CO2FIX at the landscape level – an application for the Veluwe area, the Netherlands

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ABSTRACT

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The carbon fixation model CO2FIX was adapted to run on landscape scale, and was applied to the Veluwe area, a forested region in the Netherlands. After a simulation of 500 years, the average carbon stock per ha in the forest products compartment is about 10 Mg C per ha, the carbon stock in the soil about 125 and the carbon stock in the biomass about 100, in total 235 Mg C per ha. The proceeding average sink for the whole of the Veluwe area (73180 ha) amounts to 0.037 Mt C in 2020, 0.034 Mt in 2032, and 0.009 Mt C in 2482. The actual annual sink saturates much earlier, around 2050, but continues to fluctuate. The spatial variability in the results is large and is a reflection of the temporal variability occurring in a rotation. The report discusses the accuracy of CO2FIX simulations, and compares results with other studies.

Keywords: forest carbon stock, forest carbon flux, Veluwe, greenhouse gasses, carbon sequestration

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Contents

Preface

This project was carried out through funds made available under the framework of the Dutch National Research Programme on Global Air Pollution and Climate Change (NOP-MLK), registered under nr: 958254. Additional funds were provided by the 'Climate Programme' of the Agricultural Research Department (DLO).

Summary

The underlying report is part of a sub-project 'inventory of greenhouse budgets' which as a whole has the aim to make a detailed budget of trace gas exchange for European land cover, by combining state of the art land use/cover and soil data sets, with vegetation and soil class specific source/sink strengths. One of the goals of the project is to identify and quantify the major processes and the drivers of land-use-related sources and sinks and to assess the uncertainties in the regional sink/source strength estimates as related to land data availability and to the diagnostic and predictive skills of models.

In order to meet these goals the model CO2FIX was adapted to run on landscape scale, and was applied to the Veluwe area, a forested region in the Netherlands. Each of the circa 55000 stands in this region was simulated for a period of 500 years with this model. After a simulation of 500 years, the average carbon stock per ha in the forest products compartment is about 10 Mg C per ha, the carbon stock in the soil about 125 and the carbon stock in the biomass about 100, in total 235 Mg C per ha. For the forested part of the total Veluwe area this means a stock of 17.3 Tg C. The proceeding average sink for the whole of the Veluwe area (73180 ha) amounts to 0.037 Mt C in 2020, 0.034 Mt in 2032, and 0.009 Mt C in 2482. The actual annual sink saturates much earlier, around 2050, but continues to fluctuate where a sink of around 0.4 Mg C ha^{-1} y^{-1} in some years for the Veluwe as a whole, is interchanged with a source of around 0.3 Mg C ha^{-1} y^{-1} in other years

The spatial variability in the results is large, representing the variety in forest types and management regimes. The spatial variability is a reflection of the temporal variability occurring in a rotation: long periods of gradual build-up, are interchanged with short periods of large effluxes. Spatially, in the biomass, some pixels show a large source as a result of the final felling of the stand. Part of the pixels show a small source, which indicates that a thinning has taken place, while the rest of the pixels are showing a small sink due to the growth of the forest. In the soil compartment, part of the pixels show a small source, probably due to decomposing litter after harvesting activities, while the rest of the pixels show a small sink due to carbon accumulation in the stable humus or due to input in the litter layer.

The report then discusses the accuracy of CO2FIX simulations, and compares results with other studies. CO2FIX-landscape seems a suitable tool to address some of the issues surrounding CDM projects.

1 Introduction

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 forest management and “additional human-induced” activities in the land-use change and forestry sector. In both cases the Annex I countries are committed to report the related sources and sinks of greenhouse gases in a “transparent and verifiable manner”.

Disagreements centring on these “Kyoto sinks” were inter alia responsible for the failure of the 6th Conference of the Parties (The Hague, Nov 2000). Differing opinions regarding the utility of managed land to offset emissions are indicative of uncertainties over the processes governing the spatial and temporal variation of current sources and sinks of CO_2. It is therefore important to address these questions about the terrestrial carbon sink in the European terrestrial biosphere, its causes and persistence.

To deal with these questions the project ‘Interactions between land use, atmospheric concentration of greenhouse gasses and climate in Western Europe and their consequences for post-Kyoto policy options’ was formulated. The project aims to investigate the role of land use and land use change in the climate system and to quantify the consequences of, and a potential for land use options in relation to “post-Kyoto” emission reduction and climate policies in North Western Europe. It was proposed to use, and where needed, to adapt existing state-of-the-art modelling tools in combination with socio-economic analysis and supported by available pan-European data to achieve this aim. Stand- and landscape scale biogeochemical, carbon and vegetation growth models, a regional atmospheric modelling system, a global climate model and an integrated assessment model have been used in this project.

The underlying report is part of the first subproject ‘inventory of greenhouse budgets’ which as a whole has the aim to make a detailed budget of trace gas exchange for European land cover, by combining state of the art land use/cover and soil data sets, with vegetation and soil class specific source/sink strengths. One of the goals of the project is to identify and quantify the major processes and the drivers of land-use-related sources and sinks and to assess the uncertainties in the regional sink/source strength estimates as related to land data availability and to the diagnostic and predictive skills of models. In this frame, a regional, geographically explicit, distributed forest sector carbon balance model (CO2FIX) for coupled pan-European studies was selected, adapted and tested.

Several methods exist to obtain estimates of carbon stocks and fluxes of the (forest) vegetation. The first method is the direct measurement of fluxes above the canopy with the help of flux towers, which is among others carried out at the EUROFLUX sites. The second method is to use the results of forest inventories by converting the stem volumes with the help of biomass expansion factors and carbon contents to carbon stocks and fluxes. The third method is the use of biogeochemical models which model in detail the different carbon exchange processes.

Each of these methods has its advantages and disadvantages. Flux measurements capture the exchange of carbon of the entire system, including the soil, but do not take into account carbon removed by harvesting and are not spatially representative. Inventory results are usually very accurate, but in the first place only the stem volumes and increment are concerned. The use of biomass expansion factors introduces some uncertainty in this method (Heath and Smith 2000). Combined with litterfall and soil modelling and harvest statistics, the inventory based carbon balancing method may still give a fairly reliable picture of the stocks and changes in stocks in the managed forest sector. The disadvantage of this method is that the soil compartment adds considerable uncertainty. Disadvantages of biome level gridded biogeochemical models are that they do not take into account the impact of management on e.g. forest vegetation. Too often they have considered forests to consist of Potential Natural Vegetation that is in equilibrium. Only CO_2 fertilization is then thought to cause a net sink, disregarding the fact that in many northern countries, forests are young, planted and can be seen as in a stage of vegetation rebound. Partly because of the different strengths and weaknesses of each of these methods, the obtained estimates vary greatly.

In the first subproject, land cover data and soil data sets are combined with vegetation and soil class specific source/sink strengths to make a map of the carbon stocks and fluxes in Europe. For the forest vegetation the second method is used, where carbon stocks and fluxes are derived from national forest inventories (Schelhaas and Nabuurs 2001). These stocks and fluxes are averages at a national or provincial level. Within a province or country, a large variability in stocks and fluxes will exist, depending on tree species, productivity, forest management, age, etc. The aim of this report is to assess the variability within such an average and to compare these different methods in order to obtain an idea about the uncertainty margins of the methods used in constructing the carbon map of Europe. Further we want to obtain insight in the main processes of carbon fluxes and the factors that drive them.

In order to meet these goals the model CO2FIX (Mohren et al. 1999, Mohren and Klein Goldewijk 1990) was applied to the Veluwe area, a forested region in the Netherlands. Each of the circa 55000 stands in this region was simulated for a period of 500 years with this model. The CO2FIX model was developed to quantify the C stocks and fluxes in the forest (whole tree), soil organic matter compartment and the resulting wood products at the hectare scale. It was originally designed for even-aged monospecies stands in The Netherlands (Mohren and Klein Goldewijk 1990a), but has also been used for a wide variety of (mostly even-aged) forest types from all over the world, including some selective logging systems (Nabuurs and Mohren 1993, Ordóñez 1998), forest types across Europe (Nabuurs and Schelhaas in review), and agroforestry systems in the tropics (de Jong et al. 1998). Some of the results of CO2FIX have been used in the IPCC 1995 climate change assessment (Brown et al. 1996).

2 Models and data

2.1 The CO2FIX model

CO2FIX quantifies the carbon budget of a forest-soil-wood products chain at the stand (i.e. hectare) level on an annual base and for multiple rotations. It also has a feature to scale up to the project level using the rotation length as the number of afforestations to be carried out. The following description has largely been taken from Mohren et al. (1999).

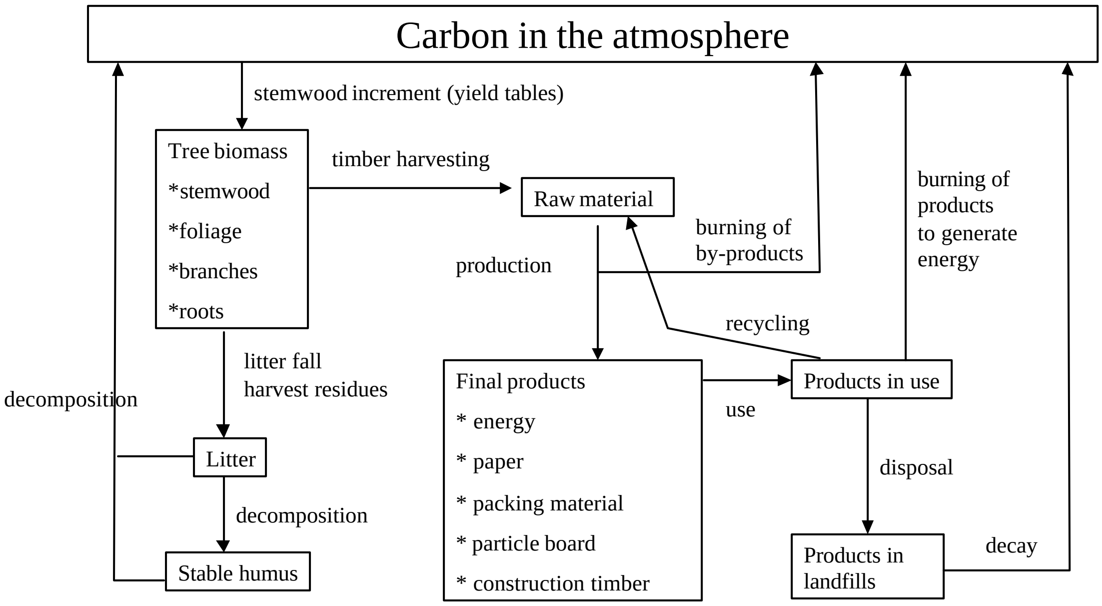

Figure 2.1 Carbon fluxes/processes (arrows) and carbon stocks (boxes) in a forest ecosystem and its wood products as distinguished in CO2FIX.

The model comprises the compartments as given in figure 2.1. CO2FIX can be parameterised by published data (often yield tables) on growth rates and amounts of biomass in the various forest types together with forest soil carbon data. Growth of foliage, branches, and roots is incorporated as an additional allocation of dry matter increment relative to the stem wood increment. This, together with expected life spans of those tree organs determines the biomass of those organs in the stand and determines the rate of litterfall.

The dynamics of the forest soils compartment are characterised by decomposition rates of litter and stable humus and humification rates of litter. Initial values for dead wood, litter, and soil stable humus can be based on current knowledge in literature. It is assumed that both litter and dead wood on top of the mineral soil and stable humus incorporated in the mineral soil, belong to the soil organic matter compartment.

The forest product compartment is incorporated in the model according to a specified harvesting regime. The harvested wood (in case of thinnings as a percentage of the standing volume) is allocated by the user to five product groups. Products are assumed to decay exponentially with the average residence times of carbon in energy wood, paper, packing wood, particle board, and construction wood usually being estimated at respectively 1, 2, 3, 20 and 35 years.

For wood products, a recycling option is also available. In case of recycling, the wood product does not decay exponentially, but the whole amount is, at the end of its life span, moved to a wood product of lower quality. Construction wood is e.g. recycled to particle board and then again particle board is used as energy wood. When the wood product has come to the end of the life span of its last use, all the carbon is emitted in one year. There is no land fill compartment in the present version of CO2FIX.

With basic wood density (dry matter weight per fresh volume) and carbon content data from literature, volume and dry matter are converted to carbon. For further details of the model see Mohren & Klein Goldewijk 1990b. The model produces an annual output of stocks and fluxes of carbon for different parts of the forest biomass, the wood product compartment, and the soil organic matter compartment.

2.2 Modifications to the model

Nothing was changed in the CO2FIX model except that it was made possible to start the simulation during the rotation instead of only at the beginning of a rotation. An extension was build around the core program that compiles the desired input per single stand, runs the model and stores the output.

2.3 Study area

The selected study area was the Veluwe region of the Netherlands (figure 2.2). This area was chosen because it is the most densely forested area of the Netherlands and detailed data on the stand level were available. This area mainly consists of sandy soils, which were degraded due to over-exploitation in the past. Re-afforestation started in the end of the 19^{th} century and continued in the first half of the 20^{th} century. The main tree species used to afforestate was Scots pine. Some Scots pine stands have been regenerated already once or twice, others are still in their first rotation. In general, the forest is rather young, with the majority of the trees planted after 1920 (figure 2.3). Oak and birch are gradually invading in the Scots pine stands, and some stands have been converted to other species. Apart from Scots pine, some other species have been used, like Douglas fir, larch and Norway spruce. Next to these formerly degraded forest soils there are stands that have been forest for a longer period. These are mainly on the richer soils and consist of beech and oak. The tree species distribution of the Veluwe is shown in figure 2.4. The total forest area of the Veluwe is ca. 73 180 ha, divided over ca. 55 000 stands.

Figure 2.2 The shaded area roughly indicates the area under study, the Velwe.

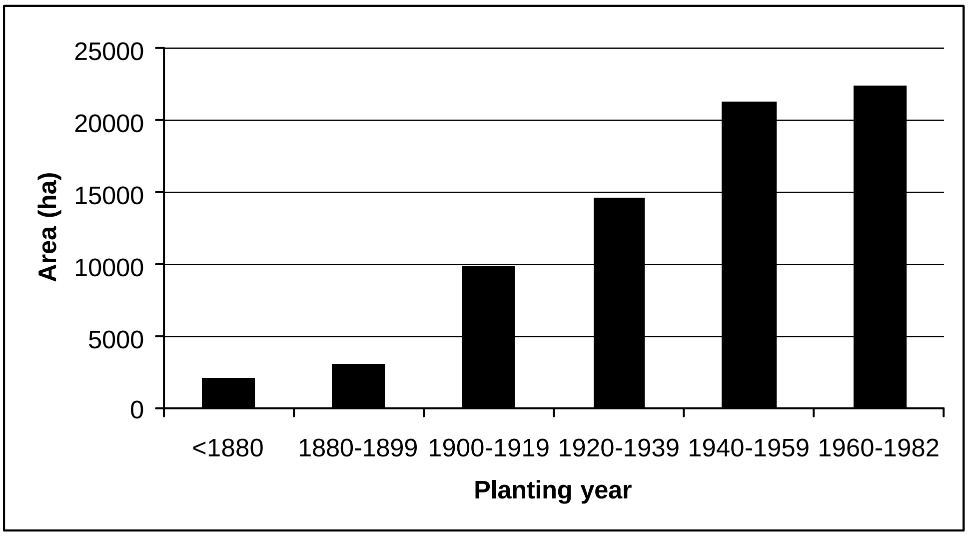

Figure 2.3 Distribution of the forest area of the Veluwe over planting years.

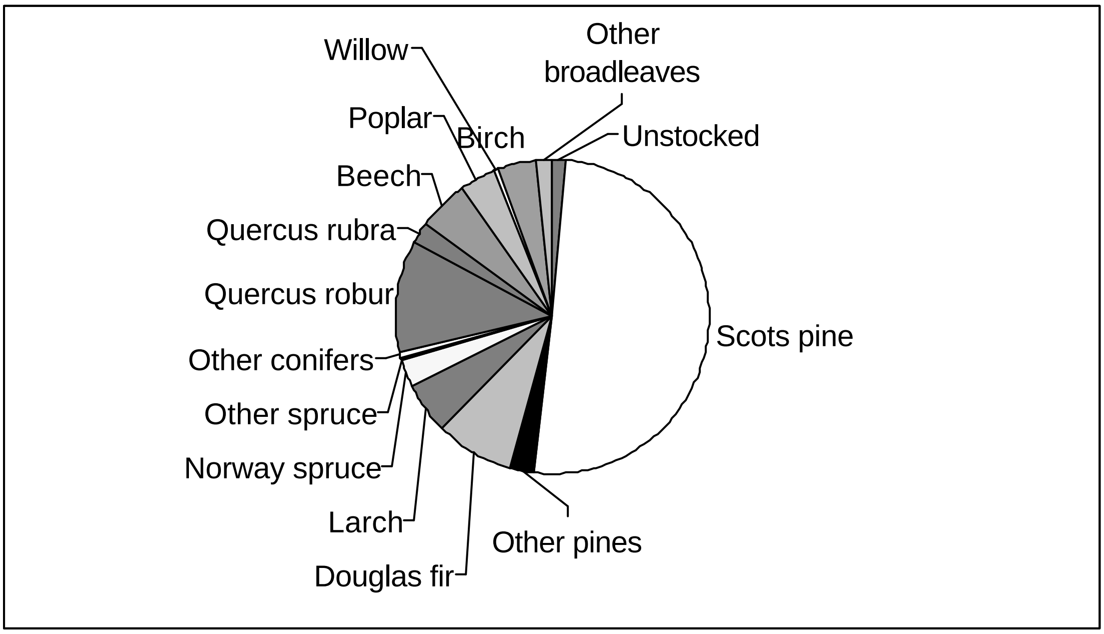

Figure 2.4 Tree species distribution in the Veluwe area..

2.4 Initialisation and parametrisation

The stand-level data used to initialise the model are based on the Fourth Dutch Forest Statistics, carried out from 1980-1983, on average is assumed 1982. For this forest statistics all forest stands in the Netherlands were assessed. During field visits several stand characteristics were described. From these characteristics were used: tree species, area, age, dominant height, standing volume, growth class and the co-ordinates of the stand.

Production

For the parametrisation of stem wood production the yield tables from Jansen et al. (1996) are used. In table 2.1 is shown which yield tables are used for which tree species. By using actual age and dominant height, a site class according to Jansen et al. is assigned. In the forest statistics a growth class is assessed, which gives an indication if the stand is growing less, normal or better than could be expected on that site. If the stand is growing less than expected, one site class lower is assigned, if the stand is growing better than expected, one site class better is assigned.

Table 2.1 Yield tables (from Jansen et al. 1996) used per tree species.

Tree species	Yield table
Pinus sylvestris	Scots pine
Pinus nigra var. maritima	Corsican pine - interior country
Pinus nigra var. nigra	Austrian pine - interior country
Other pines	Scots pine
Pseudotsuga menziesii	Douglas fir - normal density
Larix spp.	Japanese larch
Picea abies	Norway spruce
Juniperis communis	Scots pine
Other conifers	Norway spruce
Quercus petraea, Quercus robur	Pedunculate oak
Quercus rubra	Red oak
Other oaks	Pedunculate oak
Fagus sylvatica	Beech
Populus spp.	Poplar - planting density 6m
Salix spp.	Alder
Betula spp.	Birch
Fraxinus excelsior	Ash
Alnus glutinosa	Alder
Acer campestre, Acer pseudoplatanus	Ash
Robinia pseudoacacia	Robinia (old CO2FIX input)
Prunus avium	Birch
Carpinus betulus	Beech
Ulmus spp.	Beech
Other exotic broadleaves	Beech
Other indigenous broadleaves	Pedunculate oak

The allocation factors for foliage, branches and root production were copied from existing CO2FIX runs for comparable species. Then for each species runs were made for the lowest and the highest site class and the development of foliage, branch and root biomass was checked. The allocation factors were adapted so that the biomass in these compartments was not declining, except for thinnings and final felling. Nabuurs and Mohren (1993) gave in their study an overview of results from studies where the distribution of biomass over these compartments were given for various tree species and ages. The allocation factors were adapted so that the relative distribution of biomass over these compartments was comparable to the results of their study.

Further, the relative allocation to these compartments was made dependent on the actual site class. Generally, in stands with a high production (good sites), relatively less biomass is allocated to the other compartments in relation to the stem (Kramer and Mohren 2001). The relative allocation varies from 0.8 for the best site class to 1.1 for the poorest site class.

Initialisation of tree biomass

Stem biomass is initialised with the standing volume from the forest statistics. From test runs per tree species relationships are derived between stem biomass and biomass in foliage, branches and roots, depending on age. These relationships are used to initialise the biomass in these compartments.

Soil initialisation

The soil organic matter compartment consists of dead wood, litter layer and stable humus in the soil. The dead wood compartment of all forest types was initialised with the average amount of dead wood presently in the Dutch forests, which is 3.6 $m^3 ha^{-1}$ (Schoonderwoerd and Daamen 2000).

In the study of Nabuurs and Mohren (1993), estimates are given for the amount of carbon in the stable humus for different soil types in the Netherlands. Per tree species an estimate was made on which range of soils they are generally planted in the Netherlands (table 2.2). Within this range of soil types the highest site class was assigned to the richest soil type and the lowest site class to the poorest soil type, although this general relationship is largely influenced by the ground water level (Schoenfeld and Waenink 1974), but no estimates were available for that. For intermediate site classes a linear interpolation was done. So the stable humus component is dependent on the actual site class of the tree species.

The study of Nabuurs and Mohren also gives an estimate for the average amount of carbon in the stable humus and in the litter layer. The ratio between these was used to initialise the litter layer relative to the amount of stable humus. Table 2.3 gives the amount of carbon in different soil types and in table 2.4 the ratio between litter layer and stable humus is shown.

Table 2.2 Possible range of soil types (Dutch classification system: see for an explanation Appendix 1) per tree species.

Tree species	Poorest soil type	Richest soil type
Pinus sylvestris	Vlakvaaggrond	Enkeerdgrond
Pinus nigra	Vlakvaaggrond	Haarpodzol
Other pines	Vlakvaaggrond	Enkeerdgrond
Pseudotsuga menziesii	Duinvaaggrond	Enkeerdgrond
Larix spp.	Duinvaaggrond	Enkeerdgrond
Picea abies	Veldpodzol	Holtpodzol
Juniperis communis	Vlakvaaggrond	Haarpodzol
Other conifers	Veldpodzol	Holtpodzol
Quercus petraea, Quercus robur	Duinvaaggrond	Enkeerdgrond
Quercus rubra	Duinvaaggrond	Holtpodzol
Other oaks	Duinvaaggrond	Enkeerdgrond
Fagus sylvatica	Haarpodzol	Enkeerdgrond
Populus spp.	Enkeerdgrond	Beekeerdgrond
Salix spp.	Enkeerdgrond	Beekeerdgrond
Betula spp.	Duinvaaggrond	Haarpodzol
Fraxinus excelsior	Enkeerdgrond	Beekeerdgrond
Alnus glutinosa	Laarpodzol	Vlierveengrond
Acer campestre, Acer pseudoplatanus	Laarpodzol	Enkeerdgrond
Robinia pseudoacacia	Holtpodzol	Enkeerdgrond
Other broadleaves	Haarpodzol	Enkeerdgrond

Table 2.3 Dry weight stocks of soil organic matter (stable humus) in Dutch soils to 1 m depth (Nabuurs and Mohren 1993), (Dutch classification system: see for an explanation Appendix 1).

Soil type	Dry weight of soil endorganic matter (Mg/ha)
Vlierveen	733
Holtpodzol	226
Veldpodzol	182
Haarpodzol	185
Enkeerdgrond	314
Laarpodzol	127
Beekeerd	130
Vlakvaag	28
Duinvaag	84

Table 2.4 Ratio between carbon in the litter layer and the stable humus for different forest types (Nabuurs and Mohren 1993).

Tree species	Forest floor (Mt C, whole Netherlands)	Stable humus (Mt C, whole Netherlands)	Ratio
Scots pine	3.8	9.5	0.400
Austrian and Corsican pine	0.18	1.5	0.120
Douglas fir	0.15	1.7	0.088
Japanese larch	0.26	2.1	0.124
Norway spruce	0.13	1.6	0.081
Indigenous oak	0.74	3	0.247
Beech	0.1	0.9	0.111
Poplar and willow	0.11	1.5	0.073
Ash	0.03	0.4	0.075
Alder	0.01	0.2	0.050
Birch	0.06	0.9	0.067
Red oak	0.11	0.5	0.220

Products

For the product compartment no initialisation has been done. Generally, no good estimates are available on the amount of carbon stored in wood products, and it is impossible to divide them by forest type. Further the amount of carbon in products is relatively small, compared to the amounts in the biomass and in the soil.

Management regimes

For each tree species a general management regime has been defined, which consists of the ages when thinning takes place, the rotation length and the allocation of the wood over the different product types. These regimes are derived from Sikkema and Nabuurs (1994) and earlier CO2FIX studies. In table 2.5 the thinning and final felling ages are shown, as well as the allocation of the harvested wood over the different wood product groups.

Table 2.5 Thinning and final felling regime per tree species and the allocation over the different products. The last line per tree species represents the final felling.

	Age	Thinning %	Dead wood	Energy wood	Paper	Packing wood	Particle board	Con-struction wood
Scots pine, Corsican pine, Austrian pine	40	0.08	0.1	0.1	0.5	0.3	0	0
	60	0.1	0.1	0.1	0.3	0.4	0	0.1
	80	0.12	0.1	0.1	0.2	0.2	0	0.4
	90		0.1	0	0.1	0.4	0	0.4
Douglas fir	40	0.08	0.1	0.3	0	0.5	0.1	0
	60	0.1	0.1	0.1	0	0.3	0.4	0.1
	80	0.12	0.1	0.1	0	0.2	0.2	0.4
	100		0.1	0	0.1	0.4	0	0.4
Larch	40	0.08	0.1	0.1	0	0.5	0.3	0
	60	0.1	0.1	0.1	0	0.3	0.4	0.1
	80		0.1	0	0	0.1	0.4	0.4
Spruce	40	0.08	0.1	0.1	0.5	0.3	0	0
	60	0.1	0.1	0.1	0.3	0.4	0	0.1
	80		0.1	0	0.1	0.4	0	0.4
Oak	40	0.12	0.2	0.8	0	0	0	0
	60	0.11	0.1	0.7	0	0.2	0	0
	80	0.1	0.1	0.45	0	0.25	0.1	0.1
	100	0.1	0.1	0.35	0	0.17	0.23	0.15
	120		0.1	0.5	0	0.06	0.1	0.24
Red oak	40	0.12	0.2	0.8	0	0	0	0
	60	0.11	0.1	0.7	0	0.2	0	0
	80	0.1	0.1	0.45	0	0.25	0.1	0.1
	100		0.1	0.5	0	0.06	0.1	0.24
Beech	40	0.12	0.1	0.7	0	0.2	0	0
	60	0.11	0.1	0.5	0	0.3	0	0.1
	80	0.1	0.1	0.3	0	0.4	0	0.2
	100	0.1	0.1	0.3	0	0.3	0	0.3
	140		0.1	0.3	0	0.2	0	0.4
Birch	40	0.1	0.1	0.4	0.5	0	0	0
	60	0.1	0.1	0.3	0.6	0	0	0
	80		0.1	0.2	0.4	0	0.3	0
Ash	40	0.1	0.1	0.8	0	0.1	0	0
	60	0.1	0.1	0.5	0	0.2	0.1	0.1
	80	0.1	0.1	0.2	0	0.3	0.1	0.3
	90		0.1	0.1	0	0.2	0.2	0.4
Alder	40	0.1	0.1	0.5	0	0.2	0.2	0
	60	0.1	0.1	0.3	0	0.4	0.1	0.1
	75		0.1	0.2	0	0.3	0.1	0.3
Poplar	20	0.4	0.05	0.45	0.4	0.1	0	0
	45		0.05	0.1	0.1	0.5	0.25	0
Robinia	20	0.1	0.1	0.4	0	0.4	0	0.1
	40	0.1	0.1	0.3	0	0.3	0	0.3
	50		0.1	0.2	0	0.3	0	0.4

Other parameters

In table 2.6 and 2.7 the other parameters that are dependent on the tree species are shown. The values for wood density (dry weight per fresh volume) are derived from a database on wood properties (Dresden 2000). Values for turnover rates for foliage, branches and roots are derived from former CO2FIX studies and have been harmonised among the species. Residence times for wood products are estimates and for the longer lasting products dependent on the general durability of the wood. The residence time of carbon in the soil and litter layer and the humification coefficient are based on former CO2FIX studies and are harmonised among the species, dependent on the degradability of the litter and the general soil type on which that tree species grows (wet or dry soils).

Table 2.6 Tree species dependent parameters.

Tree species	Basic wood density (dry matter/fresh volume) (kg/m3)	Turnover of foliage biomass (yr^{-1})	Turnover coefficient of branches biomass (yr^{-1})	Turnover coefficient for roots biomass (yr^{-1})	Humification coefficient (yr^{-1})
Scots pine	490	0.3	0.03	0.07	0.02
Corsican pine	500	0.3	0.03	0.07	0.02
Austrian pine	560	0.3	0.03	0.07	0.02
Douglas fir	470	0.3	0.03	0.1	0.05
Larch	490	1	0.05	0.07	0.04
Norway spruce	430	0.3	0.05	0.1	0.03
Pedunculate oak	650	1	0.03	0.06	0.08
Red oak	660	1	0.03	0.06	0.07
Beech	680	1	0.03	0.06	0.08
Birch	610	1	0.06	0.06	0.05
Ash	650	1	0.03	0.06	0.08
Alder	510	1	0.05	0.09	0.1
Poplar	410	1	0.06	0.1	0.1
Robinia	730	1	0.03	0.05	0.1

Table 2.7 Average residence times of carbon in different compartments in the model (in years).

Tree species	Humus	Dead wood in the forest	Litter	Construction wood	Particle board	Packing wood	Energy wood	Paper
Scots pine	275	20	5	20	15	3	1	1
Corsican pine	275	20	5	20	15	3	1	1
Austrian pine	275	20	5	20	15	3	1	1
Douglas fir	275	20	3	20	15	3	1	1
Larch	275	20	2	20	15	3	1	1
Norway spruce	350	20	6	20	15	3	1	1
Pedunculate oak	275	30	1.2	35	20	3	1	1
Red oak	275	30	2	35	20	3	1	1
Beech	275	30	1.2	35	20	3	1	1
Birch	275	20	2	20	20	3	1	1
Ash	350	30	1.2	35	20	3	1	1
Alder	450	10	1	25	10	3	1	1
Poplar	350	10	1	15	10	3	1	1
Robinia	275	30	1	35	20	3	1	1

3 Results

3.1 Temporal scale

In figure 3.1 the development of the carbon stock in different compartments is shown as an average for the whole Veluwe. The large increase in biomass over the first 50 years can be attributed to an underestimated growing stock volume in the Fourth Forest Statistics. The average growing stock according to this statistics is for the whole Netherlands 91 m3/ha and for the Veluwe area 103 m3/ha, while according to the HOSP statistics it was 156 m3/ha for the whole Netherlands (Schoonderwoerd and Daamen 2000). This underestimation is caused by the fact that for a lot of stands no estimate of the standing volume was given. The initial size of the root, branch and foliage compartments are derived from the initial growing stock and will therefore be empty as well. In the first years of the simulation, a fast build up occurs in these stands, although they will never reach the same biomass quantities as when they started with the right initial values. However, in the second rotation they will show the same biomass development. The older the stand at the beginning of the simulation, the bigger the deviation will be. Old stands are harvested earlier, so the effect will diminish over time. After about 90 years (more or less the average rotation period) this effect should be gone. Already earlier, after about 40 years, this effect cannot be distinguished clearly anymore from the figures, also due to other developments. In figure 3.1 the initial biomass is corrected using the relative difference between the volume in the Fourth Forest Statistics and the volume according to Daamen and Schoonderwoerd (2000). It is assumed that after 40 years there is no effect anymore of the initial underestimation. The biomass in that 40-year period is linearly interpolated.

Until about 2030 the biomass is increasing, because a large part of the forest is still young. As can be seen in figure 2.3, the area is not distributed evenly over the age classes, almost 60% of the area is planted in the years 1940-1982. The average rotation time is about 90 years, so most of these forests will be harvested between 2030 and 2070. In figure 3.1 this can be seen from the decrease in biomass in that period. After 2070 most of the stands are building up biomass again, after which again there is a period where the mature stands are harvested. This pattern repeats itself during the simulation, although it becomes less pronounced due to differences in rotation lengths between tree species. In general, the average carbon stock in biomass is increasing slightly.

The carbon stock of the soil compartment initially declines slightly, probably due to a rather high litter amount under Scots pine stands (see table 2.4). After a few years this litter is decomposed and decomposition and input rates become more realistic. The carbon stock in the soil compartment increases during the rest of the simulation, but its rate decreases over time. When the forests were planted, most soils were heavily degraded. Under forest cover the soils are recovering and show a steady build up of carbon again.

The carbon stock in the forest products increases quickly in the beginning because this compartment was not initialised. After about 60 years the stock stabilises at a level of about 10 Mg C per ha.

After a simulation of 500 years, the average carbon stock per ha in the forest products compartment is about 10 Mg C per ha, the carbon stock in the soil about 125 and the carbon stock in the biomass about 100, in total 235 Mg C per ha. For the forested part of the total Veluwe area this means a stock of 17.3 Tg C.

Figure 3.2, showing the simulated proceeding average annual sink after correction, the same developments can be seen. In the short term the biomass builds up quickly, but when the mature stands are harvested, this sink is temporarily lost again. In the longer term the biomass is a small sink. The soil compartment acts in a slightly different way; the annual sink is smaller, but is maintained for a much longer time. In the long term, the soil compartment appears to be a larger sink than the biomass. Figure 3.2. also shows that eventually the whole system saturates. The proceeding average sink for the whole of the Veluwe area (73180 ha) amounts to 0.037 Mt C in 2020, 0.034 Mt in 2032, and 0.009 Mt C in 2482.

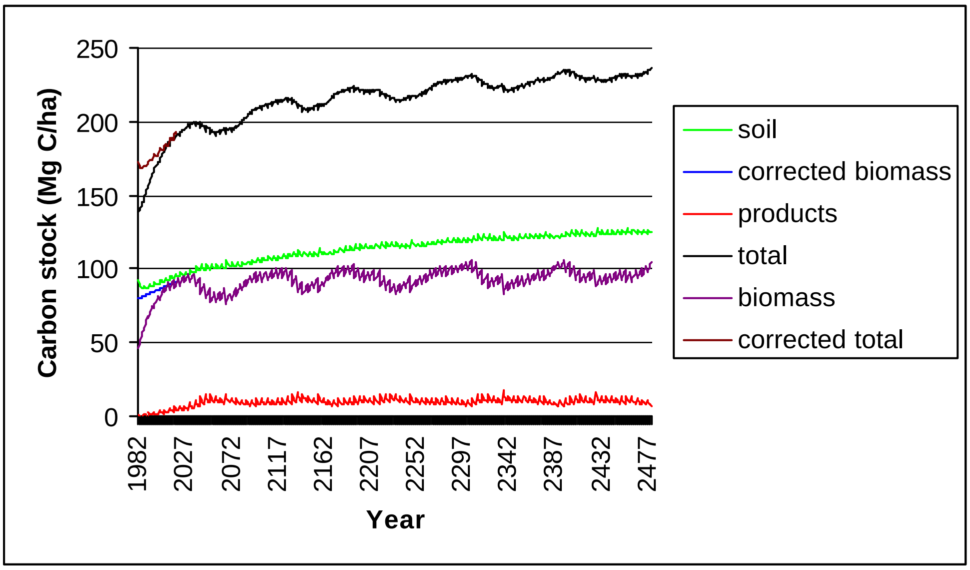

Figure 3.1. Simulated development of carbon stocks in different compartments for the Veluwe area, in Mg C ha^{-1}*. The corrected lines reflect a correction due to the initial underestimation of biomass in the input data.*

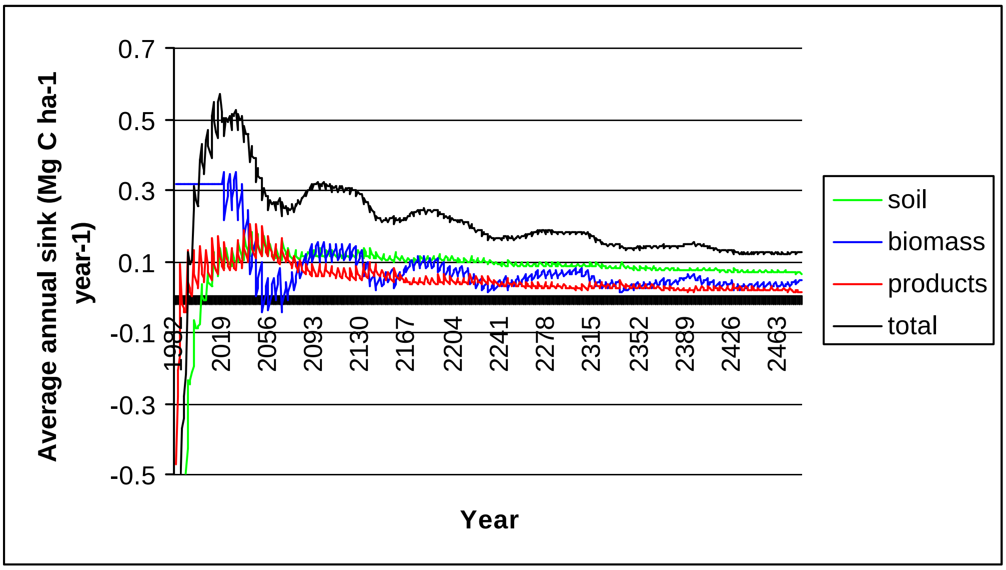

Figure 3.2 Development of the proceeding average annual sink for the Veluwe as a whole in different compartments throughout the simulation, corrected for the initial underestimation of biomass. This graph displays the proceeding average of the sink, and therefore the actual annual sink saturates much earlier, around 2050, but continues to fluctuate where a sink of around 0.4 in some years is interchanged with a source of around 0.3Mg C ha^{-1} *y*$^{-1}$ *in other years.*

3.2 Spatial distribution

In the figures 3.3-3.12, some results are shown at a spatial level. Each pixel in these figures covers an area of 500 by 500 meters and represents the total of on average 10 stands, of which each was run individually.

Figure 3.3, 3.4 and 3.5 show the spatial structure of the carbon stock in the biomass, the soil and of the total system in the years 1982, 2032 and 2482. Figure 3.6, 3.7 and 3.8 show the difference in carbon stock in these compartments between 1982-2032 and 1982-2482. In figure 3.9., 3.10 and 3.11 these differences are divided by the length of the period over which that sink or source is attained.

Figure 3.3 and 3.6 show that the carbon stock in the biomass increases over the first 50 years, but there is not much difference between the carbon stock in 2032 and 2482. The processes in the soil are slower, which can be seen from figures 3.4 and 3.7. The difference between the carbon stock in the soil in 2032 and 1982 are not that large, but have increased more between 2482 and 1982. These two stocks combined, together with the products, gives a carbon stock that increases steadily over time (figure 3.5 and 3.8).

Figure 3.12 gives an impression of the annual flux in the biomass, the soil and the entire system in the year 2027. In the biomass, some pixels show a large source as a result of the final felling of the stand. Part of the pixels show a small source, which indicates that a thinning has taken place, while the rest of the pixels are showing a small sink due to the growth of the forest. In the soil compartment, part of the pixels show a small source, probably due to decomposing litter after harvesting activities, while the rest of the pixels show a small sink due to carbon accumulation in the stable humus or due to input in the litter layer.

These figures give an indication of the spatial structure of the sources and sinks. Part of the forest can act as a source, while the whole area can act as a sink. It also gives an impression of the range over which an average flux is calculated.

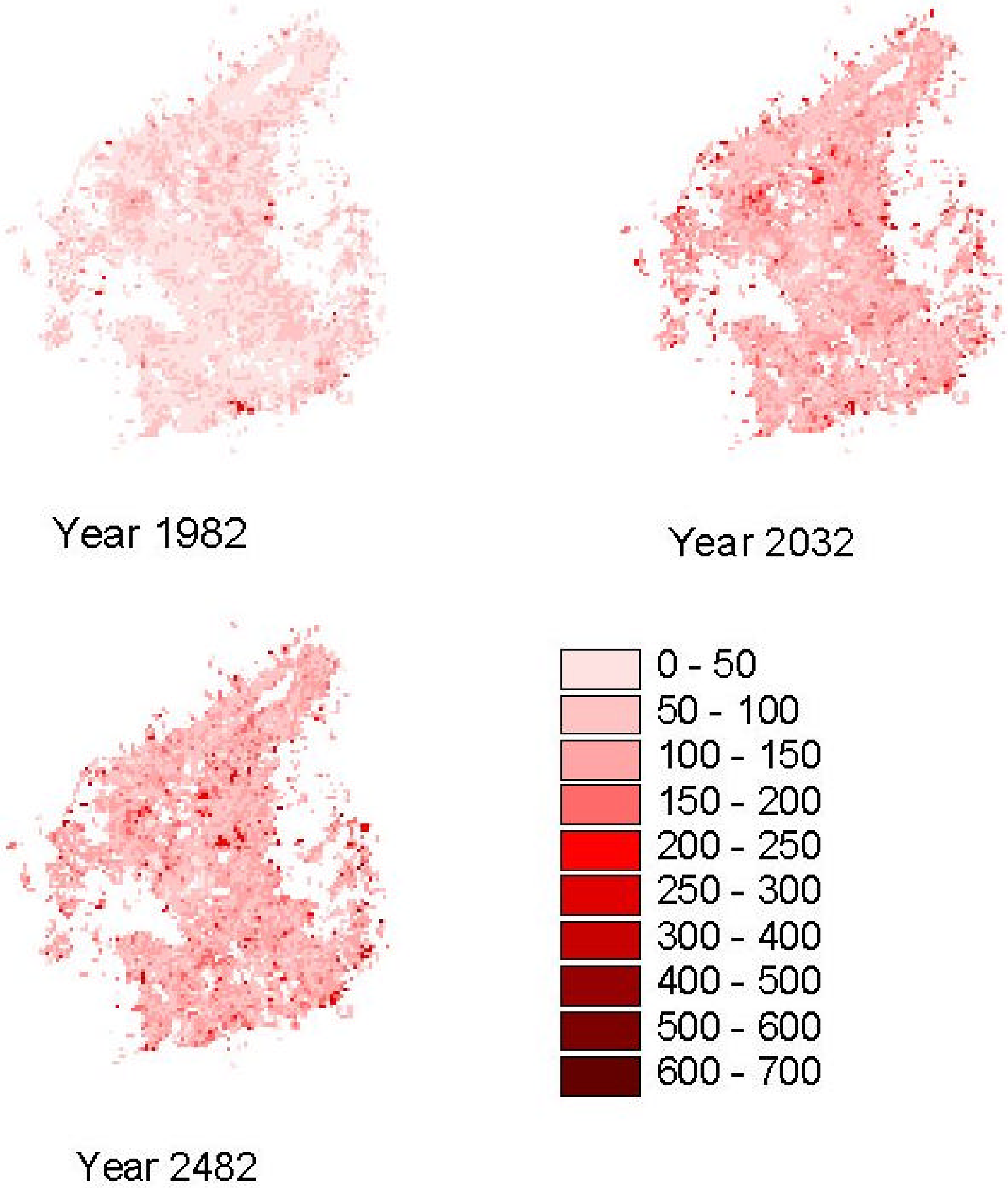

Figure 3.3 Total carbon stock in the biomass in 1982, 2032 and 2482, in Mg C ha^{-1}.

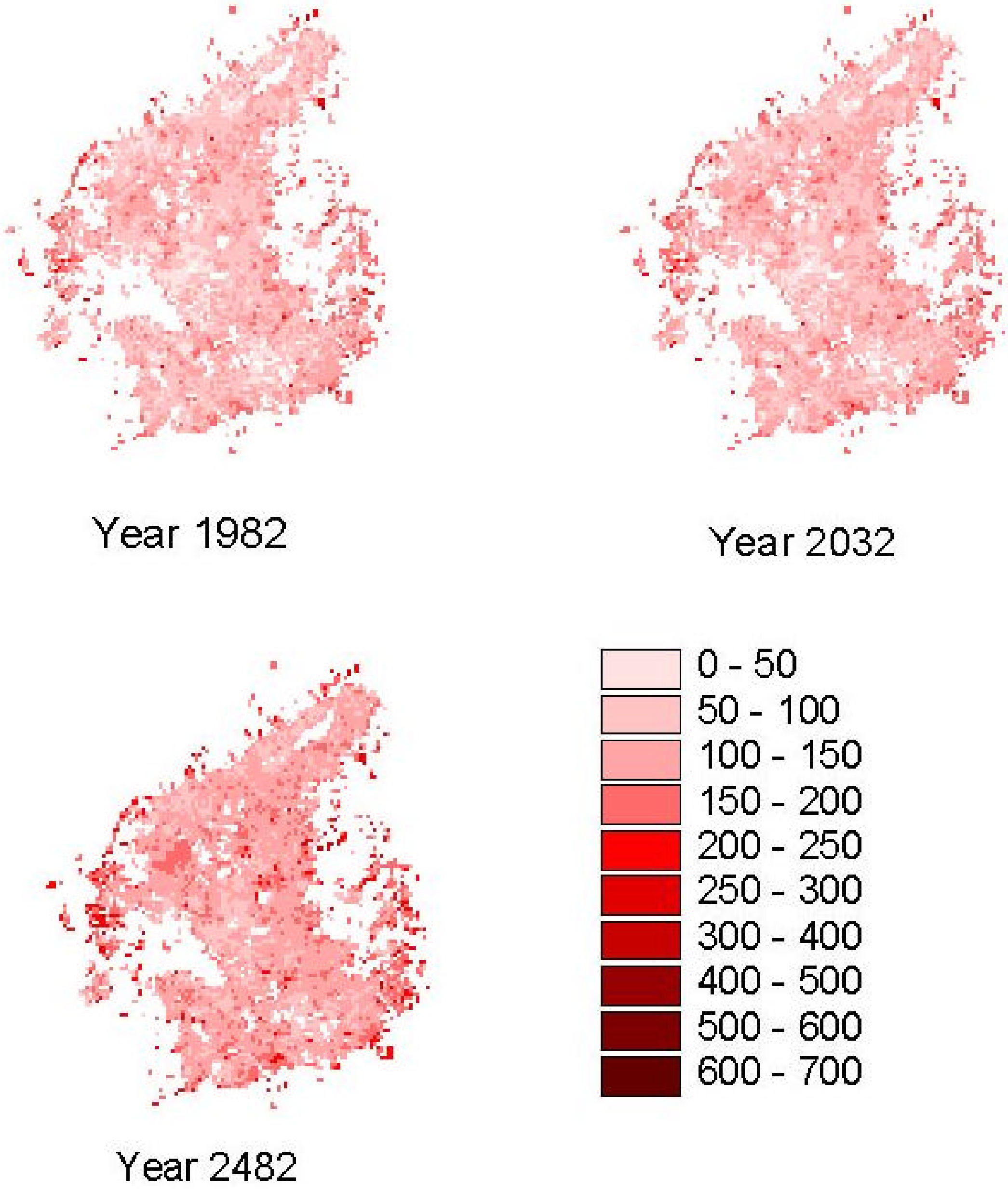

Figure 3.4 Total carbon stock in the soil in 1982, 2032 and 2482, in Mg C ha^{-1}.

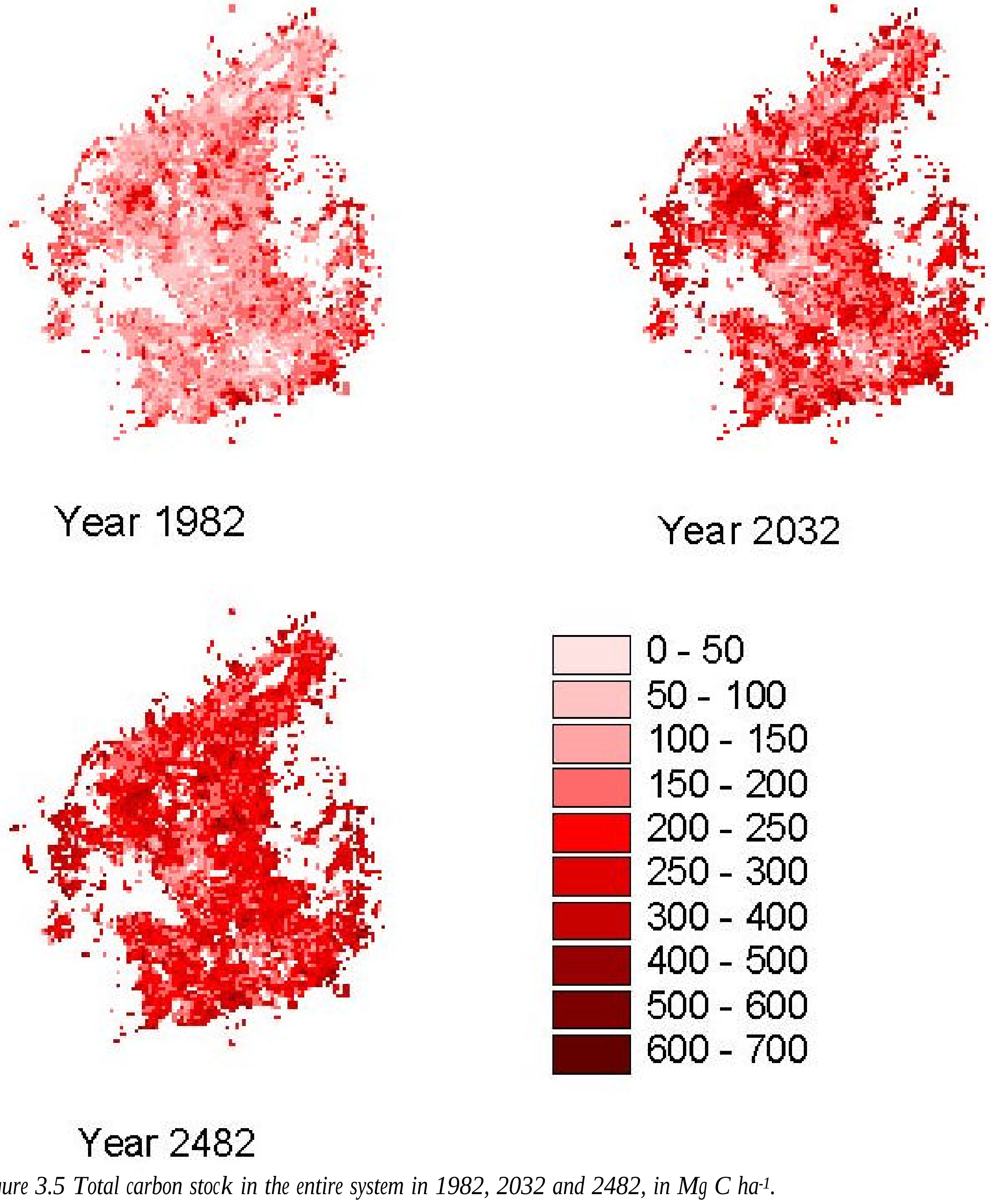

Figure 3.5 Total carbon stock in the entire system in 1982, 2032 and 2482, in Mg C ha^{-1}.

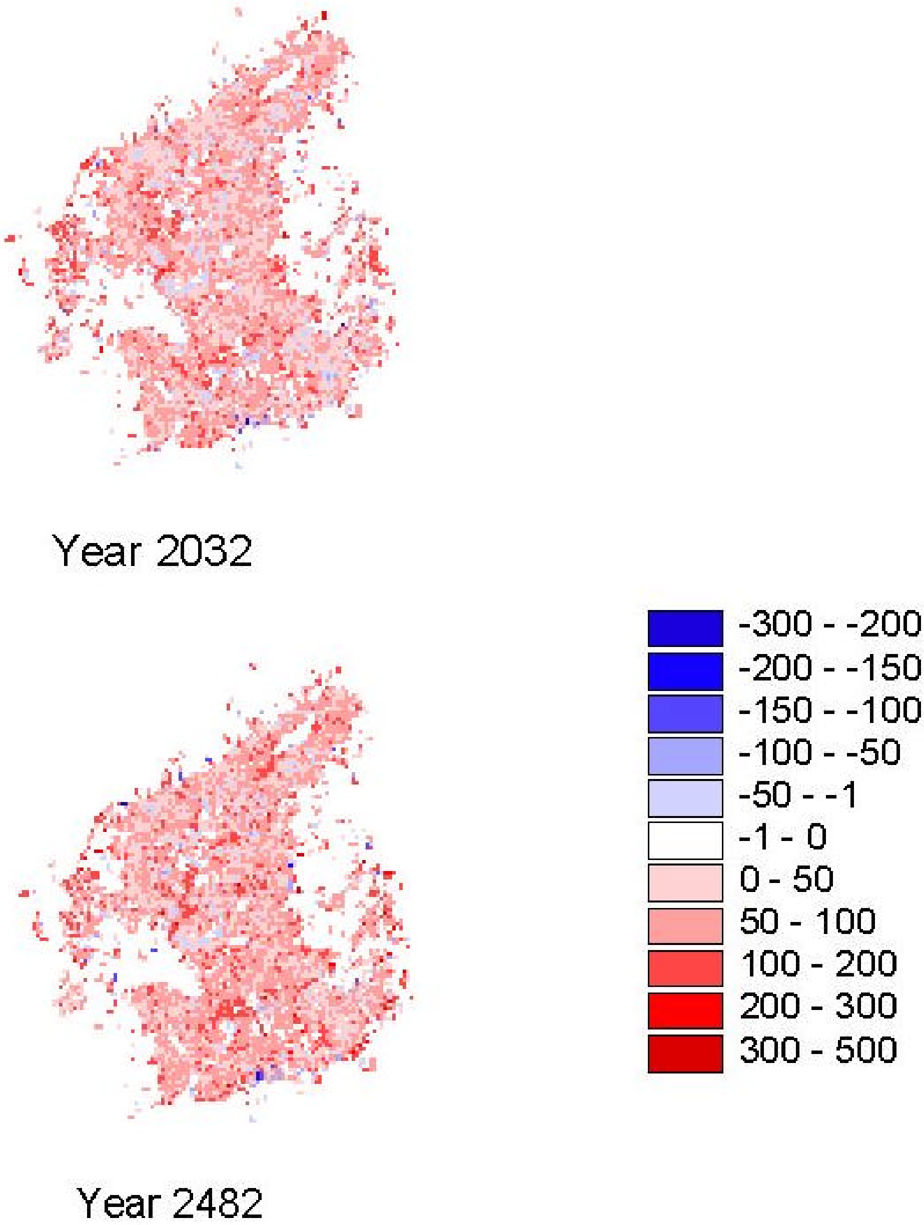

Figure 3.6 Total carbon source or sink in the biomass in the period 1982-2032 and 1982-2482, in Mg C ha^{-1}. Negative values indicate a source, positive a sink.

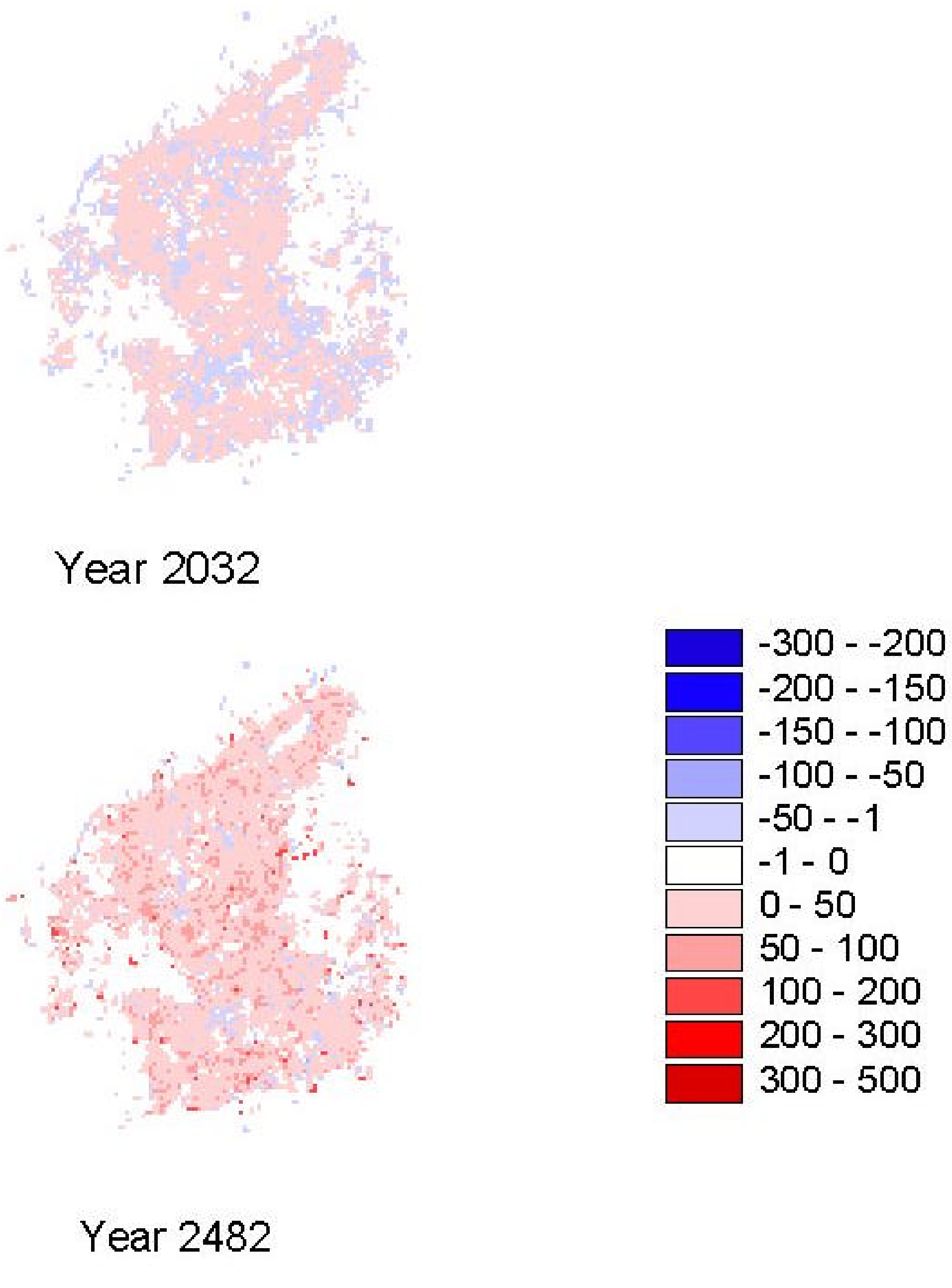

Figure 3.7 Total carbon source or sink in the soil between 1982-2032 and 1982-2482, in Mg C ha^{-1}. Negative values indicate a source, positive a sink.

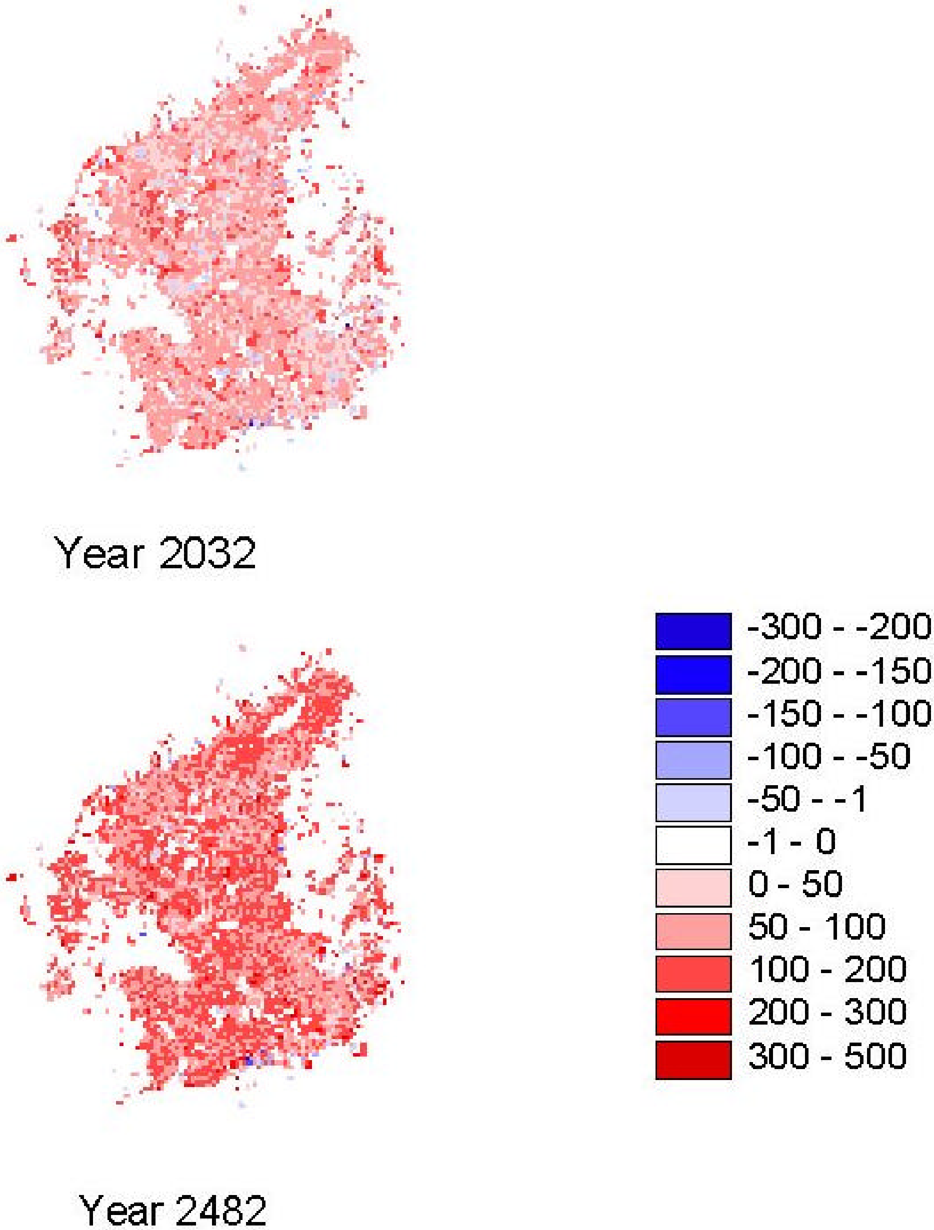

Figure 3.8 Total carbon source or sink in the total system between 1982-2032 and 1982-2482, in Mg C ha^{-1}. Negative values indicate a source, positive a sink.

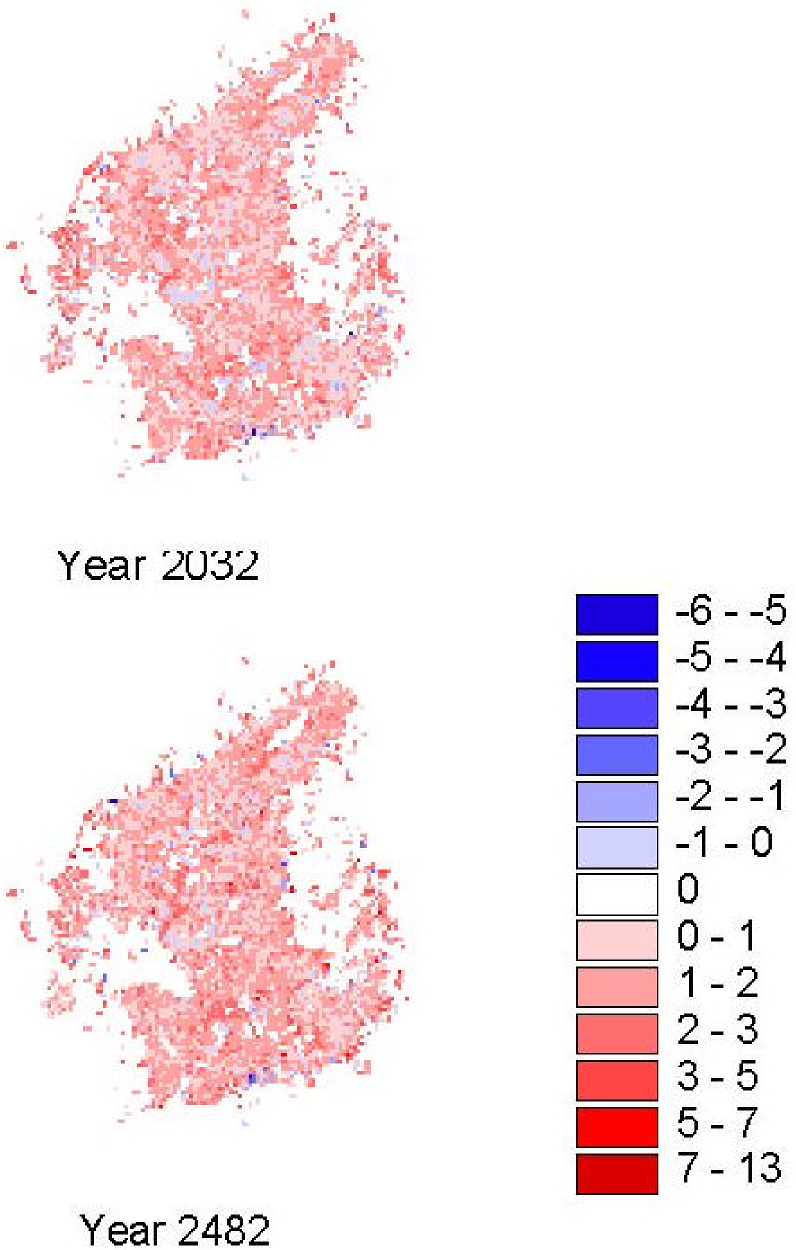

Figure 3.9 Average carbon source or sink in the biomass between 1982-2032 and 1982-2482, in Mg C ha^{-1} year^{-1}. Negative values indicate a source, positive a sink.

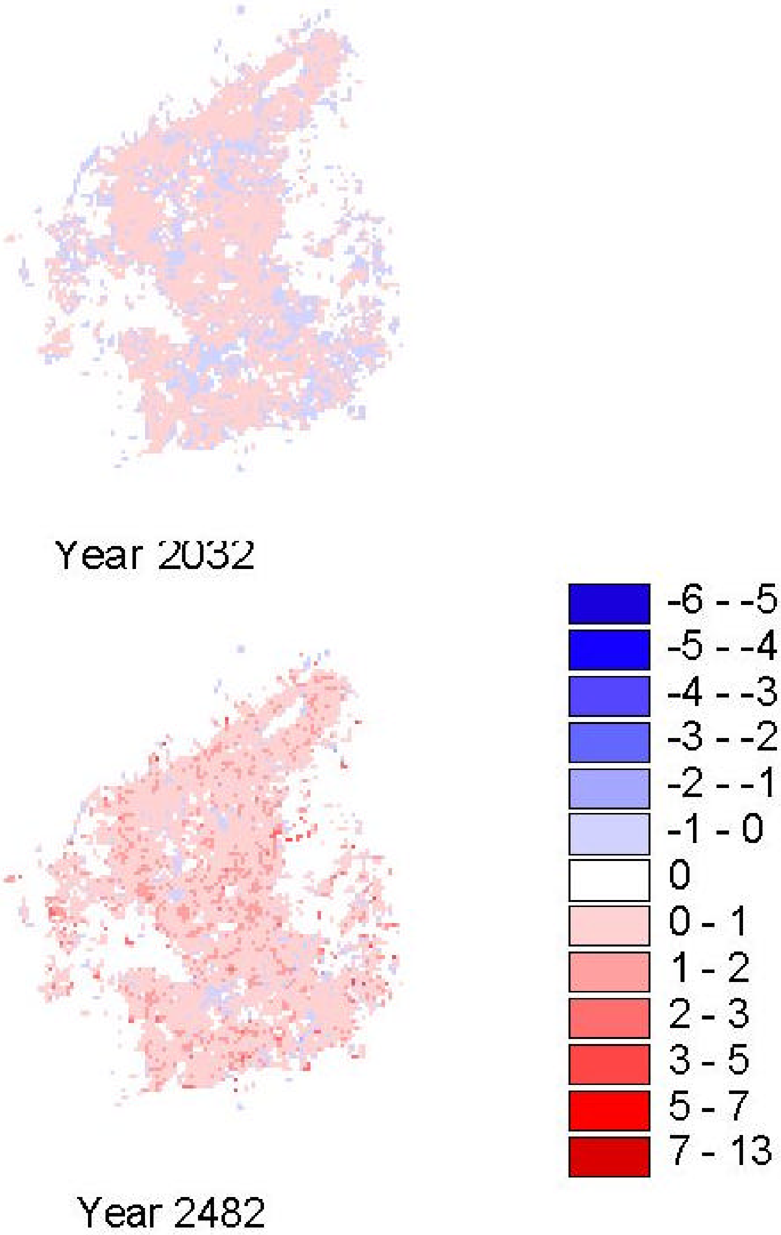

Figure 3.10 Average carbon source or sink in the soil between 1982-2032 and 1982-2482, in Mg C ha^{-1} year^{-1}. Negative values indicate a source, positive a sink.

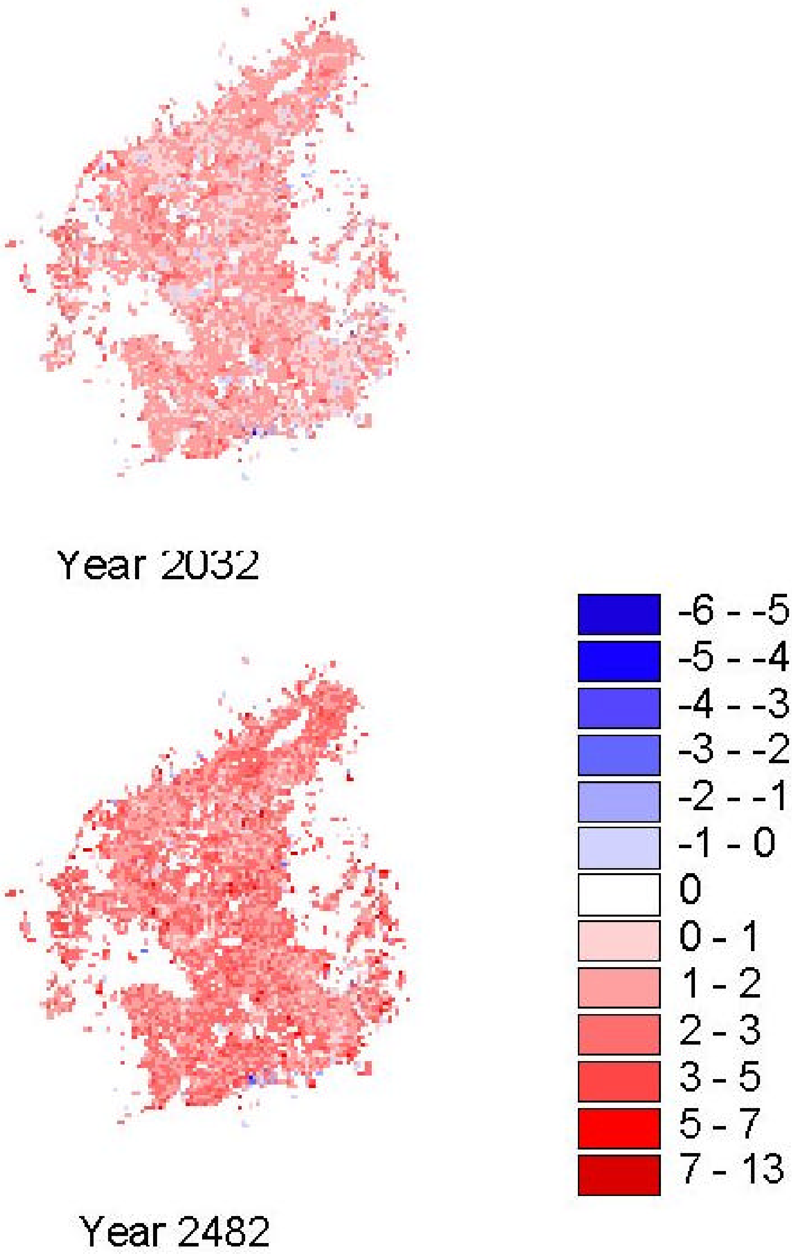

Figure 3.11 Average carbon source or sink in the entire system between 1982-2032 and 1982-2482, in Mg C ha^{-1} year^{-1}. Negative values indicate a source, positive a sink.

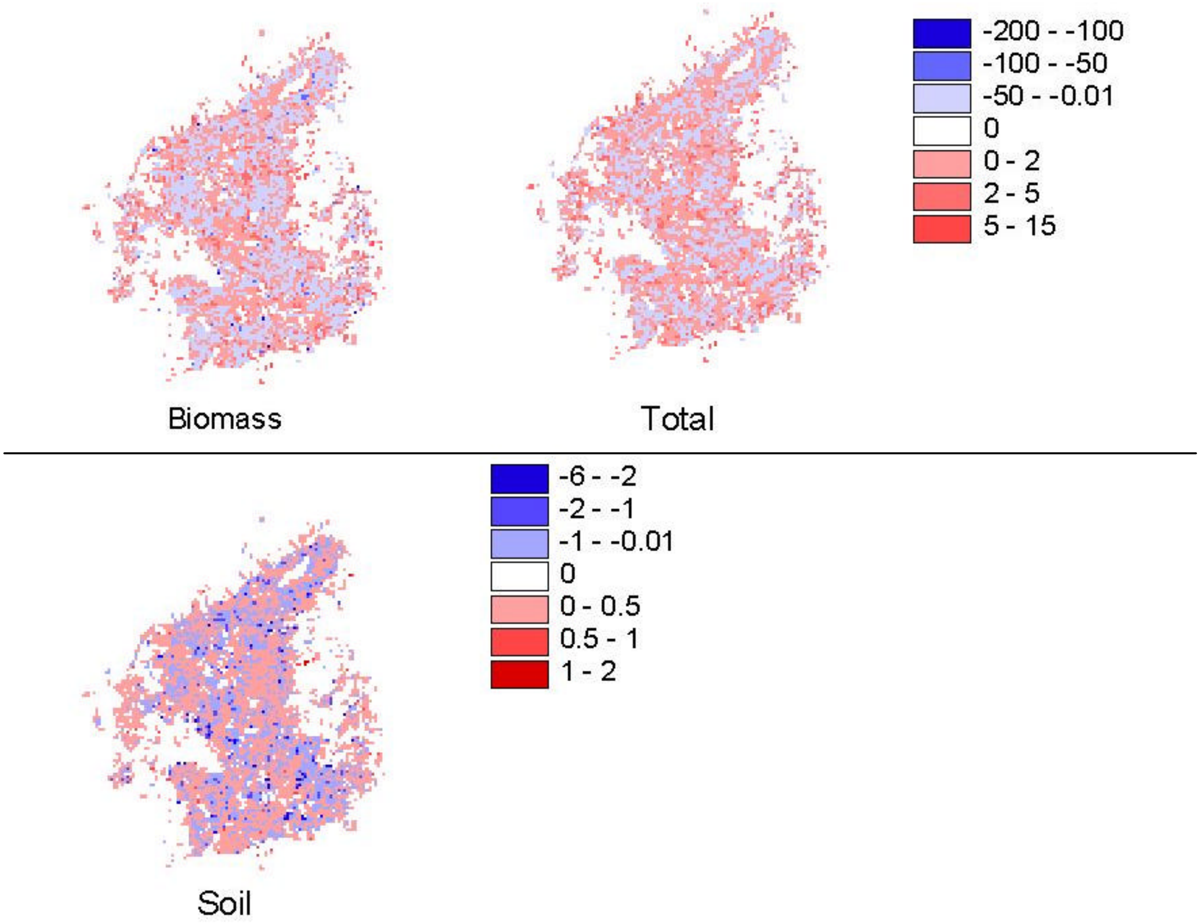

Figure 3.12 Annual carbon flux in the biomass, soil and the entire system in 2027, in Mg C ha^{-1} $year^{-1}$. These are the averages for each pixel, which may usually consist of some 10 stands. Large effluxes which may occur in a single stand after a harvest (up to –80 Mg C ha^{-1} $year^{-1}$), are therefore always somewhat compensated by the other (regrowing) stands in that pixel. Negative values indicate a source, positive a sink.

4 Discussion

4.1 Accuracy of predictions of carbon sequestration by CO2FIX

Errors in forest resource projections (and thus C balances) have two main sources (Kangas 1997):
a. the stochastic character of the estimated model coefficients;
b. measurement errors in the data or lack of data used for model construction.

Re a. In nature, an enormous variability occurs. This variability still exists within one clearly defined forest type and is the result of e.g. growth variation between years caused by weather circumstances, intra-species genetic differences, and site quality variation. This natural variability is not captured by CO2FIX because it very much relies on fixed input data from yield tables that can be seen as some sort of complete, and perfectly managed forests. Other stochastic events are management irregularity and risks caused by e.g. storm and fire. These events are not captured either. Furthermore natural variability occurs in carbon content of dry matter, basic wood density, litter and humus decomposition rates.

When parametrising CO2FIX this variability is usually dealt with by trying to find the average or median value of a parameter. Only when multiple runs are carried out in which the natural variability in e.g. growth rates, carbon content, and humus decomposition is captured, then CO2FIX provides insight in this type of uncertainty.

In the simulation, it is assumed that growth rates will stay constant. In reality, several factors can influence the future increment. As can be seen in figure 2, soil carbon is increasing, which is an effect of recovery of the soil after severe degradation in the past. This recovery will also lead to improved growing conditions for the trees (higher water and nutrient availability). Also climate change can lead to increased increments, due to higher temperatures, a longer growing season and through a CO_2 fertilisation effect. A combination of detailed stand level models and a large scale scenario model indicated a possible increase in increment of 0.9 m^3 ha^{-1} $year^{-1}$ on a European level (Nabuurs et al., In prep.). There are more and more indications that increment rates are changing already, but the causes are still not clear (Spiecker et al., 1996). Increased growth rates will probably lead to higher average carbon stocks. Due to increased litter production also the soil carbon build-up could go faster, but due to higher temperatures also the litter decomposition could increase.

In this study, some simplifications have been made, which will affect the accuracy of the outcome as well. It is assumed that all stands of a certain species are managed according to an average, fixed schedule. In reality, management will differ, depending on the forest owner and his goals, and on the actual condition of a stand. When a certain diameter size is set as goal, final felling will take place earlier on rich sites than on poor sites. When the goal is more aimed at nature conservation, final felling will be delayed or even not be carried out at all.

Further, CO2FIX is not able to take into account succession. At the moment, a lot of Scots pine stands are being invaded slowly by birch and oak. In the CO2FIX model, these stands will just be represented by Scots pine, without paying attention to the understory. Also after final harvest the stands will be regenerated in the model with Scots pine, while in reality part of the present regeneration of other species will be used, and also additional broadleaves after natural regeneration. The present management is more and more aiming at an unevenaged and mixed forest, which is not accurately modelled by the present version of the CO2FIX model.

Re b. CO2FIX relies heavily on net annual increment data from yield tables. These tables are based on long-term measurement series in permanent plots and/or forest inventories. In these measurement series, errors and/or bias can occur. Usually these errors are very small. Both forest inventories and yield tables are generally seen as very reliable. Tomppo (1996) gives standard errors of some characteristics of the National Forest Inventory in Finland: forest land area 0.4%, growing stock 0.7%, and increment 1.1%. However, we saw in this study that the volume estimation of the Fourth Dutch Forest Statistics was not very accurate, because the main aim of this inventory was to provide figures on the forest area and not on volume.

Also the accuracy of the yield tables can be questioned. As pointed out by Schoonderwoerd and Daamen (1996), increment at higher ages is underestimated by the yield tables of Jansen et al., which will affect the carbon sink in the biomass at higher ages and via the litter production also the sink in the soil at the long run.

However, where input data for CO2FIX rely on few measurements or a single series, uncertainty in the predictions will increase very much. This type of uncertainty especially exists in the soil pools.

Van der Voet (in: Nabuurs and Mohren 1993) carried out an uncertainty analysis of the model CO2FIX. He specified input uncertainties in the form of simultaneous input distributions for an even-aged forest type. The 100 simulations with randomly chosen values of input gave an average total carbon stock of 316 Mg C ha^{-1}. The standard deviation was 12% and the 95% confidence interval was 254-403 Mg C ha^{-1}. He concluded that it was mainly the litter and humus coefficients and the carbon content that determined this uncertainty, but in general it was mainly the natural variability rather than a lack of data that determined the overall uncertainty.

4.2 Comparison with other studies

One of the goals of this study was to compare different methods of estimating stocks and fluxes. Within the total project, Schelhaas and Nabuurs (2001) converted forest inventory data to carbon stocks and fluxes with the help of biomass expansion factors. They arrived at an estimated average carbon stock in the forest biomass of 76.87 Mg C ha^{-1} for the whole of The Netherlands, based on forest inventory data of 1985-1992. The average carbon stock over that period in our study is 81.9 Mg C ha^{-1} (including the initial correction of biomass), which lies within the range. Their estimated annual flux (having deducted harvest) was 0.55 Mg C ha^{-1}. Over the same period, we found an annual flux of 0.32 Mg C ha^{-1}. The difference may partly be explained by the fact that the Veluwe consists of relatively poor sites, with lower production and by the fact that the yield tables used in the current study might underestimate the current increment. Schelhaas and Nabuurs also mention that the biomass expansion factors they use are mostly established for scaling up standing volume to biomass. When these are used for upscaling increment (NEP) figures, it is assumed that also the other tree components will increase, while in reality at older ages they do not . Therefore the estimate of Schelhaas and Nabuurs could be an overestimation.

Within the carbon map for Europe produced in the overall project, soil carbon is derived from the FAO soil database (FAO/UNESCO 1981). This results in an estimate of 35.4 Mg C ha^{-1} for soils under coniferous forests in the Netherlands, within the first meter of soil and excluding the litter layer. Our estimate of the soil carbon stock lies around 90 Mg C ha^{-1}, but this includes the litter layer and dead wood. The depth of sampling varies, but lies generally within the same range. The carbon content in soil organic matter is about 58% (Nabuurs and Mohren 1993). When we convert in this way table 2.4 to carbon stocks, we find for almost all soil types a higher stock than this 35.4 Mg C ha^{-1}. Why these figures differ so much is not clear, and needs further study. A reason could be that the FAO soil map, relies on relatively few pedon descriptions, and may thus be inaccurate for local landscape scale studies. On the other hand, Nabuurs and Mohren (1993) and thus also the current study, relies on standard Dutch pedon descriptions, not necessarily for forest soils only. The latter study may have overestimated the carbon stock in soils.

The study of Nabuurs and Mohren (1993) for the whole of the Netherlands is used in our study to initialise the soil compartment, but can also be used for comparison of the biomass compartment. They found an average carbon stock in the living biomass of 59 Mg C ha^{-1}, based on data of 1991. This is considerably lower than our simulated 82.7 Mg C ha^{-1} in the same year.. The standing stock at the Veluwe is slightly higher than the total average (see Results section), but this cannot explain this large difference. Probably the cause lies in the expansion factors that have been used. Their estimated annual sink (with harvest deducted) amounts to 1 Mg C ha^{-1} $year^{-1}$, while we found 0.32. The underestimation of the increment by the yield tables contributes partly to the difference, but cannot explain the whole gap.

At the Veluwe near Kootwijk, flux measurements above the canopy of a Scots pine forest have been carried out (Valentini et al. 2000). In the period 1995-1999, the average annual flux (NEP) measured was 2.1 Mg C ha^{-1} $year^{-1}$. Over the same years, our average over the Veluwe area was 0.56 Mg C ha^{-1} $year^{-1}$, but without taking into account the forest products. So this is only the change in carbon stock of soil and biomass over that period. In the forest that has been measured, no harvesting has taken place. Moreover, this is only a measurement in a short period of the total lifespan of only one stand. This one measurement can therefore not be regarded as representative of the whole Veluwe area. On the other hand, 50% of the whole area consists of Scots pine. The stand in which Valentini et al. did their measurements, was planted in 1904 and thus increment can be expected to be below the average of the whole Veluwe area. Therefore, the difference seems to be high, but this is a more often observed feature between flux measurements and inventory-based methods. A more detailed study on the measured and modelled stand could be helpful to explain this difference.

5 Conclusion

When we correct for the underestimation of biomass in the beginning of the simulation, the amount of carbon stored in the biomass is fluctuating between 80 and 100 Mg C per hectare, depending on the age class structure. However, the average amount stored in the biomass is increasing slightly during the simulation. In the short term, there is a rather fast increase of carbon in the biomass due to the increasing age of the forest, but in the long term the sink saturates.

Due to the recovery of the soil after degrading activities in the past, the amount of carbon stored in the soil is slowly but steadily increasing. Over the whole simulation length of 500 years soil carbon increases with more than 30 Mg C ha^{-1}, which is an increase of about 36%.

At the moment, the carbon storage in the soil is slightly higher as in the living biomass, 90 and 80 Mg C ha^{-1} respectively. After 500 years the carbon stock in the biomass has increased to 100 Mg C ha^{-1}, in the soil to about 125 Mg C ha^{-1} and in the forest products compartment to 10 Mg C ha^{-1}.

These conclusions must be seen in the light of the underlying assumptions and simplifications of this study. Especially the fixed forest management in the model will deviate from the expected forest management, which is aimed at a more unevenaged and mixed forest.

The differences between various approaches and studies are the largest for the soil carbon stock, ranging from 35.4 to 90 Mg C ha^{-1}, and the total carbon sink, ranging from 0.32 to 1 Mg C ha^{-1} $year^{-1}$. Estimates of the carbon stock in the biomass show less difference, ranging from 59 to 82.7 Mg C ha^{-1}.

As shown by this study, a large variability exists within an average figure for a region or a country, which is caused by management activities and also depends on the actual state of the forest. The history of the forest plays an important role in the total carbon balance. In our study a build up of soil carbon stock is found, as a result of recovery after degrading activities in the past. Also the increase of forest biomass in the first decades of the simulation must be contributed to the history of the region, where a lot of reforestation has taken place. Therefore, we can conclude that it is also important at which point in time we look at, both in determining the actual stock and sink, but also for the development and possibilities into the future.

6 Recommendations

In order to have a better representation of the current trends in forestry, the CO2FIX-landscape model should be adapted so that also unevenaged and mixed stands can be simulated. Also a more diverse management system should be incorporated, allowing for differences between forest owners and sites. In that way alternative management regimes and baseline issues and additionality can be addressed.

Another adaptation to the model could be the incorporation of climate change effects on both increment and soil respiration. In the current study, soil types are deducted in a rather rough way from the actual site class per tree species. An improvement could be made by using digital geo-referenced soil maps instead.

The current study only aimed at the forested part of the Veluwe area. In order to make a full landscape scale carbon budget, other landuse types should be taken into account as well. With minor modifications, CO2FIX is able to simulate carbon budgets of grasslands and agricultural crops as well. By using landuse maps, a carbon budget of every landscape can be made. With such a tool it will also be possible to simulate the effects of changes in landuse, like afforestation or deforestation. In that way CO2FIX-landscape can fulfil an important role in practical issues surrounding project level carbon sequestration projects. Such projects are already being established at many places around the world.

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Appendix 1 Brief soil type description

Soil type	
Vlierveen	Peat soil, often drained, with a peat layer of more than 25 cm on a sandy acid soil.
Holtpodzol	Loamy, brown, rich sandy soil with some gravel in pushed-up glacial material
Veldpodzol	Moist, acid, poor sandy podzolic soil
Haarpodzol	Dry acid, poor sandy podzolic soil
Enkeerdgrond	Dry sandy soil, with a thick (> 25 cm) layer rich in organic matter, which was brought up in former agricultural system
Laarpodzol	Dry acid, poor sandy podzolic soil
Beekeerd	Moist to wet, acid poor sandy soil, top layer rich in organic matter
Vlakvaag	Very poor sandy / gravelly soil of which the soil profile has been eroded by wind
Duinvaag	Very poor sandy soil in the inland dune system. These soils consist of the deposits of soil profiles eroded from elsewhere and therefore contain some organic matter (0.5%) throughout the soil depth.