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Carbon in Dutch Forest Ecosystems

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Abstract

The present stock of carbon in living biomass, litter and stable humus and the annual accumulation of carbon in the stems of fifteen forest types has been quantified from inventory data on growth and standing volume, and forest soil information in combination with literature data on forest biomass. The study was carried out within the framework of the Dutch National Research Programme on Global Air Pollution and Climate Change. The forest area in the Netherlands equals about 330 000 ha. It mainly consists of young plantations of conifers such as Scots pine, Douglas-fir and larch on poor, dry sandy soils. The average age is approximately 50 years. The present average standing volume is 170 m^3 ha^{-1} and the average volume increment was 9.0 m^3 ha^{-1} yr^{-1} over the period 1984-1989. At present, approximately 63.7 Mt C is stored in the entire forest, including dead organic matter in the forest soil. Almost 60% of this is stored in the stable humus in the soil compartment. The average carbon stock in the stable humus is 113 Mg C ha^{-1}, whereas only 59 Mg C ha^{-1} is contained in the living biomass and 19 Mg C ha^{-1} is contained in the litter layer. The average stock in the living biomass is largest for beech stands with 124 Mg C ha^{-1}. Annually, about 0.66 Mt C of atmospheric carbon is stored by means of stem volume increment when harvesting is not considered. On average, for the entire forested area, at present about half of the annual storage is harvested each year, which means that the forest at present acts as a net carbon sink to the amount of approximately 0.33 Mt C yr^{-1}. At present, the largest net accumulation is attained in beech stands, and amounts to 1.8 Mg C $ha^{-1}yr^{-1}$. The average net accumulation for the entire forested area amounts at present to some 0.97 Mg C $ha^{-1}yr^{-1}$. Long rotations with species like oak, beech and Douglas-fir which may build-up a large standing biomass and which produce durable wood products, are most suitable for a long-term storage of carbon.

Keywords: CO_2, carbon dioxide, climate change, carbon storage, sequestration, biomass, soil organic matter, litter, humus, forest growth and yield.

Introduction

Through the increase of the atmospheric carbon dioxide concentration, the natural greenhouse effect is enhanced and global climate may change (Houghton et al. 1990). Forests will be vulnerable because their life cycle is long and their adaptation to changes in the environment is slow (Mohren, 1990; Prentice et al. 1991). Forests and forest soils may on the other hand be able to counteract the greenhouse effect, because they are the largest pool of carbon of the biosphere (Milleman & Boden 1985 and 1986, Bouwman 1990, Goudriaan 1987, Dixon et al. 1991). Growing forests and new afforestations may sequester atmospheric carbon dioxide (Kauppi et al. 1992, Dewar & Cannell 1992, Freedman et al. 1992). Thus, knowledge of carbon stocks and flows in forest ecosystems is required to study vegetation-climate interactions as part of the carbon cycle, and to evaluate policy options aimed at counteracting CO_2 emission.

The aim of this study is to quantify the present stocks and flows of carbon in the main forest ecosystems in the Netherlands. Twelve forest types of the standing forest and three other forest types have been identified on the basis of the 4th National Forest Inventory (Anon., 1985). For each forest type the following parameters have been quantified: present stock of carbon in living biomass, litter and stable humus, and annual accumulation of carbon in the stems through volume increment. Increase in stem biomass is the main element of carbon accumulation in forest ecosystems. Roots, foliage and branches do accumulate carbon temporarily, approaching an equilibrium carbon pool size sometime after canopy closure, when increment equals turnover losses. Accumulation of carbon in stem biomass is taken here as representative for total accumulation in the system. For a more detailed treatment in which turnover of other biomass components is taken into account, see Mohren & Klein Goldewijk (1990a, b). Harvesting has been taken into account only superficially. Decomposition of litter and of stable humus has not been taken into account explicitly, but rather an equilibrium situation in the soil was assumed. Thus, overall build-up or decomposition of total soil organic matter was ignored.

After the method is outlined, a short description of the Dutch forests, forest soils and forest types will be given. The calculations will be discussed more extensively using one particular forest type as an example. Finally, the overall results for the total Dutch forest will be presented and discussed.

Method

The calculations were based on existing forest inventories of the forested area, on the distribution of the various forest types over the soil types and on inventories of standing volume and growth together with literature data on biomass measurements, basic wood density, carbon content and soil organic matter content.

Based on the 4th National Forest Inventory (Anon., 1985), four terrain types and twelve forest types of the standing forest were used, based on the main tree species in the stand. These forest types cover 85% of the total forested area of the Netherlands which amounts to 330 000 ha in total. Table 1 gives the area distribution of the forest types considered.

The present standing volumes for each type of standing forest were derived from the latest growth inventory, in which 1220 plots have been remeasured over a period of 5 years, starting in 1984. This inventory contains the latest and most accurate figures available (Anon., 1991). Although the volume data include bark, basic wood density has been applied (Laming et al., 1978; Dixon et al., 1991) to obtain stem dry weight. By using a ratio of stem dry weight to total dry weight derived from literature data (Cannell, 1982; Kimmins et al., 1985) total biomass dry weight was estimated from stem dry weight. Using a carbon content of 50% (Ajtay et al., 1977) the carbon stock of the total biomass was calculated (Table 2).

For those tree species which were not considered separately in the growth inventory (mainly species of less economic importance), best guesses of the standing volume were made based on yield table volumes at average age in an average site class. For the terrain types spontaneous forest, coppice and natural regeneration forest (together comprising 18% of the forest area) best guesses of the standing volume were made based on the species composition. It was assumed that the standing volume of the three terrain types spontaneous forest, coppice and natural regeneration forest was 80%, 50% respectively 60% of the volume recorded for a corresponding standing forest type.

The distribution over the soil types of the standing forest types was derived by combining the digital 4th National Forest Inventory with the digital soil map of the Netherlands, scale 1 : 50 000 (data provided through pers. comm. to W. De Vries, Winand Staring Centre, Wageningen). For each combination of soil type and tree species of the standing forest the relative site class from Schütz & Van Tol (1982) was combined with the growth assessment from the growth inventory (Table 3, Anon., 1991), together with existing yield tables and data from permanent sample plots from the Institute for Forestry and Nature Research (pers. comm. to E. Dik, Institute for Forestry and Nature Research, Wageningen). Together with basic wood density and a carbon content of 50%, a gross annual carbon accumulation through volume increment was estimated for each forest type and site (Table 4). In this flux calculation, harvesting was ignored. To arrive at a total net carbon budget, harvesting and decomposition of harvested products, should be accounted for, but this was not attempted as accurate data on product life-time were lacking.

Stocks of carbon in the stable humus were calculated from organic matter content estimates per soil horizon of each soil type. These figures, together with bulk density measurements (Hoekstra & Poelman, 1982), average soil horizon thickness from general profile descriptions (Beuving, 1984) and a humus carbon content of 58% (Buringh, 1984) resulted in stocks of carbon in the stable humus (Table 5). Forest floor carbon stocks were derived from representative forest floor dry weight measurements from various literature sources (Cannell, 1982; De Vries et al., 1990; Kimmins et al., 1985), using a litter carbon content of 50% (Ajtay et al., 1977) (Table 6). In case of soil carbon in either litter or stable humus, equilibrium conditions were assumed thereby ignoring any net build-up or decrease of soil organic matter. Obviously, this will not be the case when arable land is afforested, but was done here for reasons of simplicity.

Results

Forest inventory data

In Table 1, the area of each tree species per forest terrain type is presented based on

Table 1. Area of the Dutch forest distinguished according to terrain type and tree species (ha) (Anon., 1985).

Terrain types (Anon., 1985):

Standing for.:	Standing forest: forests with a crown pojection of 60% and more, usually managed in clearfellings.
Spontaneous:	Closed forests developed through natural regeneration of trees in open areas with no active management.
Coppice:	Closed forests with vegetative regeneration on the stumps after clearfelling, it can either be outgrown coppice or still be managed as coppice.
Nat. reg. forest:	Natural regeneration forest: open forests with a crown projection of 20 to 60%, developed through natural regeneration of trees on open areas.

Tree species[1]:	ps	pn	pm	lk	pa	oc	qr	fs	pe	sa	fc	ag	bp	qru	od	Grand total
Terrain type:																
Standing forest	98213	16302	15722	18015	13262	5829	27084	7150	14333	947	3411	967	5506	5124	2732	234624
Spontaneous	15112	*	0	0	*	432	1566	0	*	488	*	748	5387	63	88	23970
Coppice	0	0	0	0	0	0	13114	*	*	3873	751	2328	1804	153	218	22250
Natural reg. forest	5010	*	*	0	0	0	1006	*	*	937	*	353	5290	21	87	13084
Total	118335	16302	15722	18015	13262	6261	42770	7150	14333	6245	4162	4396	17987	5361	3125	278679

[1] ps: *Pinus sylvestris* (Scots pine)
pn: *Pinus nigra* var. *maritima* & var. *nigra* (Corsican pine & Austrian pine)
pm: *Pseudotsuga menziësii* (Douglas-fir)
lk: *Lariks kaempferi* (Japanese larch)
pa: *Picea abies* (Norway spruce)
oc: other conifers (sitka spruce, hemlock, grand fir)
bp: *Betula pendula* (birch)
qru: *Quercus rubra* (red oak)
od: other deciduous species (sycamore, wild cherry)
qr: *Quercus robur* and *Quercus petraea* (indigenous oak)
fs: *Fagus sylvatica* (beech)
pe: *Populus* spp. (poplar species)
sa: *Salix alba* (willow)
fe: *Fraxinus excelsior* (ash)
ag: *Alnus glutinosa* (alder)

* Area too small to be relevant here (usually only a few hectares)

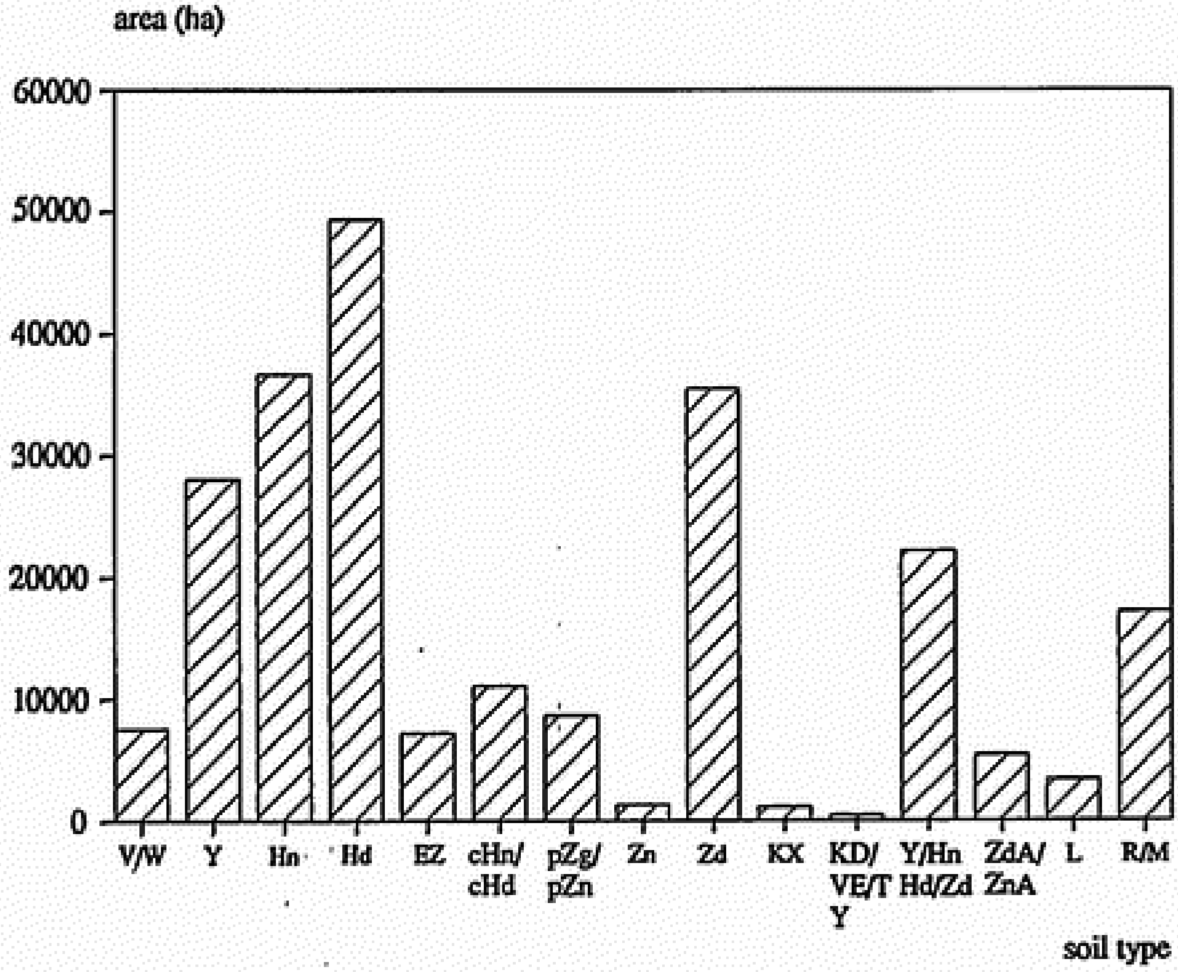

Fig. 1. Distribution of the area of standing forest of the Netherlands over the soil types (see appendix for the FAO soil type).

the 4th National Forest Inventory (Anon., 1985). The four terrain types represent 85% of the total afforested area of the Netherlands. The standing forest of Scots pine is the most important forest type as it covers almost 40% of the total afforested area. Figure 1 gives the distribution of the standing forest of the Netherlands over the soil types considered. It is clear that the Dutch forest is concentrated on a limited number of poor, dry sandy soils, notably the gleyic, humic and leptic Podzols (Y, Hn & HD) and the albic Arenosols (Zd). According to the inventory data, the average standing volume was 170 m^3ha^{-1} and the average stem volume increment over the period 1984-1989 was 9.0 $m^3ha^{-1}yr^{-1}$ (Anon., 1991).

Example: carbon stocks and flows in standing forest of oak

The standing forest of indigenous oak in the Netherlands consists mainly of pedunculate oak (*Quercus robur*) with some sessile oak (*Q. petraea*). Already at the first afforestations with the establishment of private estates, pedunculate oak was the preferred tree species. Later, during the large scale afforestations oak was established on a wide range of soils. This explains the fairly even distribution over the germination decennia (Fig. 2) and the distribution over a wide range of soil types (Fig. 3). The total area of standing forest of indigenous oak is approximately 27 000 ha and the average age of the stands is 60 years. Photo 1 presents a typical stand of pedun-

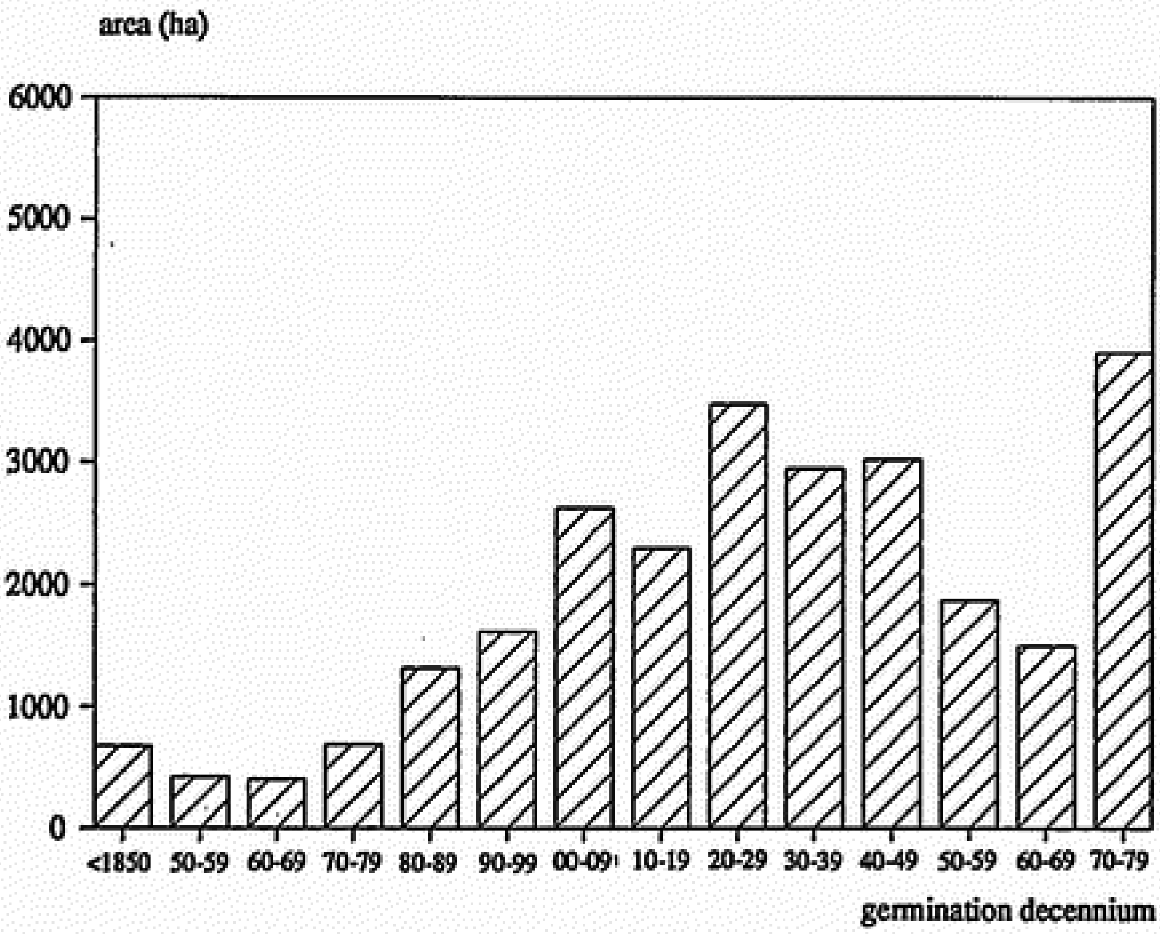

Fig. 2. Distribution of the area of standing forest of pedunculate oak in the Netherlands over the germination decennia.

culate oak with a potential to produce high quality wood.

Carbon stock in the living biomass. According to the HOSP-inventory (Anon., 1991), the present average standing volume is 187 m^3 ha^{-1} in the standing forest of indigenous oak. At a wood density figure of 545 kg m^{-3} (Laming et al., 1978) this results in a total stem dry weight of 101.9 Mg ha^{-1}. At the present average age of oak, about 61% of the total living biomass can be assumed to be stored in the stems (Cannell, 1982), giving an estimate of total biomass dry weight of 167 Mg ha^{-1}. At a carbon content of 50% and a total area of 27 084 ha this results in a total carbon stock in standing forest of oak of 2.26 10^6 Mg C.

Annual accumulation of carbon in the stems. The distribution of oak over the soil types (Figure 3) was combined with the relative site class per soil type (Schütz & Van Tol, 1982). These were coupled to the actual average growth of 7.0 $m^3ha^{-1}yr^{-1}$ according to the growth inventory (Anon., 1991) and the yield table for pedunculate oak in Sevenster (1993) after Oosterbaan (1988). This resulted in growth estimates for sites of good, moderate and limited fertility of 9.0, 7.0 and 5.0 $m^3ha^{-1}yr^{-1}$ respectively (see Table 3 & 4). The results of the growth inventory of oak matched very well with the current increment at the average age of 60 years on a moderate site class in the yield table, where a current increment of 6.8 $m^3ha^{-1}yr^{-1}$ is indicated.

Photo 1. Example of a good growing stand of pedunculate oak in the Netherlands on a relatively wet site. The age is estimated at 70 yrs; current volume increment is approximately 8 $m^3 ha^{-1} yr^{-1}$.

Table 4 gives the summary calculations resulting in a total gross carbon accumulation of 51 10^3 Mg C yr^{-1} through volume increment of oak. The average gross accumulation per unit of area is 1.87 Mg C $ha^{-1} yr^{-1}$ (harvesting not accounted for).

Carbon stock in the stable humus. The carbon stocks in the stable humus of the soil types were found as is described before (Table 5). Humus dry weight was multiplied by 0.58 to obtain the total stock of carbon (Ajtay et al., 1977; Schlesinger, 1984). Under oak, the stock of carbon in the stable humus compartment was estimated to be 3.0 10^6 Mg C, taking into account the distribution over the soil types (Fig. 2). The average stock per hectare is 111 Mg C (Fig. 4).

Carbon stock in the litter layer. From various literature sources, the amount of dry matter of the litter layer at the forest floor in oak forest was estimated at an average of 55 Mg ha^{-1} (e.g. De Vries et al., 1990; Kimmins et al., 1985). At a carbon content of 50%, this equals 27.5 Mg C ha^{-1}, and 0.74 10^6 Mg C for the entire area of oak (27084 ha, see Table 6).

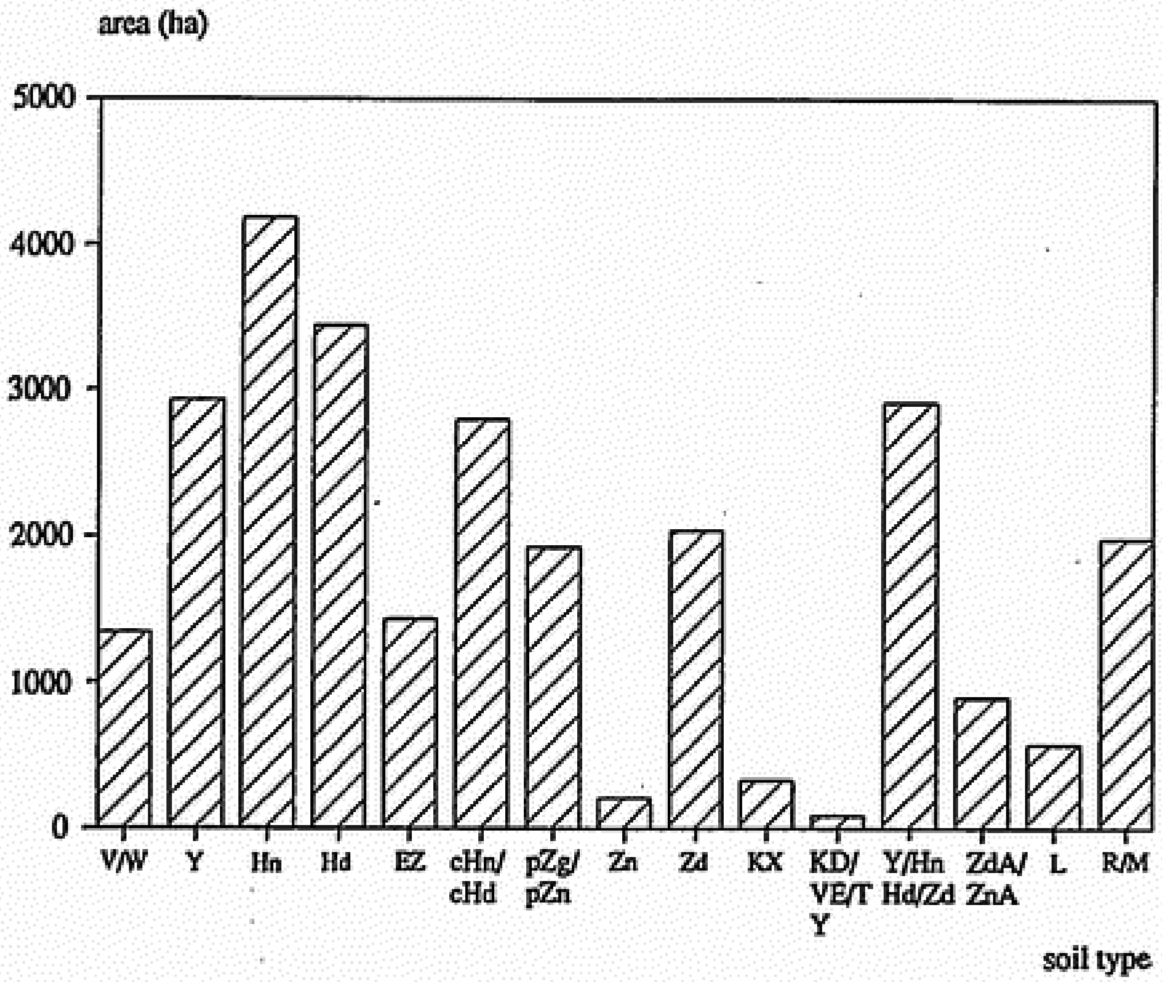

Fig. 3. Distribution of the area of standing forest of pedunculate oak in the Netherlands over the soil types.

Carbon stocks and flows for the entire forest area

For the other forest types, carbon stocks in the living biomass were quantified in the same way as was described above for oak. The results for all forest types are presented in Table 2. Estimated rates of carbon accumulation in the stem biomass are given in Table 4, using current average stem volume increments as given in Table 3.

For the 280 000 ha in Table 1, the stock of carbon in the living biomass amounts to 15.87 10^6 Mg C. Of this, Scots pine forest stores about one third, 5.44 10^6 Mg, mainly because of the large area occupied by Scots pine stands. It appears that at present beech holds the largest amount of dry weight, and thus of carbon, per hectare. This is due to the large average standing volume which beech has obtained (285 m^3 ha^{-1}). The stock of carbon for beech is 124 Mg C ha^{-1}, where the average for all forest types together is 59 Mg C ha^{-1}. Other tree species having a large standing stock of carbon are indigenous oak and red oak with 84 and 89 Mg C ha^{-1}, respectively. Poplar stands, sometimes considered to be efficient carbon storers because of their high growth rate on fertile sites, contain only 36 Mg C ha^{-1}. This is due to the short rotations, resulting in a relatively small average stock of carbon. Thus, although growth rate maybe high, the average amount of carbon stored is low due to the relatively short period in which accumulation of biomass is allowed to take place.

Table 2. Standing volume, dry weight and carbon stocks in the living biomass of the distinguished Dutch forest types.

	Area (ha)	Standing volume ($m^3 ha^{-1}$)	Wood density ($kg m^{-3}$)	Stem dry weight ($Mg ha^{-1}$)	Stems as % of total dry weight (%)	Total biomass dry weight ($Mg ha^{-1}$)	Total dry weight per forest type (10^6 Mg)	Total carbon stock per forest type (10^6 Mg C)
Reference	1	2	3,4	5				6
Forest type								
P. sylvestris	98 213	168	442	74.3	67	110.9	10.9	5.44
P. nigra	16 302	160	442	70.7	66	107.1	1.74	0.87
P. menziesii	15 722	197	460	90.6	78	116.2	1.83	0.92
L. kaempferi	18 015	187	480	89.8	73	123.0	2.22	1.11
P. abies	13 262	177	362	64.1	59	108.6	1.44	0.72
Q. robur	27 084	187	545	101.9	61	167.0	4.52	2.26
F. sylvatica	7 150	285	579	165.0	66	250.0	1.79	0.89
P. x euramericana	15 280	150	357	53.6	75	71.5	1.09	0.55
F. excelsior	3 411	110	463	50.9	65	78.3	0.26	0.13
A. glutinosa	967	100	370	37.0	72	51.4	0.06	0.03
B. pendula	5 506	130	480	62.4	69	90.4	0.49	0.25
Q. rubra	7 856	200	545	109.0	61	178.7	1.41	0.70
Spont. forest	23 970	124	420	52.1	67	77.8	1.87	0.93
Coppice	22 250	80	482	38.6	61	63.3	1.41	0.70
Natural reg.	13 084	86	458	39.4	68	57.9	0.76	0.38
Total	278 679							15.87

References: 1: Anon., 1985; 2: Anon., 1991; 3: Laming et al. 1978; 4: Bosshard 1974; 5: Cannell 1982, Kimins et al. 1985; 6: Assuming a carbon content of dry weight of 50%, Ajtay et al. 1977.

Table 3. Average current stem volume increment of the tree species at the present average age in the Dutch forest ($m^3 ha^{-1} yr^{-1}$) on the soil types considered (Anon., 1991, Schütz & Van Tol 1982, Anon., 1985, Sevenster 1993, pers. comm to E.J. Dik). See Table 1, note 1, for abbreviations of the tree species; see Appendix A for the FAO names of the soil types.

Soil type:	Tree species											
	ps	pn	pm	lk	pa	qr	fs	pe/sa	fe	ag	bp	qru
'Vlier' peat (V/W)	6	8.5	9	7	17	7	8	14	10	8		
'Holt' podzol (Y)	8.5	11.5	17	15	13	7	16	9	7	6		
'Veld' podzol (Hn)	8.5	11.5	13	11	13	7	12	9	7	6		
'Haar' podzol (Hd)	6	8.5	13	11	9	5	8	9	7	6		
'Enk' earth (EZ)	8.5	11.5	17	15	17	9	16	14	10	8		
'Laar' podzol (cHn/cHd)	8.5	11.5	13	11	17	7	12	14	7	8		
Black 'beek' earth (pZg/pZn)	6	11.5	13	11	17	7	12	14	10	10		
'Vlak' vague (Zn)	6	8.5	9	7	9	5	8	9	7	6		
'Duin' vague (Zd)	6	8.5	13	11	9	5	8	9	7	6		
Boulder loam (KX)	6	11.5	9	7	13	7	12	9	7	6		
'Krijt' earth (KD/VE/T)	*	*	*	*	13	7	12	14	7	6		
Associations (Y/Hn/Hd/Zd)	6	8.5	13	11	13	7	12	9	7	6		
Sea dune 'vlak' vague (ZdA/ZnA)	*	11.5	*	*	*	7	12	9	10	8		
Rade 'brick' (L)	*	11.5	*	*	*	9	16	14	13	10		
'Polder' vague (R/M)	*	8.5	*	*	*	9	12	18	13	10		
Average											7	7
Current increment at average age on moderate site according to the yield tables	6.4	12.1	14.3	8.7	15.0	6.8	12.1	12.7	8.1	8.5	5.5	5.4
HOSP growth inventory data	6.8	9.5	13.1	11.6	13.5	7.0	12.8	14.6	8.4	8.4	8.4	8.4
Average of all recordings of available sample plots	10.0	13.1	12.5	11.3	16.8	#	#	13.5	#	#	#	7.1

*: Area too small. #: No or only very few recordings.

The current volume increments presented in Table 3 combined with the distribution of the tree species over the soil types allow estimation of the total annual carbon flow associated with accumulation of stem biomass. Results in Table 4 indicate an annual sequestration of 0.56 10^6 Mg C yr^{-1} through stem volume increment in 85% of the Dutch forest. Assuming this to be representative for the other 15% as well, the total annual sequestration can be estimated at 0.66 10^6 Mg C yr^{-1}. The average annual carbon accumulation amounts to 1.99 Mg C per hectare. These figures are gross values as carbon removal through harvesting and subsequent release through decomposition was not accounted for sofar. Most of the wood is used for paper and packing wood and most likely will decompose within a few years. Taking into account that at present half the current increment is harvested annually (Anon., 1991), net accumulation of carbon through volume increment and accumulation of stem biomass amounts to 0.33 10^6 Mg C yr^{-1}.

Table 4. Current carbon accumulation through stem biomass increment, using the distribution of the forest types over the main soil categories, and the relative site class per soil type, resulting in the area per site class (column 3). References 1: Anon., 1985, and pers. comm. to W. De Vries; 2: Anon., 1991; 3: Laming 1978; 4: Bosshard 1974; 5: carbon content of the dry weight biomass is 50% (Ajtay et al. 1977) (The data given in the table for the total area per tree species can be slightly different from those in Table 1 and 2 because of different data-base origin, and due to rounding errors when converting afforested area to standing forest per soil type.

	Relative site class	Area (ha)	Current volume incr. ($m^3 ha^{-1} yr^{-1}$)	Wood density ($kg\ dw\ m^{-3}$)	Stem dry weight increment ($Mg\ ha^{-1} yr^{-1}$)	Total stem dw increment for the total area ($10^3\ Mg\ yr^{-1}$)	Present annual carbon sink in total biomass ($10^3\ Mg\ C\ yr^{-1}$)
Reference		1	2	3,4			5
Forest type							
P. sylvestris	I	34 963	8.5	442	3.75	131.1	65.6
	II	61 803	6.0	442	2.65	163.8	81.9
	III	1 443	3.5	442	1.55	2.2	1.1
P. nigra	I	6 378	11.5	442	5.08	32.4	16.2
	II	9 922	8.5	442	3.76	37.3	18.7
	III	2	5.5	442	2.43	0.05	0.02
P. menziesii	I	4 030	17.0	460	7.82	31.5	15.8
	II	11 211	13.0	460	5.98	67.0	33.5
	III	482	9.0	460	4.14	2.0	1.0
L. kaempferi	I	3 264	15.0	480	7.20	23.5	11.8
	II	13 470	11.0	480	5.28	71.1	35.6
	III	1 282	7.0	480	3.36	4.3	2.2
P. abies	I	2 401	17.0	362	6.15	14.8	7.4
	II	6 899	13.0	362	4.71	32.5	16.2
	III	3 960	9.0	362	3.26	12.9	6.5
Q. robur	I	3 994	9.0	545	4.91	19.6	9.8
	II	17 405	7.0	545	3.82	66.5	33.2
	III	5 886	5.0	545	2.73	16.1	8.0
F. sylvatica	I	2 477	16.0	579	9.26	22.9	11.5
	II	2 968	12.0	579	6.95	20.6	10.3
	III	1 706	8.0	579	4.63	7.9	3.9
P. × eur-americana	I	8 096	18.0	357	6.43	52.1	26.0
	II	4 001	14.0	357	5.00	20.0	10.0
	III	3 183	9.0	357	3.21	10.2	5.1
F. excelsior	I	1 963	13.0	463	6.02	11.8	5.9
	II	936	10.0	463	4.63	4.3	2.2
	III	511	7.0	463	3.24	1.7	0.8
A. glutinosa	I	278	10.0	370	3.70	1.0	0.5
	II	476	8.0	370	2.96	1.4	0.7
	III	212	6.0	370	2.22	0.5	0.2
B. pendula	II	5 506	7.0	480	3.36	18.5	9.3
Q. rubra	II	7 856	7.0	545	3.82	30.0	15.0
Spont. forest	II	23 970	5.0	420	2.10	50.3	25.2
Coppice	II	22 250	8.4	482	4.05	90.1	45.1
Natural reg.	II	13 084	7.1	458	3.25	42.5	21.3
Total		288 268					557.5

Table 5. Dry weight and carbon stock of the stable humus for each soil type.

Soil type	Stable humus dry weight (Mg ha^{-1})	Carbon stock in stable humus (Mg ha^{-1})
'Vlier' peat	733	425
'Holt' podzol	226	131
'Veld' podzol	182	106
'Haar' podzol	185	107
'Enk' earth	314	182
'Laar' podzol	127	74
'Beek' earth	130	75
'Vlak' vague	28	16
'Duin' vague	84	49
Boulder loam	127	74
'Krijt' earth	63	37
Associations	168	97
Sea dune 'vlak' vague	92	53
'Rade' brick	106	61
'Polder' vague	137	79

The largest carbon accumulation per hectare can be obtained in beech forests on sites of good fertility, giving a gross carbon flux of 4.64 Mg C ha^{-1}yr^{-1}. Beech is followed by Douglas-fir on good sites with 3.92 Mg C ha^{-1}yr^{-1}. These are gross rates for the best sites (relative yield class I), and the net carbon accumulation for the total area of beech, accounting for 50% harvest, amounts to 1.8 Mg C ha^{-1}yr^{-1}.

Table 5 gives the estimated carbon stocks in the stable humus for the soils considered here, as calculated from standard soil profile descriptions. For more detail see Nabuurs and Mohren (1993). Table 6 summarizes the total stock of carbon in the biomass, the forest floor and the stable humus. The total stock of carbon in the 280 000 ha considered here amounts to 54.2 10^6 Mg C. This is stored in living biomass (15.87 10^6 Mg), litter (7.0 10^6 Mg), and stable humus (31.3 10^6 Mg), and refers to 85% of the Dutch forested area. Assuming the same average for the remaining area, the carbon stock in the total afforested area can thus be estimated to be 63.7 10^6 Mg C. Of this, almost 60% is stored in the stable soil humus. On average, an amount of 113 Mg C ha^{-1} was contained in stable soil organic material. The stocks of soil carbon on the impoverished soils like the 'Vlak' vague and 'Duin' vague soils (Arenosols and Albic Arenosols, respectively) are relatively small due to the previous intensive sod cutting and resulting wind erosion.

An overall graphical representation of the stocks of carbon is given in Fig. 4. From Fig. 4 the importance of the stable humus in the soil is obvious for all forest types. This stock differs per forest type because of different distributions over the soil types. Since birch and alder are concentrated on the peaty soils, the stock of stable humus is larger under these forest types. Scots pine stores most carbon because of its large area. The stock of carbon in the litter layer is largest under Scots pine, probably because of its high average stand age and the occurrence on poor soil types with a relatively slow decomposition of litter. Spontaneous forests consist to a large extent of Scots pine also, which explains the large stock of carbon in the litter layer of this

Table 6. Total stocks of carbon (Mt C) in each forest type, separated into the living biomass, forest floor and stable humus. Respectively derived from Table 2, literature data on dry weight in the forest floor and table 5 in combination with the distribution of the species over the soil types.

	Area (ha)	Living biomass	Forest floor	Stable humus
Standing forest				
Scots pine	98 213	5.44	3.80	9.5
Austrian and Corsican pine	16 302	0.87	0.18	1.5
Douglas-fir	15 722	0.92	0.15	1.7
Japanese larch	18 015	1.11	0.26	2.1
Norway spruce	13 262	0.72	0.13	1.6
pedunculate oak	27 084	2.26	0.74	3.0
beech	7 150	0.89	0.10	0.9
poplar and willow	15 280	0.55	0.11	1.5
birch	5 506	0.25	0.06	0.9
ash	3 411	0.13	0.03	0.4
alder	967	0.03	0.01	0.2
red oak	7 856	0.70	0.11	0.5
Other forest types				
spontaneous forest	23 970	0.93	0.80	2.8
coppice	22 250	0.70	0.36	2.7
natural regeneration forest	13 084	0.38	0.20	2.0
Total (Mt C)		15.87	7.00	31.3

forest type. Forest types with a high average stand age, store most carbon per hectare in the living biomass. Examples are indigenous oak, beech and red oak. Fast growing species such as poplar, usually cultivated in relatively short rotations, contain a relatively small stock of carbon per hectare.

Discussion

Per unit of area, the stock of carbon in the living biomass in forest ecosystems is much larger than in arable crops due to the long life-span of trees in which they can accumulate carbon, especially in stems. The total stock of carbon of 63.7 10^6 Mg C for the entire forested area is relatively small when compared to the annual emission of 50 10^6 Mg C yr^{-1} (Van der Born et al., 1991). However, the present annual net accumulation of carbon in the stems (0.33 10^6 Mg C yr^{-1}) equals about 0.7% of the total emission, illustrating the level of importance of carbon fixation by means of photosynthetic assimilation by vegetation in the Netherlands.

The results of this study rely heavily on standing volume and volume increment data from the latest forest growth inventory (HOSP data; Anon., 1991). At this moment, these figures are the most reliable and up to date, although they are considerably higher than what was generally accepted for Dutch forests. The HOSP inventory data apply to the period 1984-1989, and at this moment it is unclear whether these data point to an actual increase in growth rates, as was reported for other European countries also (Kauppi et al., 1992), or whether the previous estimates were simply garded to some extent as momentary, stand and site dependent estimates. Gradually, forests reach their maximum attainable biomass and net growth declines. At present, net volume increments occur because most stands are in an early stage of development. The results given for carbon accumulation in the stems must be interpreted with care, as half of the volume increment is harvested and products decompose fairly rapidly. Annual accumulation in the branches and roots was not taken into account, because the stock of carbon in these compartments was already considered and it was assumed that no net accumulation of branch and root biomass occurs. This may have led to some underestimation of the annual accumulation. The average net annual accumulation was found to be 0.97 Mg C $ha^{-1}yr^{-1}$ on average for the entire forest, taking into account that approximately half of the increment is harvested. Wolf & Janssen (1991) give a figure of 0.66 Mg C $ha^{-1}yr^{-1}$, but as with the standing stock, their estimate was based on old increment estimates, whereas the results presented here are based on more recent information. Also this study uses the current annual increment as related to the period 1984-1989. Obviously, as the forest stands age, harvesting will increase until it is equal to overall increment. In that case, net carbon fixation will be zero.

The stock of carbon in the litter layer at the forest floor of Scots pine stands is considerably larger than for other forest types, although practically all other forest types are situated on poor, dry sandy soils as well. This difference may have been caused by the fact that the estimate for the amount of litter under Scots pine were obtained from chronosequences of stands in The Netherlands. Data for other forest types were obtained from literature sources referring to stands abroad. As the local pine litter data indicate a larger stock of carbon than indicated in foreign literature, it is possible that the stock of carbon in the litter layer under other forest types is underestimated.

The data for organic matter content in the mineral soil were derived from a series of representative soil profile descriptions from the Dutch Soil Survey Institute (Stiboka). The average stock of carbon in stable humus of 113 Mg C ha^{-1} is in agreement with results given by Milleman & Boden (1986) who mention for this stock under temperate forests figures of 110 to 120 Mg C ha^{-1}. The present stocks of stable soil humus were assumed to be in equilibrium, hence no net accumulation or decomposition is assumed. In case of afforestation of agricultural lands and in case of primary succession on sandy soils, forest development may lead to gradual accumulation of soil organic matter due to less soil disturbance and increased litter fall. At the same time, soil acidification and climate change may affect decomposition of soil organic matter, and an analysis of long-term carbon storage in a changing environment will have to take these phenomena into account. Continuing acidification is expected to affect forest ecosystem dynamics in the near future (Mohren, 1991), to the extent that growth rates will decrease through leaching of base cations and changes in pH and Aluminium status of the rooted soil, with obvious consequences for ecosystem carbon relations.

The results from this study are in agreement with results given by Mohren & Klein Goldewijk (1990a) on stocks of carbon stored on average in the long-term. In their analysis, they found for Scots pine, pedunculate oak and poplar long-term average stocks of carbon in the living biomass of 59, 99 and 35 Mg C ha^{-1}, respectively. The present stocks found in this study are 55, 83 and 36 Mg C ha^{-1}, respectively. The value found here for Douglas-fir (59 Mg C ha^{-1}) is much less than the estimate of Mohren & Klein Goldewijk (1990a), who give a value of 131 Mg C ha^{-1}. This indicates that most Douglas-fir stands are relatively young, and will continue to accumulate carbon for quite some years to come.

Implementation of the Dutch Forestry Policy Programme (Anon., 1986) and other forest expansion programmes (Anon., 1993) will have a positive effect on the storage of carbon in the Dutch forests. With longer rotations and more attention for oak, beech and Douglas-fir the stock of carbon in the living biomass will certainly continue to increase until at least well into the next century. Through elongation of the product use, the average storage may increase further, although the contribution of this to total storage is limited (Mohren & Klein Goldewijk, 1990a; Dewar & Cannell, 1992).

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References

Ajtay, G.L., P. Ketner & P. Duvigneaud, 1977. Terrestrial primary production and phytomass. In: B. Bolin, E.T. Degens, S. Kempe & P. Ketner (Eds.), The global carbon cycle. p. 129-181, John Wiley and Sons, Chichester.

Anonymous, 1985. Census of forest in the Netherlands. Volume 1: the forested area, 1980-1983. (In Dutch). Netherlands Central Bureau of Statistics, in cooperation with the Netherlands State Forest Service, Staatsuitgeverij, The Hague, 83 pp.

Anonymous, 1986. Long-term Forest Policy Plan: Statement of the Government. (In Dutch). Tweede Kamer der Staten Generaal. Vergaderjaar 1985-1986. Staatsuitgeverij, The Hague, 162 pp.

Anonymous, 1991. Harvested volume, standing stock and annual increment in the Dutch forest. (In Dutch). Report of the Supervisory Committee on 'Statistics of Wood Harvest and Prognosis of Harvestable Stemvolume', Utrecht, 15 pp.

Anonymous, 1993. Good soil for new forests. (In Dutch). Report to the Government of the Panel on Forest Expansion, 35 pp.

Beuving, J. 1984. Moisture and hydraulic conductivity characteristics, bulk density and composition of soil profiles in sandy, loamy sand, clay, and peat soils. (In Dutch). Institute for Land and Water management, Wageningen, ICW-Report nr. 10, 26 pp.

Bosshard, H.H. 1974. Holzkunde, Band 2: Zur Biologie, Physik und Chemie des Holzes. Birkhäuser Verlag, Basel, 312 pp.

Bouwman, A.F. (Ed.), 1990. Soils and the greenhouse effect. Proceedings of the International Symposium: Soils and the greenhouse effect. John Wiley and Sons, Chichester, 575 pp.

Buringh, P. 1984. Organic carbon in soils of the world. In: M. Woodwell (Ed.), The role of terrestrial vegetation in the global carbon cycle: measurement by remote sensing. p. 91-110, John Wiley and Sons, Chichester.

Cannell, M.G.R. (Ed.), 1982. World forest biomass and primary production data. Academic Press, London & New York, 391 pp.

De Vries, W., A. Hol & S. Tjalma, 1990. Literature study into stocks and residence times of mineral elements in forest ecosystems. (In Dutch). The Winand Staring Centre for Integrated Land, Soil, and Water Research, Report 94, 205 pp.

Dewar, R.C. & M.G.R. Cannell, 1992. Carbon sequestration in the trees, products and soils of forest plantations; an analysis using UK examples. *Tree Physiology* 11: 49-71.

Dixon, R.K., P.E. Schroeder & J.K. Winjum, 1991. Assessment of promising forest management practices and technologies for enhancing the conservation and sequestration of atmospheric carbon and their costs st the site level. United States Environmental Protection Agency, Office of Research and Development, Washington, EPA/600/3-91/067, 138 pp.

Freedman, B., F. Meth & C. Hickman, 1992. Temperate forest as a carbon storage reservoir for carbon dioxide emitted by coal fired generating stations. A case study for New Brunswick, Canada. *Forest Ecology and Management* 55: 15-29.

Goudriaan, J. 1987. The biosphere as a driving force in the global carbon cycle. *Netherlands Journal of Agricultural Science* 35: 177-187.

Hoekstra, C. & J.N.B. Poelman, 1982. Bulk density of soils, measured for the most common soil types in the Netherlands. (In Dutch). Soil Survey Institute (Stiboka), Wageningen, report nr. 1582, 47 pp.

Houghton, J.T., G.J. Jenkins & J.J. Ephraums, 1990. Climate Change: the IPCC Assessment. Cambridge University Press, Cambridge, 365 pp.

Kimmins, J.P., D. Binkley, L. Chatarpaul & J. de Catanzaro 1985. Biogeochemistry of temperate forest ecosystems: literature on inventories and dynamics of biomass and nutrients. Petawawa National Forestry Institute, Canadian Forestry Service, Information Report PI-X-47 E/F. 227 pp.

Kauppi, P.E., K. Mielikäinen & K. Kuusela 1992. Biomass and Carbon budget of European forests, 1971-1990. *Science* 256: 70-74.

Laming, P.B., J.F. Rijsdijk & J.C. Verwijs 1978. Timber types, information for practical applications. (In Dutch). Houtinstituut TNO, Delft, 390 pp.

Milleman, R.E. & T.A. Boden 1985. Major world ecosystems ranked by carbon in live vegetation: a database. Carbondioxide Information Center, Oak Ridge National Laboratory for the US Department of Energy, Oak Ridge, 164 pp.

Milleman, R.E. & T.A. Boden 1986. Worldwide organic soil carbon and nitrogen data. Oak Ridge, Carbon-dioxide Information Center. Oak Ridge National Laboratory for the US Department of Energy, Oak Ridge, 136 pp.

Mohren, G.M.J. 1990. Effects of climate change on forests and forestry. (In Dutch). In: W.J. Wolff (Ed.), Report of a workshop held at 2 October 1990 at Wageningen, on the Report of Working Group II of the Intergovernmental Panel on Climate Change. (In Dutch), p. 40-48. Institute for Nature Management, Arnhem, Leersum, Texel, report nr 90-21.

Mohren, G.M.J. 1991. Integrated effects. In: G.J. Heij & T. Schneider (Eds.), Acidification Research in the Netherlands, Final report of the Dutch Priority Programme on Acidification, p. 387-464. Studies in Environmental Science 46, Elsevier, Amsterdam.

Mohren, G.M.J. & C.G.M. Klein Goldewijk 1990a. CO_2-fixation in forests. Forestry in the Netherlands as a means within the framework of the climate/CO_2-problem. Research Institute for Forestry and Urban Ecology, 'De Dorschkamp', Wageningen, Report nr. 613, 86 pp.

Mohren, G.M.J. & C.G.M. Klein Goldewijk 1990b. CO_2FIX: A dynamic model of the CO_2-fixation in forest stands – Model documentation and listing. Research Institute for Forestry and Urban Ecology 'De Dorschkamp', Wageningen, Report nr. 624, 96 pp.

Nabuurs, G.J. & G.M.J. Mohren 1993. Carbon stocks and fluxes in Dutch forest ecosystems. Institute for Forestry and Nature Research, Wageningen. IBN Research Report 93/1, 85 pp.

Oosterbaan, A. 1988. Yield table of pedunculate oak (Quercus robur L.). (In Dutch). Research Institute for Forestry and Landscape Planning 'De Dorschkamp', Wageningen, Extended Report nr. 22(1), 31 pp.

Prentice, I.C., M.T. Sykes & W. Cramer 1991. The possible dynamic response of northern forests to global warming. *Global Ecology and Biogeography Letters*, 1991: 129-135.

Schlesinger, W.H. 1984. Soil organic matter: A source of atmospheric CO_2. In: M. Woodwell (Ed.), The role of terrestrial vegetation in the global carbon cycle: measurement by remote sensing. John Wiley and Sons., Chichester.

Schütz, P.R. & G. van Tol (Ed.) 1982. Establishment and management of forests and plantations. (In Dutch). Research Institute for Forestry and Landscape Planning 'De Dorschkamp', Wageningen, 504 pp.

Sevenster, J. (Ed.) 1993. Yield tables for the main tree species in the Netherlands. (In Dutch). In preparation.

Van der Born, G.J., A.F. Bouwman, J.G.J. Olivier & R.J. Swart 1991. The emission of greenhouse gasses in the Netherlands. National Institute of Public Health and Environmental Protection, Bilthoven, Report no. 222901003.

Wolf, J & L.H.J.M. Janssen. 1991. Effects of changing land use in the Netherlands on net carbon fixation. *Netherlands Journal of Agricultural Science* 39: 237-246.

Appendix A

Soil type according to Stiboka classification	Stiboka soil code	Soil type according to FAO
'Vlier' peat	V/W	Dystric Histosol
'Holt' podzol	Y	Leptic podzol
'Veld' podzol	Hn	Gleyic podzol
'Haar' podzol	Hd	Humic podzol
'Enk' earth	EZ	n.s.c: sandy man-made humus soil; enriched with sods
'Laar' podzol	cHn/cHd	n.s.c: Humic podzol with thin man-made humus soil
Black 'beek' earth	pZg/pZn	Humic Gleysoil
'Vlak' vague	Zn	Arenosol
'Duin' vague	Zd	Albic Arenosol
Boulder loam	KX	n.s.c: boulder clay
'Krijt' earth	KD/VE/T	Rendzina
Associations	Y/Hn/Hd/Zd	n.s.c: Small patches of varying soil orders
Sea dune 'vlak' vague	ZdA/ZnA	Calcaric Arenosol
Rade 'brick'	L	Orthic Luvisol
'Polder' vague	R/M	Eutric Fluvisol

n.s.c.: no suitable category.