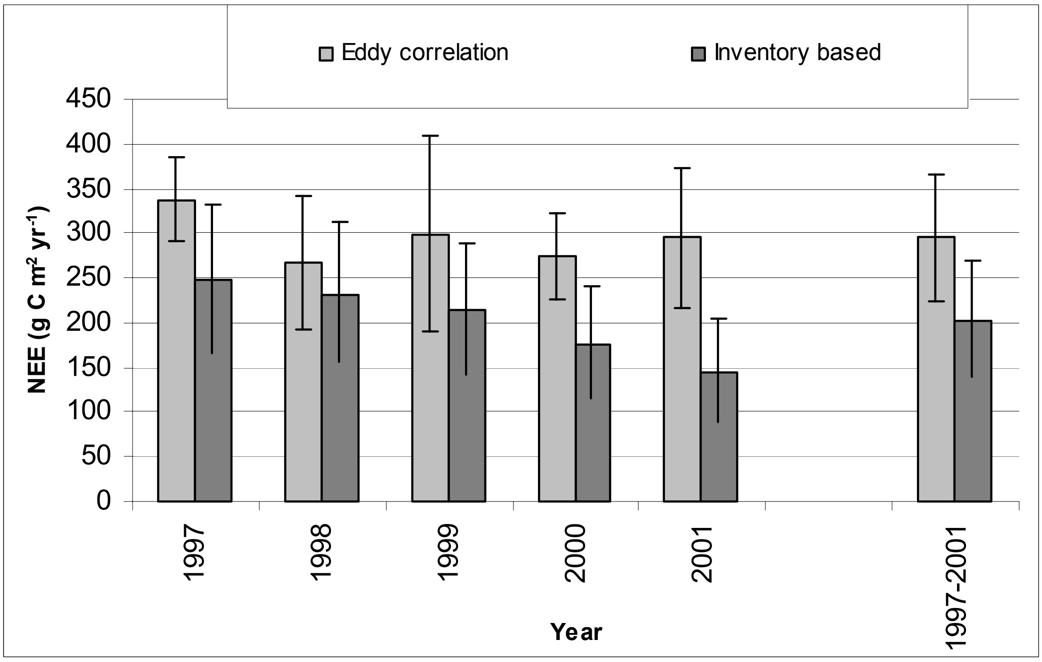

Figure 3.4 Comparison of the NEE, as estimated by the eddy covariance method and by the inventory based carbon budgeting method (tree compartment only). The broken line gives an estimate for the total NEE by the inventory based carbon budgeting method, including an estimate by literature sources of the range of the contribution of the soil and non-tree vegetation.

The year to year trend differs for the two methods. The inventory based method shows a gradual decline from 1997 to 2001, while the eddy covariance method fluctuates without a clear trend. An explanation for a difference in trends could be that weather influences the different compartments in different ways. For example, a dry year can reduce the growth of the trees, resulting in a decreased sink as estimated by the inventory based method. At the same time, decomposition of litter can be hampered as well by drought, resulting in a lower respiration from the soil. The difference between these two fluxes, as measured by the eddy covariance method, can still be of about the same size as in a "normal" year. However, such differences in weather can explain only differences in year to year variability between the methods, but cannot explain absolute differences, nor the five year trend difference as found here.

4 Accuracy

4.1 Introduction

In this chapter we will focus further on the accuracy of both methods. We will do this by discussing the various assumptions made, methods and models used, and other possible sources of errors, as well as their expected effect on the overall result.

4.2 Eddy covariance measurements

4.2.1 Uncertainty due to instrument errors (calibration)

The most sensitive instrument of an eddy covariance set-up is the gas analyser. The random error due to the accuracy of the instrument is negligible. However the systematic error introduced by the calibration of the instrument is not. The most common procedure is to calibrate the instrument on regular time intervals, varying from once a day to once every few months. The calibration is done using high quality reference gases to determine drift or span. As the averaging intervals are relatively short (often 30 minutes) it is primarily the span that determines the size of this systematic error. These calibration results and the uncertainty in the derived correction values linearly translate into uncertainties in the calculated fluxes.

4.2.2 Uncertainty due to theoretical assumptions

Among others Aubinet et al. (2000) give the assumptions underlying the calculations and the corrections needed to derive the flux from the raw data using the eddy covariance technique. The following elements play a role in these calculations: one point sampling, time response, sensor separation, tube losses, digital filtering, supporting structures, finite sampling scheme and signal-to-noise. There is still a lot of discussion going on about the “best” assumptions to apply (e.g. Massman and Lee 2002). It is evident that some of these assumptions such as stationarity and zero horizontal advection apply better to some sites than to others. However, to assess the uncertainty involved with these assumptions is difficult.

A possible method is to recalculate the raw data using different assumptions. In almost all cases it is impossible to determine if one assumption leads to a lower degree of uncertainty than another. However, the standard deviation of the fluxes derived using the different assumptions in comparison to an arbitrary reference value gives a good approximation of the associated uncertainty. Following the most recent discussions on this topic and trying out different assumptions on a number of sites Kruijt et al. (2002) found that the highest uncertainties were associated with: the time constant used for detrending, the length of the averaging interval, the low frequency correction and to applying the lateral rotation.

4.2.3 Uncertainty introduced by filling missing data

As showed among others by Falge et al. (2001), the number of missing data in a data series is the main source of the magnitude of the uncertainty in the filled data series. The method used to fill the data gaps is of less concern. However, it is recommended to use a method that estimates the flux as a function of the physical environment (e.g. Goulden et al. 1996). Gaps in data records may occur due to:

- Instrument failure
- Data rejected because of:
  A. for example range checking on the raw data, leading to removal of records from the data series,
  B. night time conditions: i.e. low u*,
  C. contaminated flux due to fetch conditions.

Contaminated flux due to fetch conditions is not really relevant as long as the site description clearly states the vegetation surfaces in the foot print area. If certain specific wind directions are known to give erroneous data due to for example roughness elements that are extreme, it is assumed that these data are rejected. This will then increase the data gap and thus add uncertainty involved with the data gap filling method.

The uncertainty associated with the filling of gaps due to instrument failure or the rejection of data resulting from for example range checking is straightforward. For an example of quality checking of data the reader is referred to Aubinet et al. (2000) and for a discussion on data gap filling methods to Moors and Dolman (2001) and Falge et al. (2001).

In the gap filling procedure used for this study, first weather data are filled using neural networks driven by other short timestep data measured at the site in combination with data from neighbouring forest stations. If no short timestep data is available at the site, the missing weather data are filled in by taking datasets containing all weather variables from neighbouring forest stations. Then, energy and water flux data are filled in using complete records of weather data and neural networks trained on the site. To fill in the gaps in the CO_2 flux series only daily data are used. A neural network that was trained on all weather data, flux data and soil moisture was used to produce daily average CO_2 flux. Further details on this gap filling procedure may be found in Moors and Dolman (2001). The strong covariance between latent heat flux and CO_2 flux, as can be expressed by a neural network, is used to produce the more or less "synthetic" data for 1995 and to a lesser extent 1996. All other data was measured, or when required periodically filled in.

An extreme example of the quality of this gap filling is shown in Fig. 4.1. Here the estimated versus observed daily NEE is shown for 1999. The network in this case was trained on data from 1997 and 1998 only, and 1999 daily data were completely generated. The slope of the regression line is 0.86, while the neural network estimates explain 88% of the variance. The use of this gap filling technique thus allows the use of data of 1995 when only energy and water fluxes were measured at the site.

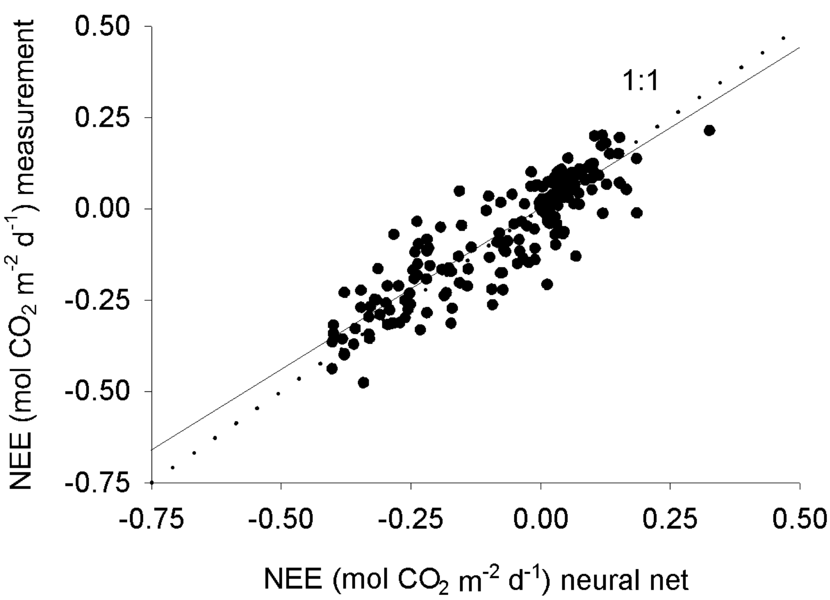

Figure 4.1 Daily NEE for 1999 as estimated from a neural network trained using data from 1997 and 1998, compared with the measured daily values.

4.2.4 Overall Uncertainty

In general the performance of an eddy covariance system is best checked by the degree of energy balance closure (Lloyd et al. 1996). For this site satisfactory agreement was obtained by Dolman et al. (1998) and Elbers et al. (1996) in an earlier study. In Figure 4.2 the energy balance closure is shown for daily sums of latent and sensible heat in 1997. The data apply only to dry days. A regression line fitted to the data has a slope of 0.89 with an y-axis intercept of 3.41 (r^2 =0.87). The good closure result may be related to the fine fetch conditions, but the separate measurements of the radiation components also will contribute to an accurate determination of the net available energy at this site.

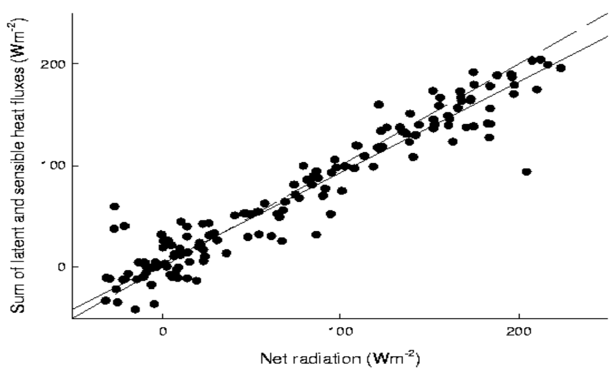

Figure 4.2 Energy balance closure for daily sums of latent and sensible heat in 1997. The data apply only to dry days.

It is commonly accepted that the total or biotic flux should be independent of the friction velocity. This can be tested by plotting the storage flux and eddy covariance flux separately as well as their sum against the friction velocity. Here, biotic flux is calculated from the half-hourly flux as measured by the eddy covariance system and the storage flux, estimated from the concentration profiles:

$$F_{biotic} = F_{eddy} + F_{storage}$$

In Figure 4.3 the average fluxes are plotted for the year 1997 against the friction velocity classes. It becomes apparent from this figure that at $u_* > 0.25$ ms^{-1}, the storage flux becomes small, the eddy covariance flux constant with friction velocity and the NEE also. At $u_* < 0.25$ ms^{-1} the storage flux becomes bigger and appears to compensate for the "loss" in the eddy covariance flux. On this basis, no correction for low u_* was made. The most likely cause for this is the complete absence of any large-scale topography in the area and the virtually unlimited fetch conditions. This would prevent the occurrence of systematic night-time drainage flows.

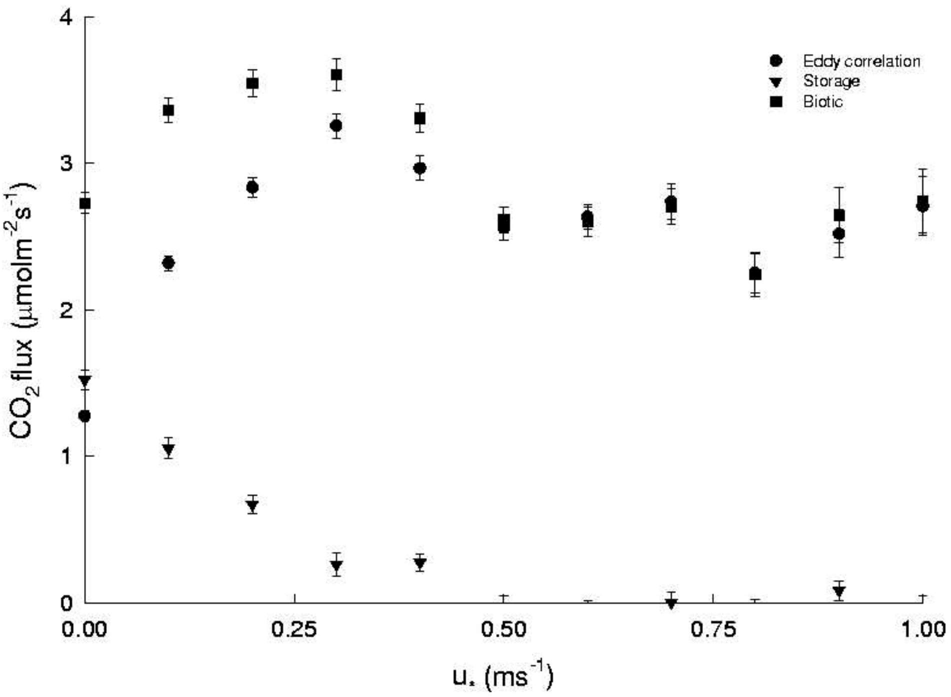

Figure 4.3 Average fluxes for the year 1997 plotted against the friction velocity classes

4.3 Inventory based carbon budgeting

Modern forest inventory methods are usually regarded as very reliable in estimating timber volumes. Since the standing volumes are high in relation to the increment, accurate estimates are of vital importance. Inventory results can therefore provide a reliable basis for estimates on the tree parts of the carbon cycle.

Sources of errors in forest inventories can be divided into the following groups (Kohl et al. 2000; Nabuurs and Karjalainen 2001):

- Sampling errors
- Assessment errors including measurement and classification errors
- Prediction errors caused by models
- Non-statistical errors

Sampling errors result from the fact that the sample that is measured does not represent the whole population well enough. In our case, we applied a systematic sampling design, with a comparatively high density. Since the forest area is fairly homogeneous, we can assume that the samples we measured are representative for the whole forest.

Assessment errors are either measurement errors or classification errors. Usually measurement errors are caused by careless application of measurement rules, or are caused by systematic deviations of measurement instruments. We tried to minimise this source of errors by measuring carefully and calibrating the instruments at the beginning of each day.

The next source of errors are **prediction errors** caused by models. Attributes that are not directly assessed, like dead branch weight and carbon in the total biomass, can be subjected to these errors. The most common kind of prediction errors occurs when models are applied outside the range where it is validated for, such as extrapolations to higher diameters, or outside their geographic range. In this study, we used several models (see section 2.3.2): 1) relation between tree diameter, tree height and tree volume, 2) relation between tree diameter and tree height, 3) regression between individual tree increment and plot characteristics 4) relation between tree diameter and biomass, 5) relation between branch diameter and branch biomass, 6) decomposition of woody biomass, and 7) relation between biomass and carbon.

Re 1). The relation between tree diameter and tree volume is taken from the monitoring system "Meetnet Functievervulling". This relation is based on a large sample of trees within The Netherlands (about 1800 trees). Since our stands are not very special regarding age or tree dimensions, we can assume that the diameters and heights fall within the validated range of the model. Further, the model is derived from trees measured in The Netherlands, so the model is applied within its geographical range. In cases like this, an equation based on diameter and individual tree height is usual, but our sample was too small to derive a diameter-height relationship. As a check, we can compare the volumes for the sample trees as calculated by Equation 2.1 and as calculated by the equation used by Dik (1984), which uses the individual tree height. The result is a good fit, but at higher diameters the absolute tree volume is underestimated by 5% (Figure 4.4).

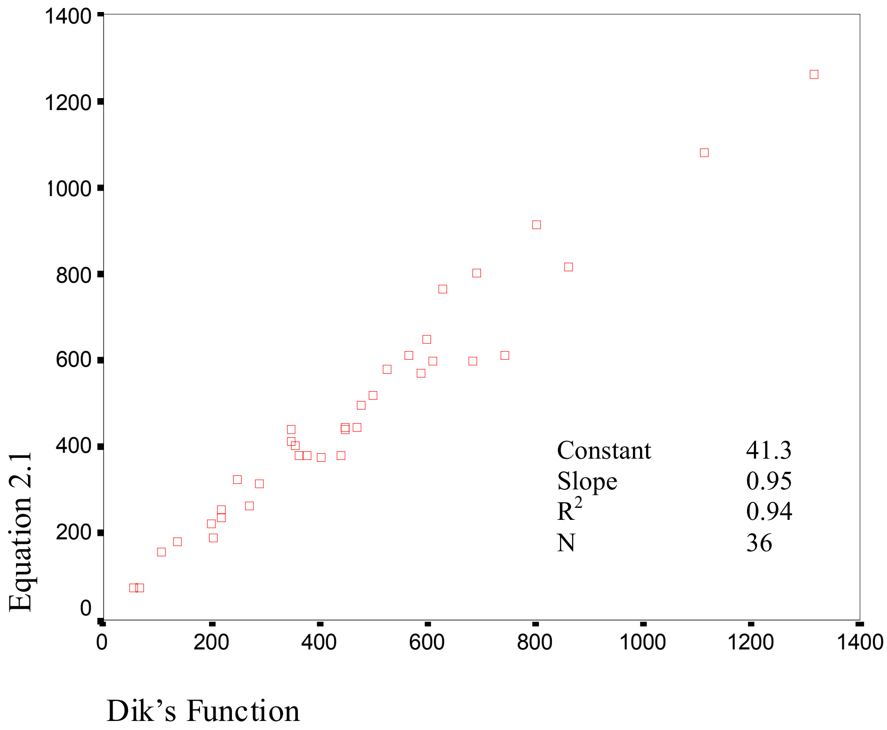

Figure 4.4 Comparison between individual tree volume as calculated by Equation 2.1 and by using the equation by Dik (1984), which uses individual tree height instead of dominant height.

Re 2). The relation between diameter and height is based on the one sample tree per sample plot, so 36 trees in all. This is a rather small sample, and the resulting relationship has an R^2 of only 0.46 (Figure 4.5). Despite the rather poor fit, the resulting deviation will be not large, since basically the difference between two heights is used, and not the absolute height. Further, the model was applied only slightly outside the range of diameters for which it was fit, since the trees have grown only some centimetres over the period of consideration. The relationship is based on trees from the site itself, so the model is not applied outside its geographical range.

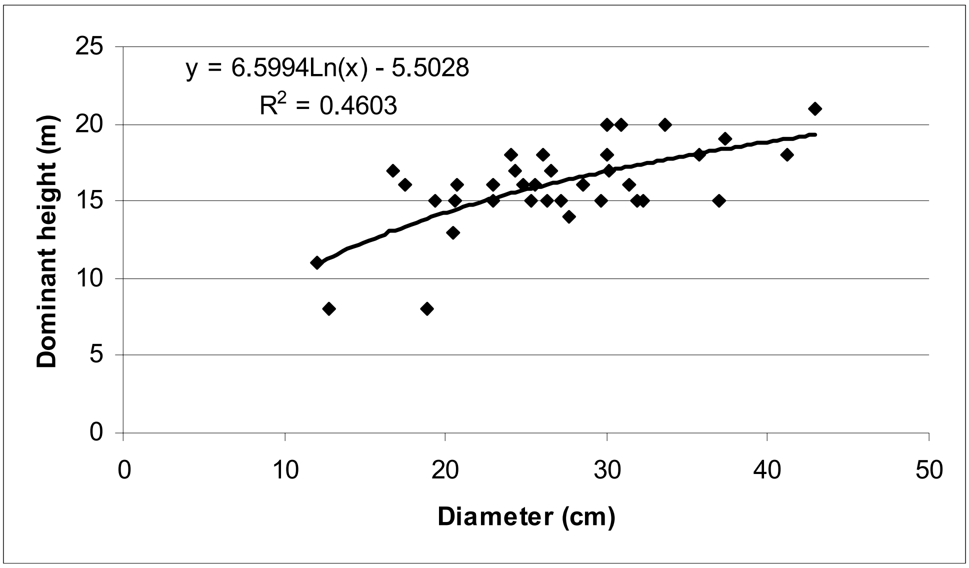

Figure 4.5 Derived relationship between tree diameter (dbh) and dominant height.

Re 3). The observed individual tree increment of the sample trees is extrapolated to the plot level by a regression of individual tree increment on plot characteristics. The variables mean annual increment per tree (MAI, tree volume divided by tree age) and basal area (BA) were found to be the only significant explanatory variables for the calculated increment over the period 1991 - 2002 (Figure 4.6).

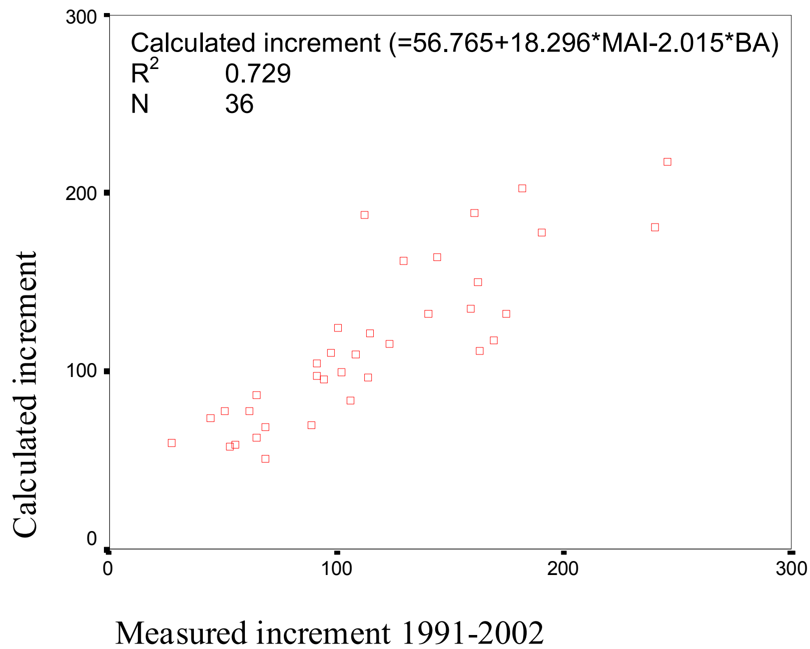

Figure 4.6 Comparison between calculated increment per tree over the period 1991 - 2002 (using mean annual increment per tree (MAI, tree volume divided by tree age) and basal area (BA)) and measured increment over the same period.

The preceding three models all have their influence on the calculated increment. As a rough check, we can compare the calculated increment for the study area with the published national average increments of Scots pine. Since the stocking density is lower than average, we compared the increment relative to the standing wood volume. The resulting increment for age class 40 is lower than the national average (Figure 4.7), but is based on only one observation. For the other age classes the calculated increment is close to the national average, so we can assume that the three underlying models do not introduce an easy observable bias.

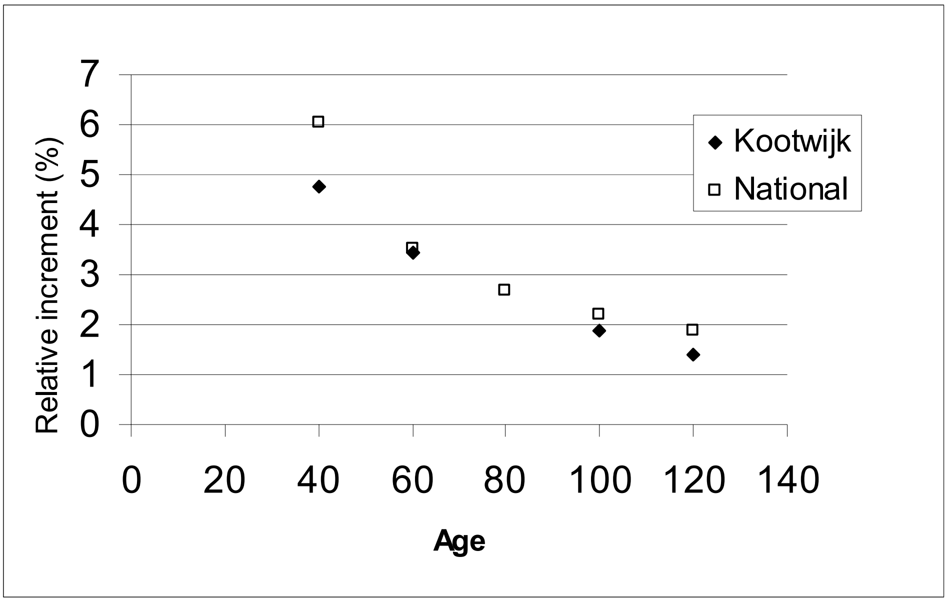

Figure 4.7 Comparison of increment relative to standing wood volume as calculated for Kootwijk and as average over the Netherlands (Daamen 2000).

Re 4). The relation between tree diameter and the biomass in different tree compartments is derived from a dataset with measurements of Scots pines from all over Europe. Their diameters range from 1.8 until 50 cm, so our diameters are within this range. These models are based on data from different European countries, so we indirectly assumed that the allometric relations are valid for whole Europe. However, local differences in climate or site conditions could cause differences in these allometric relations, causing errors in our estimates for tree biomass in different compartments. This is demonstrated by Liski and Mäkipää (2002) on two datasets for Scots pine from Finland and Catalonia (Spain), which show considerable differences in allometric relations. Moreover, the dataset on which our models are based does not originate from a systematic sampling system, but is entirely dependent on studies that have been carried out in other projects. Often such studies had other goals than just collecting allometric data, which might influence the sampling system, so such measurements do not need to be representative for the whole population of trees.
In the inventory in 1997, the biomass of individual trees has been estimated as well (Sabaté, unpublished). By plotting the results of this inventory against the models used here, the validity of those models can be checked. The estimates of Sabaté for foliage and branch biomass are generally lower than the models (Figure 4.8). For the

stem biomass the fit seems to be very good. Since the stem forms the major part of the biomass, the total fit for these three compartments together is very good as well. Since no measurements were done on the root system of the trees, the validity of the root model cannot be checked. In general, observations on the root system are few, since it is very time consuming to do such measurements. Therefore, the root models are usually more uncertain than the aboveground parts.

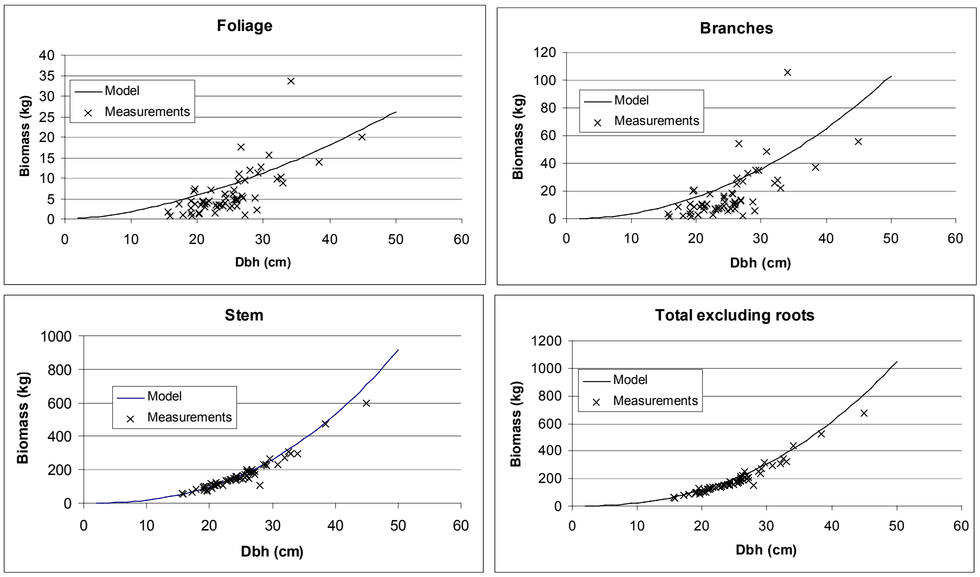

Figure 4.8 Models of Vaessen (2001) versus measurements from Sabate(unpublished) for stand 26a.

Re 5). The relation between branch diameter and branch biomass is derived from measurements taken at the site itself, so we cannot expect inaccuracies from this model regarding the geographical range. The fit of this model is very good with an R^2 of 0.97. However, in this study the model is applied far outside the range where it was fitted for. The largest branch diameter from the model sample was 6.7 cm, whereas only branches larger than 5 cm in diameter were sampled in our inventory, with the largest almost 23 cm. The parabolic shape of the model could mean that the biomass at high diameters will be overestimated. However, from Figure 3.2 we see that the influence of the total dead woody biomass is only small. Another point were a deviation could occur is when branches have broken into pieces on the ground. In that case the model will overestimate the real dry weight of that part of the branch.

Re 6). In the model for decomposition of woody biomass, the factor k needs to be estimated. This is done, based on data for The Netherlands. A drawback of this method is, that only the decomposition of the currently still visible woody parts is taken into account. A branch that is not visible (or recognisable) anymore this year, will have contributed to the release of carbon the years before. On the other hand, the decomposition slows down over time, so when a woody part is not recognised, it is very much decomposed already, and therefore its contribution will be small. The decomposition of small branches will have gone faster, but will also have only a small effect on the total. All in all, this method will give a small underestimation of the release of carbon of dead woody biomass.

Re 7). The relation between biomass and carbon is assumed to be constant (50%) within and between all tree compartments. According to Janssens et al. (1998), carbon contents in a similar Scots pine stand in Brasschaat (Belgium) were:

Stems	48.94%
Needles	48.2%
Branches	51.6%
Roots 5 - 50mm	51.1%
Roots >50mm	48.9%

These values are quite close to the assumed 50%, although they are not calibrated for Loobos.

Non-statistical errors are errors that occur due to human work. These can be errors in measurements, sampling, calculation of results, etcetera. Although it is tried to avoid such errors, they can occur everywhere.

Upscaling

In the forest inventory method, the results of the 36 sample plots are averaged to get an estimate comparable to that of the eddy covariance method. However, these 36 plots do not contribute equally to the flux as measured by the eddy covariance method. The real contribution of each plot depends on the actual wind speed and direction. Plots closer to the tower and located south-west of the tower will have more influence. Therefore we calculated for each plot a weighting factor, derived from the actually measured wind speeds and direction at the tower. If we calculate the weighted average over the plots for the uptake in the current trees, we obtain an estimate that equals to 99.6% of the estimate assuming an equal influence. Therefore we can conclude that the upscaling method does not lead to significant inaccuracies.

Other compartments

In order to estimate the total NEE, literature based estimations for the soil and ground vegetation were used. They can only be regarded as an approximation, since local circumstances may deviate considerably. The actual decomposition of litter is dependent on the weather conditions and can vary from year to year. Moreover, due to the large variability within soils, it is very difficult to get an accurate estimation. However, the values we obtained for soils are quite consistent in literature and seem to match well with the observed amount of litter at the site.

5 Discussion and conclusions

The carbon exchange of a relatively homogenous pine forest in the central parts of the Netherlands as estimated by an inventory based approach was compared with an estimate based on eddy covariance measurements.

Each method is based on a different approach. The inventory based method measures (indirectly) carbon pools at two different points in time (typically every 5 to 10 years) and derives NEP and NBP from changes in these pools. The eddy covariance measurement uses micro-meteorological principles to directly measure the exchange between the land-surface and the atmosphere (i.e. NEE). Besides these methodological differences, the methods may refer to different temporal and spatial scales (although not in the current study). The inventory based approach is used on a annual or longer time scale and covers an area at the forest plot scale, up to millions of hectares through a sampling design. The eddy covariance approach is typically used on a hourly to annual time scale and covers a variable area (approximately 1 – 20 ha) depending on the flux footprint. Both methods have their strong and weak points, which are subject of ongoing research.

Through the inventory based carbon budgeting method, (measurement of stem wood volume and coarse woody debris) combined with literature estimates and visual assessment of soil and ground vegetation, an estimate of the NEE over the period 1997 - 2001 of 202 g C m^{-2} yr^{-1} was obtained, with a confidence interval of 138 - 271 g C m^{-2} yr^{-1}. The estimate obtained by the eddy covariance method was 295 g C m^{-2} yr^{-1} on average for the same period, with a confidence interval of 224 - 366 g C m^{-2} yr^{-1}.

The eddy covariance measurements in Loobos are part of a European network of flux towers, the CarboEuroflux network. At 14 sites across Europe, the same eddy covariance measurements are carried out. For two Scots pine stands (Hyytiälä, Finland and Brasschaat, Belgium), comparable studies like ours have been conducted.

In Hyytiälä, a study is done by Liski and Mäkipää (2002), in a Scots pine stand planted in 1962. Their "inventory based" estimate of the NEE of 250 g C m^{-2} yr^{-1} matched very well with the NEE as measured by the eddy covariance method, which was also 250 g C m^{-2} yr^{-1}.

In Brasschaat, a study has been conducted by Janssens et al. (1998). They measured carbon stocks and fluxes of various parts of the carbon cycle in a Scots pine stand planted in 1929. The eddy covariance measurements showed an average sink of 110 g C m^{-2} yr^{-1}, with an inter-annual variation of 260 g C m^{-2} yr^{-1} (Arnaud et al., personal communication). The "inventory based" method indicates a much larger sink, but there is considerable uncertainty in the estimated accumulation in the soil, since soil respiration and litter fall are measured for only one year. Both quantities are usually highly variable and not correlated at all (Janssens et al. 1998).

When we compare the estimated contribution of the tree part to the total NEE for these three sites, we see that they agree quite well, with 163 g C m^{-2} yr^{-1} for Loobos, 183 g C m^{-2} yr^{-1} for Hyytiälä and 200 g C m^{-2} yr^{-1} for Brasschaat. The estimates for the contribution of the soil compartment show a considerably larger range, which is partly the result of the short monitoring period at Brasschaat, and the fact that we only have a literature estimate for Loobos. This demonstrates the uncertainty associated with the soil compartment.

The risk of using a short time frame for comparison is also demonstrated by Barford et al. (2001). They did a comparable study and found that the inter-annual variability was considerable. Their conclusion was: "Biometric C budgets should not be expected to reconcile with NEE in a single year due to annual shifts in C fluxes.(…) Reconciliation of a biometric budget with NEE in a single year is evidently subject to large errors, and several years are required to determine mean rates of C sequestration using either biometry or eddy covariance.".

In this project where the comparison of methods for annual sink estimates was brought back to exactly the same vegetation type, the same years, and the same scale, the eddy covariance method gave an estimate 46% higher than the inventory conversion method. The time frame of 5 years may be enough to take care of the inter-annual variability of both methods and thus limit the uncertainties due to the different time scales of both methods. As there were 36 plots used for the inventory based method, it is believed that the above ground carbon pools are representative for the area corresponding to the flux-footprint. However, this is not necessarily the case for the below ground carbon pools that were estimated from literature, thus there is still some uncertainty left in the spatial representation of both methods. The pools that were not directly measured and thus giving the highest uncertainty are the below ground carbon stocks. In other studies (e.g. Janssens et al., 2001 and Ehman et al., 2002) inter-annual variability of NEE was mostly attributed to the variability in soil respiration. As below ground and above ground carbon pools may have the same magnitude, this may well explain most of the differences found between both approaches. To a lesser extent these differences may also be attributed to processes not taken into account in the present study, such as the seepage of carbon by hydrological pathways, carbon fluxes by VOC's or grazing.

Future actions to improve the accuracy of the inventory method could consist of reducing uncertainties regarding the non-tree vegetation and the soil compartment. The estimate for the soil compartment could be improved by measurements at the site for carbon pools and modelling the fluxes with the help of turnover parameters of biomass for the litter inputs. Further, for the tree biomass part, the fit of models for branches and foliage could be improved, as well as the model for branch biomass in relation to branch diameter. Due to a lack of data, the root model could not be validated. Since the below ground compartment is always the most unsure part, special attention should be paid to that part. For the micro-meteorological method the uncertainty could be reduced by improving our knowledge on among others the effects of nocturnal drainage flow and the influence of low frequency eddies on the total flux. The present results and suggested improvements are supported by other studies such as Curtis et al. (2002).

Overall, the results showed large uncertainty in net sink estimates when carried out by two independent methods. This indicates that it is not straightforward to design a sound National System for monitoring and reporting of the total land area and for accounting of the Kyoto parts. This National System requires a stimulation programme to reduce uncertainty in the presently available methods. It may consist of a combination of remote sensing, land use and land use change GIS based systems, national inventories in forests, forest soils, agricultural soils, combined with ad-hoc research, existing inventories, and existing statistics. Furthermore it should be completed through special programmes not only of the measurement techniques e.g. biomass expansion factors, uncertainty ranges, non-CO_2 GHG emissions factors, improved and advanced measurement systems, and local and regional climate vegetation modelling, but also of the underlying processes. A possible set up of such a national system will be dealt with in the next report.

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