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Institute for Economics

Quantification and Monetary Valuation of Carbon Storage in the Forests of Germany in the Framework of National Accounting

by

Matthias Dieter and Peter Elsasser

BFH

Bundesforschungsanstalt für Forst- und Holzwirtschaft

Federal Research Centre for Forestry and Forest Products

and the

Chairs of Wood Biology,
Wood Technology and World Forestry of the

University of Hamburg

Bundesforschungsanstalt für Forst- und Holzwirtschaft Hamburg
Address: Leuschnerstr. 91, D-21031 Hamburg
Postal address: Postfach 80 02 09, D-21002 Hamburg
Phone: 049-40 / 73962-301; Fax: 049-0 / 73962-317

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Contents

Abbreviations and definitions

Statistical terms

SNA	System of National Accountings
ESA	European System of Accounting
n.a.	not available

Forest terms

dm	dry matter
DBH	diameter at breast height
o.b.	over bark
u.b.	under bark
FFI	Federal Forest Inventory
FDB	Forest Data Bases
srb	short rotation broadleaves (birch, alder, poplar, willow etc.)
lrb	long rotation broadleaves other than beech and oak (ash, maple, lime, elm etc.)
cw	coarse wood (stems and branches with at least 7 cm diameter over bark, measured at the thin end)
sw	small wood (branches and twigs under 7 cm diameter over bark)
rb	root biomass
ab	aboveground biomass
n	Needles

Others

t	Tons
Mt	mega tons
CO_2e	carbon dioxide equivalent

Note: Language not checked.

Acknowledgements

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1 Carbon Stocks and Carbon Stock Changes in German Forests and Forest Soils in Physical Terms

1.1 Introduction

Up to now, only a few goods and services of forests are included in the Systems of National Accounts (SNA) and the European System of Accounting (ESA). They may be accounted directly (such as timber or game) or indirectly (such as noise protection services expressed in higher real estate values). Other services such as water purification can be deemed to be included in the gross added value if the producers of market products, i.e. drinking water, capture a resource rent. Otherwise these services are not included in the national accounts. From a welfare theoretical perspective their values appear in a higher consumer surplus. EUROSTAT has founded the Task Force on Forest Economic and Environmental Accounting to review the theoretical and practical possibilities to include all forest goods and services into ESA/SNA; special emphasis is given to the avoidance of double counting, and data availability restrictions have to be considered.

Since a valuation of the carbon binding service of forests is in essence merely a multiplication of volumes and prices, the valuation of this specific service was deemed to be comparatively simple and hence chosen for an appraisal. At its meeting of September 9th and 10th, 1999, the Eurostat Task Force on Forest Economic and Environmental Accounting recommended that only the total net increase in carbon storage should be taken into account for the valuation of the carbon binding services of forests.

Total net increase corresponds to the stock change between two reporting dates. Generally, stock changes can be estimated in two ways:

- **Comparison of stock inventories of different reporting dates**

  If periodical stock-inventories are available, the changes can be calculated by subtraction of the stocks of two respective reporting dates. If necessary, the result can be divided by the length of the period between the inventories to result in annual changes.

- **Stock estimation and growth modelling**

  If only results of a single inventory and a single estimation of stocks are available, the changes can be assessed by using growth models .

According to the project purpose (which is a valuation of the periodical carbon binding service of forests) only short-term changes are considered in this report. Short-term changes are especially caused by anthropogenic impacts. Long-term changes due to e.g. soil evolution are not measurable annually and thus not taken into account.

1.2 Objects of investigation

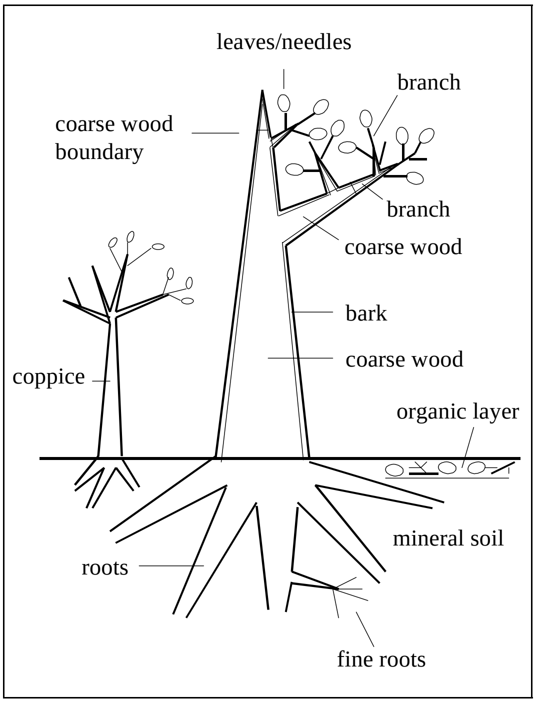
Carbon is fixed in different organic components in forests and forest soils. Figure 1 shows a classification of these components, divided into aboveground and underground items. The highlighted organic components mark the items for which data are available for Germany. These items are separately discussed below. Figure 2 shows a scheme of the relevant organic components.

Figure 1: Classification of organic components in forests and forest soils

	alive	**dead**
aboveground	coarse wood 1)	coarse wood 1)
	small wood	small wood 2)
	needles, leaves	needles, leaves 2)
	understory	understory
	herbage	herbage
underground	tree roots	tree roots
	understory roots	understory roots
	herbage roots	herbage roots
		organic layer
		humus components and compounds in mineral soil 3)
	animals	animals

highlighted components: data on Germany available
1) inclusive bark
2) dead small wood, needles and leaves are considered to be included in the figures of the humus layer
3) including perpetually renewing fine roots

Figure 2: Scheme of organic components in forests and forest soils



1.3 Data base

The amount of information on carbon stocks and stock changes in forests and forest soils varies with the different interests in the organic components of forests and with the ease of measuring them. The commercially most important product of forests is coarse wood, and the measurement of stems is much easier than that of underground components. Due to both reasons, data availability on coarse wood is rather good; national inventories and growth models exist for coarse wood which are, in the majority of cases, differentiated for tree species and site classes. Much fewer data are available for the stocks and stock changes of branches, foliage, roots, and soil biomass.

Up to now, there is no harmonised data base concerning forest area and coarse wood stock volumes for Germany. Prior to the reunification, forest area, coarse wood stock volumes, tree species distribution and other relevant forest key figures of the old *Laender* have been surveyed by the Federal Forest Inventory (FFI) which took place in the years 1987 to 1990. For the new *Laender,* different separate Forest Data Bases (FDB, e.g. "*Datenspeicher Waldfonds"*) provide data on forest area, coarse wood stock volumes, tree species distribution and other relevant forest key figures for the reference year 1993.[1] The FFI is a sample inventory with a geographical raster of 4 km times 4 km whereas the FDB are a collection of all inventory data of the universe of the forest enterprises in the new *Laender*. All presented above- and underground biomass estimations are related to these two inventories.

For the purposes of estimating the stocks and changes of the different kinds of organic components in German forests, the huge amount of inventory data must be summarised. All used inventory data (in particular area and coarse wood stocks) have been structured as follows:

- Even-aged forests (i.e. high forests, coppice forests, and coppice-with-standard-system forests) are stratified according to *Laender*, tree species groups, and age classes. This results in a three-dimensional table of 1872 cells (16 *Laender* x 9 tree species groups x 12 age classes of 20 years each).
- For selection forests as well as for understory and for reservation of standards, neither tree species nor age data are available from the inventories. Consequently, these groups are only stratified by 16 *Laender,* as is the case with temporary gaps ("forest area presently without forest plants").

Essential dendrometric key figures like stand height are mean values for these stratums. Small scale differences based on site classes or ownership influences have been levelled off in this way. All expansion factors on coarse wood figures, as used for the other biomass components (see the following chapters), have been applied to these strata.

1.4 Forest area

The overall forest area, estimated on base of the National Forest Inventory and the different separate Forest Data Bases amounts to 10.4 Mio. ha. Table 1 shows the forest area differentiated for the old and new *Laender* and the forest types. Areas that are viewed as forests by definition, but are not meant for timber production are not taken

[1] Currently the second Federal Forest Inventory (the second one for the old *Laender*, the first one for the new *Laender*) takes place. The results will show the forest area and state of the forests in Germany as well as the change in areas and coarse wood stocks in comparison to the first inventory.

into account. Those areas may be forest enterprise buildings, timber storing locations or Christmas tree plantations. They amount to ca. 330.000 hectares.

Table 1: Forest area [ha] for the old and new Laender according to FFI and FDB, respectively; reporting times: 1987-10-01 (FFI), 1993-01-01(FDB)

forest type	**old Laender (NFI)**	**new Laender (FDB)**	**total**
even aged forests, coppice forests, coppice-with-standard-system forests	7,191,213	2,766,422	9,957,635
forest area, at present without forest plants	38,422	42,539	80,961
selection forests	143,395	43,496	186,891
productive forest area	7,373,030	2,852,457	10,225,487
non-productive forest area	182,252	0	182,252
total forest area	**7,555,282**	**2,852,457**	**10,407,739**

Data source: BMELF, 1992, tab. 1.2, 2.1.5.10; BMELF, 1994, tab. 1.2, 1.3, 4.1

As can be seen, the most important forest types in Germany are even aged forests, coppice forests and coppice-with-standard-system forests. Among those, even aged forests hold the majority with 99 % of the area.

There have been some changes in forest area after the first Federal Forest Inventory and the reporting year of the different separate Forest Data Bases, respectively. In Germany considerable areas are deforested each year for traffic, industry and housing purposes. Vice versa, agricultural land is afforested. Additionally, there are notable subsidies for farmers afforesting marginal sites. Information on afforestation and deforestation are available for single *Laender* only. For the entire Federal Republic of Germany however, there are no consistent data on humanly induced forest area changes. The extent of natural colonisation is not reported anywhere. Hence forest area changes cannot be reliably quantified, specifically not for different forest types. Although most experts' opinion holds that Germany's forest area increases marginally altogether, we conservatively assume that the area balance remains constant over the years.

National parks and biosphere reservations include core zones in which forest management is refrained from. It has to be asked whether these areas should be neglected in a carbon balance or not. In a climax phase, unmanaged forest ecosystems show a stock flow equilibrium which would require to exclude national parks and biosphere reservation core areas from carbon change estimations. For the time being however, German national parks and biosphere reservations are only a few decades old. All those forests have been managed before they obtained protection status. Hence it can be argued that presently, even forests in the core zones of national parks and biosphere reservations still have an overall net increment and hence act as carbon sinks. Consequently, the respective forest area is not subtracted from total forest area.

1.5 Aboveground biomass

1.5.1 Coarse wood

1.5.1.1 Coarse wood conversion factors

For a consideration of forests as carbon sinks, stand volumes (m³ o.b.) must be converted into weight units (ton dry matter) at first. Table 2 shows the applied conversion factors for the respective tree species. The conversion factor of ton dry matter into ton carbon is assumed to be 0.5, without further distinction between tree species.

Table 2: Conversion factors: t dm / m³ o.b.

oak	beech	lrb	srb	spruce	fir	douglas fir	pine	larch
0.66	0.68	0.65	0.41	0.43	0.41	0.47	0.49	0.55

Source: LOHMANN, 1980, p. 26 ff.
lrb: other long rotation broadleaves, srb: short rotation broadleaves

1.5.1.2 Coarse wood stocks

As mentioned above, most information about biomass stocks and stock changes in forests are available for aboveground coarse wood components. Table 3 shows the carbon pool in standing coarse wood after conversion into tons of carbon, estimated on base of the Federal Forest Inventory and different separate Forest Data Bases, respectively.

Table 3: Coarse wood carbon stocks [1.000 t C] for the old and new Laender according to FFI and FDB, respectively; reporting times: 1987-10-01 (FFI), 1993-01-01(FDB)

forest type	old Laender (FFI)	new Laender (FDB)	total
even aged forests coppice forests, coppice-with-standard-system forests	529,561	149,349	678,910
temporary gaps	0	0	0
selection forests	12,055	2,699	14,754
understory, reservation of standards	27,222	3,478	30,700
productive forests	568,838	155,526	724,364
non-productive forests	n.a.	n.a.	n.a.
total coarse wood stock	**568,838**	**155,526**	**724,364**

Source: BMELF, 1992, tab. 2.2, 2.3, 2.1.5.1-2.1.5.9; BMELF, 1994, tab. 2.3, 4.1, 4.2, 4.3 (modified)

1.5.1.3 Coarse wood fluxes

1.5.1.3.1 Coarse wood increment

Coarse wood increment had to be estimated for the different forest types. For even aged forests, coppice forests and coppice-with-standard-system forests, yield tables have been used.[2] The yield tables have been applied to the stratified inventory data, described in chapter 1.3. With the information about height and volume from the inventory databases, coarse wood increment could be estimated for each age class and tree species class. The coarse wood increment adds up to ca. 83 Mio. m³ o.b. per year, or 8.3 m³ o. b. per hectare and year, respectively. Conversion into carbon storage increment leads to ca. 21 Mio. t C per year for even aged forests, coppice forests and coppice-with-standard-system forests together.

The use of yield tables requires several assumptions and simplifications of which the most important shall be pointed out. Firstly, there is the assumption that the thinning concepts specified in the yield tables are applied in reality. This assumption is strongly idealising and may not hold precisely, as prevailing management concepts in Germany have changed in the past. Secondly, yield tables imply clear cuts at the end of each rotation. In Germany however, clear cutting has become very rare as an end use method. More common methods are shelter harvesting or selective harvesting. These concepts are characterised by long end use time spans (even up to some decades) and by decreasing stock density during this time. Forest growth in dependence of decreasing density is not included in the yield tables. Thirdly, yield tables currently only exist for pure, even aged stands. This means that inventory data of mixed and uneven aged stands must analytically be divided into fictive pure and even aged stands for simulation. Growth relations between different tree species or the impact of understory on forest growth are thus not reflected by the yield tables. These are shortcomings of the used models. However, yield tables are the best and most common instruments for increment estimations in Germany as yet.

Figures concerning carbon storage enhancement in the first years after afforestation are very rare. LISKI et al (2000, p. 93) apply the average net annual increment of tree biomass on forests and other wooded land to estimate the carbon stock changes of trees accounted for under Article 3.3 of Kyoto Protocol for the EU (15). BURSCHEL et al. (1993, p. 72) report carbon sequestration figures in aboveground biomass after afforestation for Germany that vary between 0.5 (oak) and 3 t C/ha/a (douglas fir), depending on tree species. For forest areas which have been momentarily without plants by the time of inventory, an annual increment of aboveground dendromass (stems, branches and needles) of 1.5 t C/ha/a is assumed for this study.

"Selection forests" is a rather inhomogeneous forest type group. Selection forests can be found with high timber stocks (1,000 m³ o.b./ha) as well as with low ones (100 m³ o.b./ha). Correspondingly, annual coarse wood increments range between 18 and 4 m³ o.b./ha (MEYER, 1977, p. 390). In Germany selection forests can be found predominantly in the Southern *Laender*. In *Allgäu,* annual coarse wood increments of 5.6 to 9.8 m³ o.b./ha have been measured. For updating the selection forests stock, an annual mean increment of 7.7 m³ o.b./ha is assumed.

In German forests there is a respectable understory timber volume (see Table 4). Understory growth is strongly dependent on tree species and light intensity in the sub-crown stratum. But there is no detailed information neither on light conditions nor on understory area, age or density which would allow quantifying the understory increment.

[2] In Germany, the most commonly used growth models are yield tables; mathematical growth models scarcely exist. Yield tables are tree species specific data matrices which relate empirically observed volume, increment (and some other variables) of a forest stand to age and height of the stand. They usually distinguish between several yield classes, rotation periods, and thinning strategies. As such, they are the result of a specific combination of natural and economic conditions. The tabulated stand volume is generally the amount of coarse wood per hectare, i.e., stems and branches above 7 cm diameter.

Hence an assumption is required. Understory increment is supposed to be 2 % of the stock volume per year, which is a rather careful assumption. It must be mentioned that there is also understory biomass which is not yet coarse wood and thus not included in the figures in Table 4. Comparable coarse wood increment percents of main stands (mean age 60 years, second yield class) vary between 2.8 % (pine) and 4.4 % (beech).

Table 4: Gross coarse wood carbon increment [1,000 t C/a] for the old and new Laender according to FFI and FDB, respectively; reporting times: 1987-10-01 (FFI), 1993-01-01(FDB)

forest type	**old Laender (FFI)**	**new Laender (FDB)**	**total**
even aged forests, coppice forests, coppice-with-standard-system forests	15,883	5,131	21,014
temporary gaps	58	64	122
selection forests	276	84	360
understory, reservation of standards	544	70	614
productive forests	16,761	5,349	22,110
non-productive forests	n.a.	n.a.	n.a.
total coarse wood increment p.a.	**16,761**	**5,349**	**22,110**

Source: Own estimations, based on yield tables (see Annex 1) and BMELF, 1992, 1994

1.5.1.3.2 Coarse wood removals

Harvested volume can be estimated in two different ways, using either yield table information or official statistical data on removals. The disadvantage of yield table information is that their particulars on harvested volume are only loosely related to reality. The disadvantage of the official statistical data is that removals in private forests are not collected in some *Laender* in Germany, but estimated; this estimation is rather rough in part. Even though statistical removal figures are not too reliable due to missing information on private forest owners' harvesting, statistical data are assumed to be closer to reality and especially, to be more able to reveal annual changes in harvested volumes. Gross coarse wood increment will thus be reduced by the official removal data to obtain the net increment of one year.

Removal statistics contain data for coarse wood of the four main tree species groups in Germany (spruce, pine, beech, and oak), and are differentiated for long logs and stacked short logs. While the precision of the statistics for long logs is rather satisfying, short logs are not completely captured. Following BMELF (1992-2000), they amount to about 2 Mio. m³ per year which is 5 % of the total removal on average. Stacked short logs are largely used as firewood. Altogether, there is a significant consumption of firewood by private individuals in Germany which has been estimated at about 8 Mio. m³/a (HRUBESCH 1996, p. 52), or 6 Mio. m³/a more than the "official" short log removal. To allow for this difference, the official removal data (1991-1999 average) is increased by these 6 Mio. m³/a of firewood not recorded in the official statistics. Altogether this results in annual removals of carbon fixed in coarse wood of about 12.5 Mio. t C/a in average.

Table 5: Annual coarse wood carbon removals [1.000 t C/a]

year	old Laender	total Germany
1988	10.559	
1989	11.193	
1990	21.120	
1991		11.111
1992		10.040
1993		9.991
1994		11.912
1995		13.544
1996		12.833
1997		12.980
1998		13.580
1999		13.236

source: BMELF, 1992-1998; HRUBESCH, 1996

1.5.1.4 Critical appraisal of the coarse wood estimation approach

Coarse wood increment estimation is based on data which are more than 10 years old. In the meantime, age class distribution as well as tree species distribution has changed and consequently, also the total annual increment changed. This effect is smaller when age and species distributions are rather homogenuous. A significant impact on age and species distribution has come from the two important windfalls (1990 and 1999) which especially affected Southern Germany. They caused damages that have been a multiple of the regular annual harvesting volume. This change in the natural database must be neglected in the coarse wood increment estimation as long as an updated forest inventory is not available. Anyhow, it can be assumed that the overall impact of this neglect tends to a slight underestimation of carbon sequestration changes, since the afforested windfall area is covered by young stands today which are generally characterised by higher increments than older stands.

1.5.2 Small wood (branches and twigs)

Yield tables generally contain information about coarse wood, but not about other forest biomass such as twigs and small branches (under 7 cm diameter), needles and leaves, and roots. Since the amount of carbon which is fixed in these types of forest biomass may be significant and may change over time, yield table information has to be supplemented by other approaches to account for such changes.

Data availability for all these supplementary elements of forest biomass production is markedly worse than for coarse wood. However, due to the increasing interest in ecosystem research in the last decades, several authors have investigated total biomass volume for various tree species and ages. In some of these studies, total volume is further divided into coarse wood volume and other volume elements. This makes it possible to link such information to the one provided by yield tables, using expansion factors which are either constant or (if sufficient information is available) equation-based.

1.5.2.1 Accounting for small wood

Data which allow calculating expansion factors for the amount of small wood (twigs and branches below 7 cm diameter) in relation to coarse wood could be derived from literature. Table 6 gives an overview over the studies which have been used for the respective estimations.

Table 6: Literature sources used to estimate small wood/coarse wood ratio (sw/cw-ratio)

species	tree age	data points	country	climatic zone	source
Picea abies	76	1*	D	temperate	DROSTE ZU HÜLSHOFF (1969)
	80	1*	D	temperate	BAUMGARTNER (1975) #
	50	1*	D	temperate	NEBE (1979)
	30-150	7*	D	temperate	KRAMER & KRÜGER (1981)
	55	1*	B	temperate	KESTEMONT #
	48-123	3*	D	temperate	ELLENBERG et al. (1986)
	57-106	3*	CZ	temperate	CERNY (1990)
Pinus sylvestris	30-150	7*	D	temperate	KRAMER & KRÜGER (1981)
	50	1*	D	temperate	NEBE (1979)
Pseudotsuga menziesii	22-73	7*	US	temperate	TURNER & LONG (1975)
	40	2*	US	temperate	KEYES & GRIER (1981)
	64	4*	NL	temperate	GAFFREY & SLOBODA (2001)
	450	1*	US	temperate	GRIER et al. (1974) †
Abies sibirica	41-146	33	RU	boreal	STAKANOV et al. (1998)[3]
Larix spec.	40-271	24	RU	boreal	STAKANOV et al. (1998)
Fagus sylvatica	50-170	7	D	temperate	KRAMER & KRÜGER (1981)
	70-130	4	D	temperate	PELLINEN (1986)
	130-144	2	B	temperate	DUVIGNEAUD & KESTEMONT (1977) #
	67-130	3	D	temperate	ELLENBERG et al. (1986)
Quercus spec.	30-190	9	D	temperate	KRAMER & KRÜGER (1981)
	90-120	3	B	temperate	DUVIGNEAUD et al. (1971)
	140	1	NL	temperate	VAN DER DRIFT (1991) #
Populus tremula	9-85	17	RU	boreal	STAKANOV et al. (1998)
Betula spec.	10-60	10	RU	boreal	STAKANOV et al. (1998)

** these studies have also been used for estimating needle/coarse wood ratios (see below)*
 # cited in: NABUURS & MOHREN, 1993, p. 62, 70
† cited in: TURNER & LONG, 1975, p. 685

A regression approach was chosen to account for the dependency between age and small wood portion of the trees. In a first step, a single equation was formulated which contained the small wood/coarse wood ratio as dependent variable, and tree age as well as several dummies for the respective tree species as independent variables [sw/cw-ratio = f (age, species)].[4] This equation was used to find a suitable functional form and to test

[3] Although STAKANOV et al. (1998) also presented data for boreal spruce (*Picea*) and pine (*Pinus*), these data have not been taken into account here because enough data from the temperate zone have been available. Especially the boreal spruce data showed a significantly higher small wood/coarse wood ratio than the temperate ones when a dummy variable for boreal observations was introduced into the regressions (described below). However, the difference was insignificant in the pine case; here, the respective ratio was even smaller for boreal pine. For *Abies*, *Larix*, *Populus*, and *Betula*, no data from the temparate zone were available, so that we had to use boreal data instead.

[4] It is rather likely that tree height instead of age as explanatory variable would yield better regression results, supposed that the coarse wood portion of a tree depends directly on its height: Since height is a function of age and yield class, part of the unexplained variation may be attributed to the original data's variation in yield classes. Unfortunately, neither tree height nor yield classes are reported in most of the available studies. Hence, age had to be used as a proxy.

for differences between tree species. The functional forms tested were the linear, semi-log, double-log, inverse [1/x], inverse quadratic [$1/x^2$], and inverse square root [$1/x^{1/2}$]. The latter five functional forms were considered because it can be expected that young tree stands have an exponentially higher small wood/coarse wood ratio than older ones; in very young stands, there is no coarse wood such that the small wood/coarse wood ratio approaches infinity. Hence, a non-linear decreasing function seemed appropriate. Out of all functional forms tested, the double-log had the best fit in terms of r^2 and was used in the further development of the expansion equations.[5] Moreover, the coefficients of most tree species dummies differed significantly from each other.

Due to these differences, ln(sw/cw-ratio) was regressed on ln(age) for each tree species separately in a second step. Additional dummies were introduced in two cases:

1) Poplar (*Populus*) and birch (*Betula*) were combined in a group "srb" (short rotation broadleaves) because this is the grouping which was also used in the Federal Forest Inventory. A dummy variable [*Betula*] was used to distinguish between both species.

2) The studies by DUVIGNEAUD and co-authors on beech (*Fagus*) and oak (*Quercus*) did not distinct between coarse wood and small wood, but between stems and branches instead (DUVIGNEAUD et al., 1971, p. 261). Since some branches may belong to coarse wood if they have more than 7 cm diameter, this could bias the regression. To account for this, an additional dummy for the DUVIGNEAUD-studies was used in the case of beech and oak.

Table 7 shows the regression estimates.

Table 7: Double-log regression of small wood/coarse wood ratio on age, depending on tree species: coefficient estimates and regression characteristics

species	constant	ln(age)	dummy	DF	r^2	α_F	mean sw/cw-ratio
Picea	+1.7843	-0.8931	-	15	0,59	0.00029	0.145251309
Pinus	+0.3488	-0.5286	-	6	0,65	0.01635	0.154124167
Pseudotsuga	*-2.2476*	*-0.0064*	-	*12*	*0.00*	*0.94035*	0.104963078
Abies	-0.1445	-0.2539	-	31	0,26	0.00254	0.284738276
Larix	*-2.9436*	*+0.1139*	-	*22*	*0,03*	*0.41889*	0.095704776
Fagus	+2.8939	-1.0120	+0.8860	13	0,60	0.00239	0.2145/0.1929*
Quercus	+3.4011	-1.1794	+0.9309	11	0,82	0.00008	0.2510/0.2091*
srb	-1.0761	-0.3125	+0.4148	24	0,37	0.00361	0.1172/0.1902**

**with/without observations by DUVIGNEAUD et al. (1971);*
***Populus/Betula; italics: insignificant regression results*

Determination coefficients [r^2] and overall significance of the regressions [α_F] are rather satisfying for all German main tree species, i.e. spruce, pine, beech, and oak. The results for short rotation broadleaves (srb) are somewhat weaker; but as the respective tree spe-

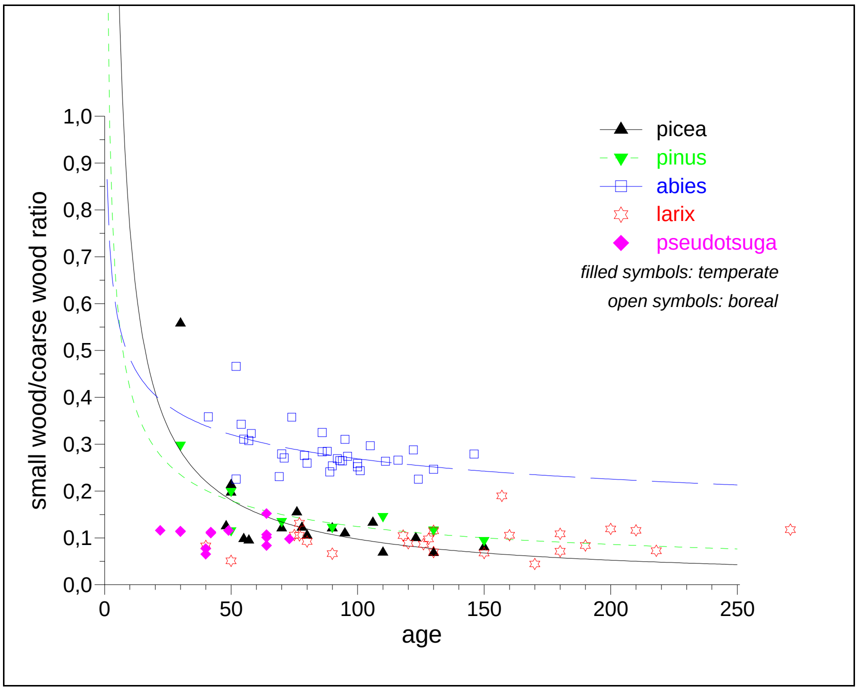
[5] In the present case, an additional advantage of a „non-linear decreasing" transformation is that extreme observations get a lower weight as compared to the untransformed linear case. Specifically, the transformation of the dependent variable (i.e. the small wood/coarse wood ratio) weights down observations with a high amount of small wood, thus leading to a comparatively „conservative" estimation of the average small wood fraction. The transformation of the independent variable (age) attributes a higher weight to observations from younger trees. This is a desirable property for the present problem since younger stands have a higher increment, and hence, have a higher influence on CO_2 fixation. Taking logarithms of both sides of the equation (as has been done here) serves both purposes.

cies have a comparatively lower share in the German forests, the results may be sufficient for the present purpose. The estimation for fir reveals a significantly higher small wood/coarse wood ratio as compared to spruce or pine. It has to be discussed if this empirical finding is trustworthy. Firstly, it must be remembered that the available fir studies refer to *Abies sibirica* instead of *Abies alba*, the most common fir species in Germany. Second, the data are solely stemming from the boreal zone where overall growth conditions are worse as compared to the temperate zone, which means that at a given age, trees have a lower height and hence a higher sw/cw-ratio. Since no data from the temperate zone were available, this effect could not be accounted for by using a dummy variable. To serve the spirit of a precautious estimation of the carbon binding service of forests, we dispensed with using the fir regression; instead, the spruce regression is adopted for fir as well.

Unfortunately, the regressions for douglas fir and larch are not significant,[6] and moreover, the positive age coefficient in the larch regression does not seem very plausible in the light of the above-mentioned arguments. Hence it was decided to use the mean small wood/coarse wood ratio as single expansion factor, not accounting for age in the case of douglas fir and larch. This results in small wood/coarse wood ratios amounting to 0.105, or 0.096, respectively. Yet it should be noted that these two species are comparatively rare in Germany, too.

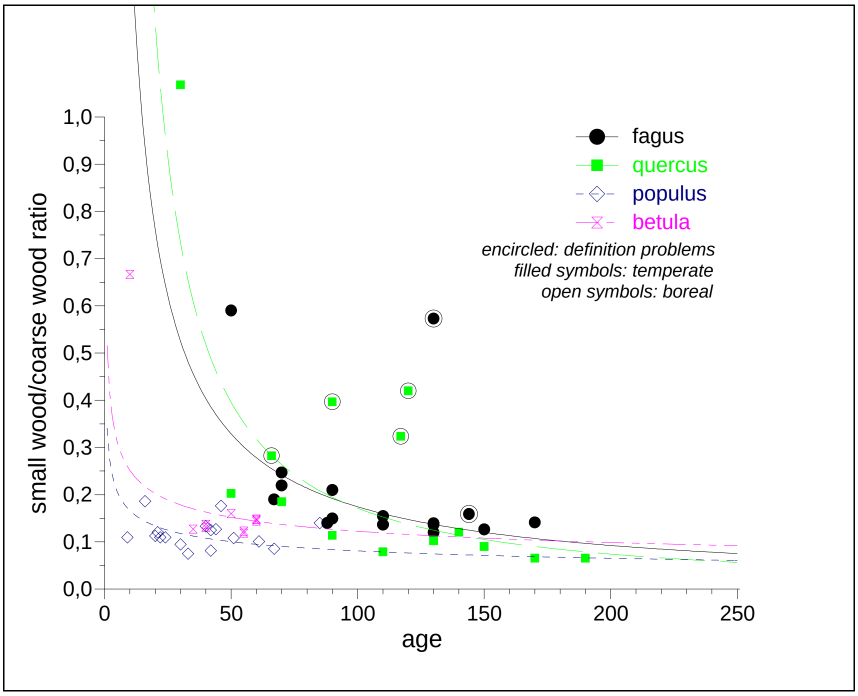
A graphical representation of raw data and associated regression lines is presented in Figure 3 (conifers) and Figure 4 (broadleaves). In Figure 4, observations by Duvigneaud and coauthors are circled (these observations have been shifted off in the regression estimates by a dummy variable as described above).

Figure 3: Small wood/coarse wood ratios of coniferous species in relation to age



6 In the case of douglas fir, this may be also due to different biomass fraction definitions in the respective original studies.

Figure 4: Small wood/coarse wood ratios of broadleaves in relation to age



1.5.2.2 Small wood stocks, increment and removals

Small wood expansion factors have been applied to even aged forests, coppice forests and coppice-with-standard-system forests having regard to stand age and tree species. Selection forests and understory are not subject of the studies cited in Table 6. Hence the respective small wood/coarse wood ratios must be assigned to these forest types without further empirical foundation. It is assumed that small wood/coarse wood ratios of selection forests and understory are approximately as high as the ratio mean values of even aged forests. Since understory is quite comparable to younger stands concerning growth features and coarse wood volumes, the applied small wood ratios rather tend to lead to an underestimation of understory small wood volume. The overall small wood/coarse wood ratios of stocks (increment) are 0.18 (0.21) for the old *Laender*, and 0.17 (0.19) for the new *Laender*, applying the regression estimates described above. Small wood increment on areas not covered with forest plants is already included in the blanket estimate of 1.5 t C/ha/a (see section 1.5.1.3.1 on coarse wood increment). Table 8 and Table 9 show the results of the small wood estimations.

Table 8: Small wood carbon stocks [1,000 t C] for the old and new Laender according to FFI and FDB, respectively; reporting times: 1987-10-01 (FFI), 1993-01-01(FDB)

forest type	**old Laender (FFI)**	**new Laender (FDB)**	**total**
even aged forests, coppice forests, coppice-with-standard-system forests	94,330	24,833	119,163
temporary gaps	0	0	0
selection forests	2,192	464	2,656
understory, reservation of standards	4,927	599	5,526
productive forests	101,449	25,896	127,345
non-productive forests	n.a.	n.a.	n.a.
total small wood stock	**101,449**	**25,896**	**127,345**

Table 9: Small wood carbon increment [1,000 t C/a] for the old and new Laender according to FFI and FDB, respectively; reporting times: 1987-10-01 (FFI), 1993-01-01(FDB)

forest type	**old Laender (FFI)**	**new Laender (FDB)**	**total**
even aged forests, coppice forests, coppice-with-standard-system forests	3,352	995	4,347
temporary gaps	- *	- *	- *
selection forests	60	16	76
understory, reservation of standards	116	13	129
productive forests	3,528	1,024	4,552
non-productive forests	n.a.	n.a.	n.a.
total small wood increment p.a.	**3,528**	**1,024**	**4,552**

** already included in the aboveground dendromass increment estimate of 1.5 t C/ha/a*

As will be reasoned in chapter 1.6 on underground biomass, forest soil organic layer is regarded as a constant stock of carbon. This means that we assume that, on balance, influxes such as twigs or foliage litter even out respiration losses due to organic decomposition processes. Consequently the respective small wood and needle volume referred to coarse wood removals has to be taken into account when estimating the overall carbon removal from forests. Official removal statistics do not provide information on the age of logs. Therefore age independent expansion factors have to be used to estimate coarse wood removal related small wood and needles losses. For each of the four tree species groups spruce, pine, oak and beech a mean expansion factor was calculated, weighted with the respective stock volume. The resulting small wood expansion factors are 0.17 for spruce, 0.16 for pine, 0.18 for oak and 0.2 for beech (firewood is assumed to consist only of beech).

Table 10: Annual small wood carbon losses due to harvesting [1,000 t C/a]

year	old Laender	total Germany
1988	1,902	
1989	2,008	
1990	3,698	
1991		1,992
1992		1,807
1993		1,796
1994		2,128
1995		2,417
1996		2,298
1997		2,304
1998		2,428
1999		2,372

1.5.3 Needles and leaves

1.5.3.1 Leaves

Due to several measurement problems, it is rather questionable whether the carbon content of living leaves should or should not be considered when calculating the carbon binding service of forests. Deciduous trees in the temperate zone (broadleaves and larch) shed their foliage annually such that it is part of the living tree during summertime, but part of the organic layer in late autumn and winter. Since it is not always clear at which time of the year the available original biomass studies have been undertaken, an inclusion of living leaves could lead to double counting if organic layer and foliage have been studied in different seasons. To serve the spirit of "conservative" estimation when in doubt, it was decided to omit the carbon content of living leaves from the calculations.

The possible underestimation stemming from this decision is supposed to be rather small even when carbon stocks are in question,[7] and it can be assumed completely negligible in the case of carbon fluxes if the age structure of a country's forests is balanced (as it nearly is in Germany). In this case, foliage production and decomposition are in a steady state in the long run annual average. (An exception would have to be made if large hardwood afforestations of low age prevailed in a country. In this case, the yearly augmentation of the tree crowns and hence, of the foliage, would enlarge this country's carbon depository by the carbon content of each year's additional leaves).

1.5.3.2 Needles

In contrast to leaves, needles normally have a life span of several years (with the exception of larch needles, as mentioned above). This makes it necessary to account for them in an analysis which is targeted at annual changes.

Needle biomass was related to coarse wood biomass in the same way as depicted above. The studies used for deriving needle/coarse wood ratios are those which have been marked with an asterisk in Table 6. Additionally, the data presented for boreal pine by

[7] In Belgian deciduous forests for example, green leaves amounted to 1 to 5 % of total aboveground biomass (DUVIGNEAUD et al. 1971:266).

STAKANOV et al. (1998; 65 observations, age ranging from 15 to 240 years) have been used here because there were only 8 observations from the temperate zone for this species which alone yielded insignificant overall results in the regression test. Unfortunately, data on *Abies* were not available (larch has been omitted because this species sheds their needles annually).

In contrast to the results above, the inverse quadratic regression equation outperformed the double log one in the case of spruce and pine. Hence, the needle/coarse wood ratio [n/cw-ratio] was estimated by [n/cw-ratio = $\beta_0 + \beta_1$ 1/age² + ε] in the case of spruce; in the case of pine, an additional dummy was introduced to separate observations from the temperate zone from the boreal ones. For douglas fir, this functional form yielded insignificant results, and the double-log form [ln(n/cw-ratio = $\beta_0 + \beta_1$ ln(age) + ε] was used again for this species. Table 11 shows the results.

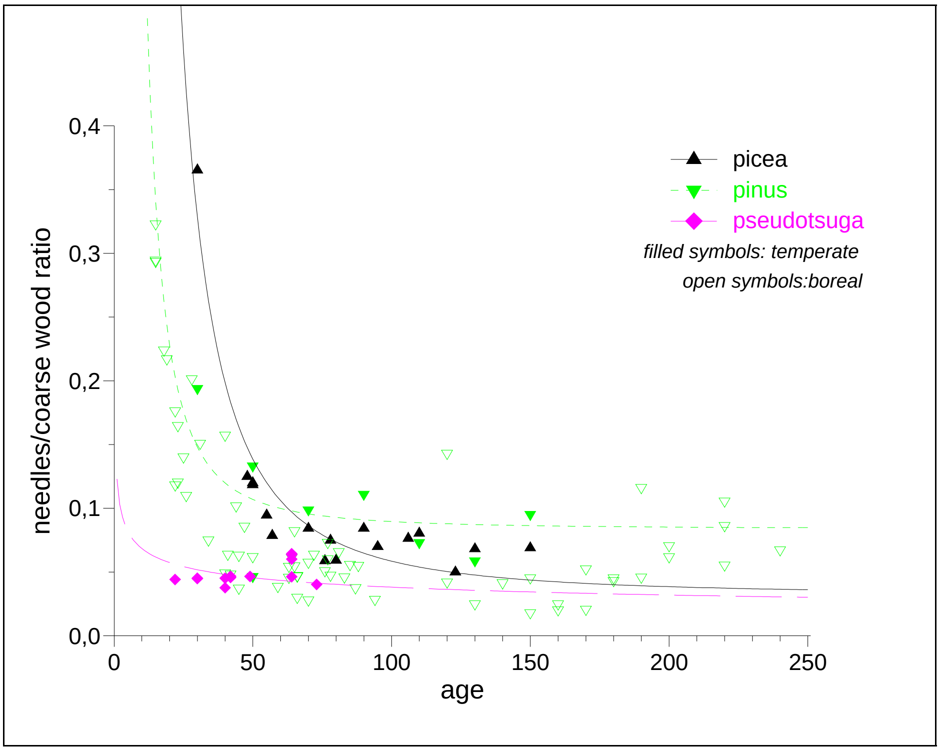
Table 11: Regression of needles/coarse wood ratio on age, depending on tree species: coefficient estimates and regression characteristics

species	**constant**	**1/age²**	**dummy**	**DF**	**r²**	**α_F**	**mean n/cw ratio**
Picea	+0.0319	266.95	–	15	0,91	0.00000	0.0987163015
Pinus	+0.0839	57.68	-0.0368	70	0,81	0.00000	0.0871075188
Pseu-dotsuga	-2.0952	**ln(age)** -0.2542	–	12	0,37	0.02078	0.0463787940

With determination coefficients [r²] of 91 and 81 percent for spruce and pine, the fit is even better than in the case of small wood/coarse wood ratio; the douglas fir regression yields weaker results, but they are still significant.[8] A graphical representation is Figure 5. Due to the lack of available data on fir, the needle/coarse wood ratio estimated for spruce has to be used for fir, too.

[8] Again, this relative weakness is (at least partly) due to definition problems: Some of the original studies did not communicate coarse wood data, but stem wood data instead; hence, the douglas fir regression line, the variance of the data on which it is based, and also the mean needles/coarse wood ratio for douglas fir are slightly biased.

Figure 5: Needle/coarse wood ratios of coniferous species in relation to age



Because of morphological differences it is rather likely that the carbon content of needles is different from that of wood. Alas, reliable figures are not available in this regard. Hence the same conversion factor for carbon content had to be assumed for needles and wood (0.5 of dry biomass). Table 12 through Table 14 show the results of the carbon stock, increment and removal estimations for needles.

Table 12: Needle carbon stocks [1,000 t C] for the old and new Laender according to FFI and FDB, respectively; reporting times: 1987-10-01 (FFI), 1993-01-01(FDB)

forest type	**old Laender (FFI)**	**new Laender (FDB)**	**total**
even aged forests, coppice forests, coppice-with-standard-system forests	47,818	11,038	58,856
temporary gaps	0	0	0
selection forests	1,131	197	1,328
understory, reservation of standards	2,513	251	2,763
productive forests	51,461	11,486	62,947
non-productive forests	n.a.	n.a.	n.a.
total needle stock	**51,461**	**11,486**	**62,947**

Table 13: Gross needle carbon increment [1,000 t C/a] for the old and new Laender according to FFI and FDB, respectively; reporting times: 1987-10-01 (FFI), 1993-01-01(FDB)

forest type	**old Laender (FFI)**	**new Laender (FDB)**	**total**
even aged forests, coppice forests, coppice-with-standard-system forests	1,547	496	2,043
temporary gaps	–*	–*	–*
selection forests	28	8	36
understory, reservation of standards	54	7	61
productive forests	1,629	511	2,140
non-productive forests	n.a.	n.a.	n.a.
total needle increment p.a.	**1,629**	**511**	**2,140**

** already included in the aboveground dendromass increment estimate of 1.5 t C/ha/a*

Table 14: Annual needle carbon losses due to harvesting [1,000 t C/a]

Year	**old Laender**	**total Germany**
1988	1,143	
1989	1,247	
1990	2,926	
1991		1,256
1992		1,112
1993		1,122
1994		1,389
1995		1,489
1996		1,406
1997		1,524
1998		1,437
1999		1,357

For needles too, mean expansion factors had to be applied to selection forests and understory. They amount to 0.09 (old *Laender*) and 0.07 (new *Laender*) for stock estimation, and 0.1 for increment estimation. For estimating needle carbon losses related to coarse wood removals, tree species dependent expansion factors have been applied. They are 0.18 for spruce, and 0.11 for pine, respectively.

1.5.4 Herbage

For Germany there neither exist comprehensive estimations of the distribution of herbage communities in forests nor estimations of the carbon sequestered by these herbage communities. BOLTE (1999) studied several single herbage species and calculated their respective aboveground carbon stocks. They average 0.4 tons carbon per hectare. Regarding the missing knowledge about spread and variation of the particular species, and regarding how low a value of 0.4 t C/ha is compared to the carbon stock in the tree biomass or in the forest soil, the herbage layer was omitted from the calculations. In the light of the presented arguments, this neglect presumably leads to an only insignificant underestimation of forest carbon stocks and carbon stock changes.

1.6 Underground biomass

1.6.1 Roots

1.6.1.1 Accounting for roots

Like mentioned above, the knowledge about underground biomass is rather small. Concerning living tree roots, there are some descriptive studies about root types, fractions of coarse and fine roots and growth patterns especially in dependence on tree species and the respective soil types (e.g., RÖHRIG, 1966; KÖSTLER et al., 1968; MITSCHERLICH, 1978; VOGT et al., 1996; LÜPKE & KUHR, 2001). Site conditions like water availability, mechanical resistance (stones) and chemical properties are emphasised as important factors influencing root volume (e.g. KÖSTLER et al., 1968).

Since aboveground biomass is also driven by those factors and much easier to measure, it seems useful to search for quantified relations between aboveground and underground (root) wood volume. But as yet there are only few models allowing for a differentiated estimation of tree root volumes, and the existing models do not allow for a distinction between tree species. Two such studies stem from KURZ, BEUKEMA, and APPS (1996) and CAIRNS, BROWN, HELMER, and BAUMGARDNER (1997). KURZ et al. (1996) as well as CAIRNS et al. (1997) estimated root biomass (rb) as a function of aboveground biomass (ab), performing meta-analyses of already existing studies. Both meta-analyses found nearly constant relations between root biomass and aboveground biomass, implying that any model which contains the ratio between those two as a dependent variable would yield insignificant results; consequently, both studies modelled root biomass directly as a function of aboveground biomass. Unfortunately, both meta-analyses led to somewhat diverging results: E.g. for a deciduous forest of 500 tons aboveground biomass per hectare, the root biomass estimate by KURZ et al. (1996) would amount to only 70 % of the estimate by CAIRNS et al. (1997). Additionally, each of these models might lead to biased estimations when applied to Central European conditions since their data base was not restricted to studies from the temperate zone only, but included original studies from tropical and boreal forests, too.[9]

To account for this possible bias, we re-estimated the root biomass-aboveground biomass regression models, using data from the temperate zone only.[10] Like in the meta-

[9] CAIRNS et al. (1997) found significant differences between climate zones in one of their models which used dummy variables to distinguish between tropical, temperate, and boreal forests. However, their global definition of "temperate" (i.e. between 26° and 50° latitude) did not take into account the Gulf Stream induced northern shift of the temperate zone in Europe.

[10] Data sources for this analysis were 1) all those studies quoted by CAIRNS et al. (1997:3-5, table 1) which stemmed from 26°-50° latitude or from sampling plots in temperate Europe, if the respective tree genus occurs in Germany; 2) those studies used by KURZ et al. (1996) which could be attributed to the temperate zone, following the same definition; 3) those studies quoted by VOGT et al. (1996, appendix B) and there attributed to the "cold temperate" climatic forest type, if not already quoted by CAIRNS et al. (1997) or KURZ et al. (1996); 4) and finally, those studies which have already been used in the present report for estimating small wood/coarse wood ratios (cf. tab. 6), if they stemmed from the temperate zone and contained root data. Double entries have been deleted if clearly identifiable. See Annex 2 for a complete description. We wish to express our thanks to Mike APPS and Michael CAIRNS (as well as their respective co-authors) for giving us access to their respective data bases.

analyses of KURZ et al. (1996) and CAIRNS et al. (1997), the linear as well as the double-log model were tested in a first step; additionally, dummies were included to test for differences between tree genera, which indeed turned out to be significant. Although both models fitted the data well in terms of r^2, neither the double-log nor the linear model seemed completely satisfying for describing the root biomass/aboveground biomass relation over a wide range of possible values: The double-log led to a noticeable underestimation of root biomass for higher values of aboveground biomass (due to the lower weight these values receive when they enter the regression in logarithmic transformation), whereas the linear model's dummy coefficients imposed interpretation problems for aboveground biomass values close to zero (e.g., the model predicted negative root biomass values in some cases which does not make sense in biological terms). Hence the square root transformation [$\sqrt{(rb)} = \beta \sqrt{(ab)} + \delta$ tree species + ε] was used which lessens both problems. After stepwise backwards elimination of insignificant variables, all dummies for coniferous tree genera (i.e. 'fir', 'spruce', 'douglas fir', and 'pine') remained in the model, as did the dummy for 'short rotation broadleaves' (srb; data available from alder, birch, and poplar). This means that all these genera differed from the 'rest' which is made up by beech and oak (which themselves did not differ significantly from each other).[11] Table 15 shows the regression estimates for the final model, and fig. 6 gives a graphical representation of data and regression results.[12]

Table 15: Regressions of root biomass on aboveground biomass: coefficient estimates and regression characteristics

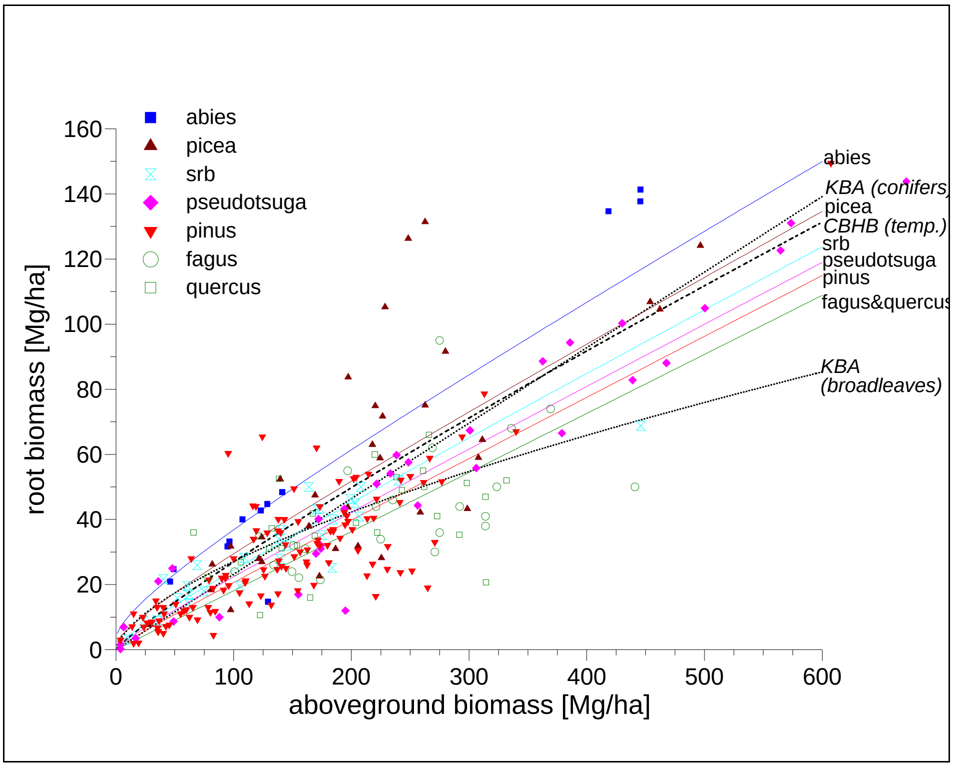
study	**equation No.**	**constant**	**ab**	**dummy**	**DF**	**r^2**	**α_F**
KURZ et al. (1996)	3 (linear, soft-wood)	–	0.232	–	259	0,71	<0.001
KURZ et al. (1996)	4 (d-log, hard-wood)	0.359	0.639	–	83	0,77	<0.001
CAIRNS et al. (1997)	3 (d-log)	-1.0587	0.8836	0.2840* (temperate) 0.1874* (boreal) 0.0 (tropical)	147	0,84†	not quoted
Present study (temperate only)	(d-sqr)	–	0.4259	1.8114** (*Abies*) 1.1690** (*Picea*) 0.6910** (srb) 0.4738* (*Pseudotsuga*) 0.2864* (*Pinus*) 0.0 (*Fagus* & *Quercus*)	266	0,80	<0.001

***dummy coefficient significant at α <1%; *significant at α <5%; †adjusted r^2*

[11] No other tree genera were tested due to the lack of data. Single observations on larch, hornbeam, and some exotic tree species were deleted from our original data set prior to testing the regression models.

[12] Note that root biomass is expressed as a function of total aboveground wood biomass but not of coarse wood biomass here.

Figure 6: Relation between root and aboveground biomass of various tree species in the temperate zone



KBA: KURZ, BEUKEMA, and APPS, 1996; CBHB: CAIRNS, BROWN, HELMER, and BAUMGARDNER, 1997

In comparison to KURZ et al. (1996) and CAIRNS et al. (1997) (dotted lines in Figure 6), the results are rather plausible: They enclose the CAIRNS et al. (1997) estimate as well as the conifer estimate of KURZ et al. (1996), and they are above the KURZ et al. (1996) double-log broadleaves estimate in the higher biomass regions. The rather big difference between conifers and broadleaves in the KURZ et al. (1996) study is at least partly due to the different equation forms applied there for conifers and broadleaves. Like in the KURZ et al. (1996) study the present estimation generally shows bigger amounts of biomass allocated in coniferous roots than in broadleaves roots (with the exception of short rotation broadleaves).[13]

1.6.1.2 Root stocks, increment and removal

Living tree root carbon stocks and increment of even aged forests, coppice forests and coppice-with-standard-system forests are estimated applying the presented regression on aboveground biomass stocks, having regard to the tree species. The overall mean root biomass/aboveground biomass ratio results in 0.18 for both stocks and increment. This figure is applied to the selection forests, the understory and the reservation of standards. Likewise, root biomass increment at temporary gaps was assumed to be 18 % of aboveground biomass increment, resulting in a root biomass increment of 0,27 t C/ha/a.

Consideration of root increment on the one hand and refraining from each kind of modelling the decomposition of dead roots on the other hand would lead to an overestima-

[13] Mean rb/ab ratios are: 0.3424 for *Abies*; 0.2673 for *Picea*; 0.2577 for srb; 0.2433 for *Pseudotsuga*; 0.2265 for *Pinus*; 0.2169 for *Quercus*; and 0.1808 for *Fagus*.

tion of (net) underground carbon increments. Thus the simple assumption is made that the root volume referred to the coarse wood removals is disintegrated in the same year as the fellings took place. For these purposes mean tree species specific root biomass/aboveground biomass ratios have to be calculated and referred to the removal figures. The respective figure is 0.18 for all of the four main tree species groups in Germany, spruce, pine, beech and oak.

Table 16: Tree root carbon stocks [1,000 t C] for the old and new Laender according to FFI and FDB, respectively; reporting times: 1987-10-01 (FFI), 1993-01-01(FDB)

forest type	**old Laender (FFI)**	**new Laender (FDB)**	**total**
even aged forests coppice forests, coppice-with-standard-system forests	122,012	33,653	155,665
temporary gaps	0	0	0
selection forests	2,768	605	3,373
understory, reservation of standards	6,239	779	7,018
productive forests	131,019	35,037	166,056
non-productive forests	n.a.	n.a.	n.a.
total tree root stock	**131,019**	**35,037**	**166,056**

Table 17: Gross tree root carbon increment [1,000 t C] for the old and new Laender according to FFI and FDB, respectively; reporting times: 1987-10-01 (FFI), 1993-01-01(FDB)

forest type	**old Laender (FFI)**	**new Laender (FDB)**	**total**
even aged forests coppice forests, coppice-with-standard-system forests	3,796	1,212	5,008
temporary gaps	11	11	22
selection forests	65	19	84
understory, reservation of standards	129	16	145
productive forests	4,000	1,259	5,260
non-productive forests	n.a.	n.a.	n.a.
total tree root stock	**4,000**	**1,259**	**5,260**

Table 18: Annual root carbon losses due to harvesting [1,000 t C/a]

Year	old Laender	total Germany
1988	2.449	
1989	2.601	
1990	4.994	
1991		2.585
1992		2.333
1993		2.324
1994		2.777
1995		3.141
1996		2.977
1997		3.025
1998		3.140
1999		3.054

As discussed above there do not exist any representative data on herbage distributions in German forests. Consequently neither living nor dead roots of herbage can be taken into account when estimating the carbon sequestration by forest soils.

1.6.2 Organic layer and mineral soil

Underground biomass has been disregarded by forestry research for a long time. In the context of the discussion on mitigation strategies for climate change, great efforts have been made in analysing the role of soils as carbon sinks. The respective studies show the great importance of forest soils for carbon sequestration. Estimations of national carbon stocks for Austria, Finland, Germany, and Switzerland consistently show that approximately twice as much carbon is stored in forest soils as compared to the above-ground tree biomass (BÖSWALD, 1998, STRICH, 1998, LISKI, 1997, PAULSEN, 1995).

1.6.2.1 Organic layer and mineral soil stocks

Due to the mutual dependence of the thickness of the humus layer and the organic content of the mineral soil, organic layer and mineral soil are analysed together. The recent and most detailed work on carbon stocks in German forest soils was done by BARITZ (1996, 1998) and BARITZ et al. (1999). The estimations are based on the National Forest Soil Inventory and regionalized using the 72 soil units of the Soil Map of Germany. The estimation amounts to an overall carbon stock in German forest soils of approximately $1.2 \cdot 10^9$ t C (Table 19). This result corresponds quite well with a previous estimation by BURSCHEL et al. (1993) which results in approximately $1.5 \cdot 10^9$ t C. The highest carbon content can be found in the top 30 cm of the mineral soil.

Table 19: Forest soil carbon stocks [1,000 t C]; reporting period: 1987-1992

layer	[1,000 t C]	[%]
forest floor humus layer	223,000	19
mineral soil from 0-30 cm	701,000	60
mineral soil from 31-90 cm	244,000	21
total organic layer and mineral soil stock	**1,168,000**	**100**

Source: BARITZ et al. 1999, p. 224

1.6.2.2 Organic layer and mineral soil fluxes

There has been only one National Forest Soil Inventory in Germany as yet. The second one is still in preparation. Thus, changes in forest soil carbon stocks can be estimated merely using soil carbon models. Most models for estimating the carbon stock in forest soils use natural realities as explaining factors. DE WIT & KVINDESLAND (1999) used two inventories for estimating the carbon stocks in Norwegian forest soils and found out that they were dependent on the carbon content of the different horizons, horizon depth, bulk density, and stony fractions. LISKI (1997) successfully modelled the carbon content of Finnish forest soils as a function of site productivity and annual temperature in the region. PAULSEN (1995) explained the carbon stocks of characteristic soil types in Switzerland with data on mean slope, soil density, humus content, stony fractions, and the depth of the soil profile.

Unfortunately, all these impact factors on forest soil carbon content are not suitable for forecasting short-term changes. Regional mean temperature, soil and horizon depths or stony fractions will stay more or less constant within the relevant time horizon of valuation. Rather than these natural realities, human impacts on forests might obtain greater importance for forest soil carbon stocks. Such human impacts may be:

- **Land use change: Afforestation and Deforestation**

  In the respective literature, agreement exists concerning the sink and source effects of land use change. Deforestation leads to carbon losses from the soil and accordingly, afforestation leads to soil carbon rise (DE WIT & KVINDESLAND, 1999). Depending on the former land use, humus tends to accumulate primarily in the organic layer after waste-land and heath afforestation, while afforestation on farmland leads to significant humus accumulation in the mineral soil as well (BARITZ, 1998). SCHOEDDER (1990, p. 61) calculates carbon sequestration in the soil which amounts to 1 t C/ha/a for afforestation of former agricultural land.

  As has been noted above related to forest area estimation, considerable areas are deforested and afforested in Germany each year. Both deforestation and afforestation result in changes in soil carbon stocks. In order to quantify these changes it would be necessary to know the former as well as the current land use for all cases of deforestation and afforestation. But for this there are no reliable statistical data for Germany.

- **Thinning and end use practices**

  Thinning and end use practices which avoid to uncover the forest floor are regarded as having no significant impact on soil carbon. On the other hand, clear cuts cause a significant decomposition of the organic layer. After clear cuts, biological activity is stimulated due to higher light intensity and temperature, and organic matter in the upper layer converts. Only a part of the carbon sequestered in the organic layer gets into the mineral soil. The other part of the carbon diffuses out from the forest soil into the air (BURSCHEL et al., 1993, p. 23). With the growth of the new stand, the soil carbon stock is built up again.

  Some authors tried to quantify soil carbon development after clear cuts. In the first 1-3 years after clear cuts, left slash leads to an increase of soil carbon especially in the organic layer (DE WIT & KVINDESLAND, 1999; JOHNSON & HENDERSON, 1995, p. 138 f). Over the next 15 to 20 years, soil carbon decreases by 5-25 % (DE WIT & KVINDESLAND, 1999; HEINSDORF et al., 1986; LISKI, 1997). LISKI (1997) found out that 10 years after the clear cut, the initial state was obtained again. Other authors guess that it takes a longer period to balance the carbon losses. Slash burning leads not only to short- and middle-term carbon losses, but to long-term carbon losses as well (JOHNSON & HENDERSON, 1995, p. 138 f).

Clear cutting is an unusual practice in Germany today. The respective short-term carbon losses can be neglected, hence. Regarding former clear cuts it could be argued that they still act as sinks in our days. On the other hand, it should be considered that calamities occur periodically which have carbon releasing effects similar to clear cuts. To answer the question whether today's carbon losses after calamities exceed carbon accumulation on former clear cut and calamity stands (or vice versa), statistical data would be required. With the exception of some damage reports after unusually extensive calamities (mostly published for state owned forests), there are no data neither on calamities (especially concerning the specifics of the affected stands) nor on the extent of clear cuts.

- **Site preparation**
  Generally, site preparation stimulates decomposition of organic matter and thus leads to increased carbon releases. Depending on the particular site preparation practice (whole field or single places preparation), accelerated growth of the new tree generation can equal or even exceed the initial carbon release (DE WIT& KVINDESLAND, 1999). Ploughing the entire area leads to carbon losses in any case (BURSCHEL et al., 1977, p. 91; HEINSDORF & KRAUß, 1974, p. 28).

  Site preparation is carried out mostly after clear cuts. Hence site preparation is of low significance for Germany (see thinning and end use practices).

- **Length of rotation period**
  Longer rotation periods imply higher carbon stocks in the soil. However, the increment of soil carbon content decreases the older the stands are (DE WIT & KVINDESLAND, 1999). When the biological age limit is approached, biomass decomposition equals gross biomass production, implying a convergence of carbon fixation to an asymptote. HEINSDORF et al. (1986) detected a very close correlation between age and overall soil carbon content of younger scotch pine stands in Northeast Germany. As their eldest investigated stand was only about 100 years old, they were able to use a regression function which shows an undamped increase over tree age; therefore their model does not allow for the declining increment of carbon stocks in old forest stands.[14] Moreover, this regression function is only valid for a single tree species and for only two site classes.

- **Change of tree species**
  Leaves can be decomposed easier by micro-organisms than needles. Additionally, micro-organisms have better conditions in broad-leaved stands due to stronger light intensity on the forest floor in spring. For both reasons, the change from coniferous stands to broad-leaved stands leads to a stronger mineralization of organic matter. Consequently, changing from coniferous to broad-leaved stands implies carbon releases from the soil carbon stock (BARITZ, 1998).

  In Germany great importance for forest soil carbon stocks arise from the variation of the lengths of rotation periods and the change of tree species. Many forest enter-

[14] They modelled carbon content in the soil as [$C_S = \beta_0 - \beta_1\sqrt{age} + \beta_2 age + \varepsilon$], with an r^2 of 96 % (91 %) for a better (worse) site, respectively (HEINSDORF et al. 1986).

prises, especially public ones, aim to enhance the quota of broadleaves and accordingly, to extend the lengths of rotation periods. But the effects of those measures on forest soil carbon contents are reverse. Scientific insights into the dependencies between tree species, stand age, stand density, and forest soil carbon stocks on given sites are not yet available. Even the effects of these measures on carbon stocks are thus not quantifiable.

- **Fire**

  Globally, fire is an important carbon source of the forest sector. In Germany, fire poses a serious threat for densely stocked, middle-aged scotch pine stands especially in the Northeast. Though there is a national forest fires statistic for Germany, due to the lack of information on regional distribution of fires and due to the lack of deeper knowledge the effects of fires on forest soil carbon stocks can not be quantified.

- **Fertilizers (including lime) and herbicides**

  As long as nitrogen is the limiting nutrient in terrestrial ecosystems, nitrogen fertilisation generally leads to carbon stock increments. After lime application, increasing as well as decreasing carbon stocks have been noticed. Herbicide application is without any verifiable effect on forest soil carbon matter (DE WIT & KVINDESLAND, 1999).

  Fertilisation and herbicides application in forests are of only little relevance for Germany. Accordingly, statistical data are scarcely existing. BERENDES & WULF (2000) investigated the use of pesticides in German forests and found out that 1% to 1.5% of the forest area has been treated with pesticides in the years 1996 and 1997. However, there is no reference stating any effects of the use of pesticides on forest soil carbon stocks.

- **Forest pasture and mulch collection**

  Forest pasture and mulch collection have great importance for the carbon content of forest soils, especially of the organic layer. An analysis of existing literature shows that in our days forest pasture and mulch collection are of no relevance for most European countries. In the case of relevance, country specific investigations would have to be analysed.

- **Drainage and irrigation**

  Drainage leads to higher oxygen content in the soil and thus to a rising biological activity. Higher biological activity means higher decomposition. Drainage thus leads to carbon stock losses (BARITZ, 1998; DE WIT & KVINDESLAND, 1999). Conversely, irrigation due to abandonment of former drainage systems implicates humus accumulation and thus carbon stock growth.

  In German forestry, there is the trend rather to restore natural conditions than to cultivate. Therefore effects of irrigation would be rather of significance than the effect of drainage. Also for these opposed effects there are no data available. Irrigation due to drought is not usual in German forests.

- **Deposition of anthropogenic emissions**

  Antropogenic emissions have ambivalent impacts on forests. Soil acidification reduces biological activity and leads to an enhancement of organic material especially in the upper (organic) layer. On the other hand, nitrogen deposition can improve site condition and thus reduce organic material, as well especially of the upper (organic) layer (BARITZ, 1998).

Anthropogenic immissions into forests have obtained public attention especially in the eighties. Since then the situation of German forests has been reported frequently. Unfortunately, changes in the conditions of forest soils are not included in these reports. Thus carbon stock changes in forest soils due to anthropogenic impurities deposition can not be estimated.

Conclusion

Summing up it must be stated that there is currently no possibility to estimate short-term changes of forest soil carbon stocks for Germany. For this reason it must be assumed that forest soil carbon stock remains constant over time.

1.7 Synopsis

Resuming the previous forest carbon estimations, Table 20 provides a synopsis over the significance of the organic components in forests and forest soils with regard to carbon storage and sequestration. German forest carbon stocks account for 2,249 Mio. t C. Nearly half of it is stored in the mineral soil. Total underground stock covers approximately 60 % of the total carbon content of German forests. Coarse wood, which is the best investigated biomass component in German forests, accounts for only one third of the total carbon stock. Net increment amounts to 0.7 % of stock value. Caused by the missing growth information on forest soil carbon content, coarse wood reaches the highest share in carbon stock net changes (64 %). Each year, nearly 15 Mio. t C are sequestered by forests and forest soils in Germany, net of harvests.

Table 20: Estimated carbon stocks and carbon stock net changes of organic components in German forests and forest soils; referred to reporting time 1987-1999 respectively 1993-1999

organic components	**carbon stock [1,000 t C]**	**[%]**	**net changes [1,000 t C/a]**	**[%]**
coarse wood	724,364	32	9,610	64
small wood	127,345	6	2,286	15
needles	62,947	3	690	5
roots	166,056	7	2,309	16
humus layer	223,000	10	0 *	0
mineral soil	945,000	42	0 *	0
total	2,248,712	100	14,895	100

** conservatively assumed zero (=steady state) due to lack of reliable data*

The expansion factors used to derive these results fit well to the respective estimates of other authors (e. g. BURSCHEL et al, 1993; SCHÖNE & SCHULTE, 1999). For a comparative discussion, see DIETER & ELSASSER (2002).

2 Approaches to a Monetary Valuation of Carbon Sequestration by German Forests[15]

2.1 Introduction

"Air" is probably the front-runner among older economics textbook examples for a free good, i.e. a good for which no scarcity exists. Without scarcity, there is neither a need for markets nor for market prices to evolve, and it would not make much sense to attach a money value to such a free good. But as the signs increase that the world is threatened by a gradual climate change which can at least partly be ascribed to rising greenhouse gas concentrations in the atmosphere (cf. HOUGHTON et al. 2001 for an overview), "air" – or more precisely, air of a certain quality – ceases being a free good; its limited capacity of serving as an emission sink for all sorts of production processes makes it a scarce production factor itself. Hence, it enters the sphere of economics, gaining economic value. This does not necessarily mean that there are markets for this good: by and large, air quality has mainly been addressed by regulations instead of markets as yet; it has thus still remained a global public good not directly priced by a market.

In fact, comprehensive markets for all those elements which make up "air quality" are still not fully developed today, although first examples have been established in some countries for certain substances (emission certificates for SO_2 in the USA are an example). The development of certificate markets for carbon is just at its nascent stage, and they are still far from operating as a world wide routine business. Therefore the price information available today is not reliable enough as to base an economic valuation of the carbon binding service of forests exclusively on prices; the market price approach has to be supplemented by additional approaches.

Consequently, three approaches are being presented in this report. The first is *damage valuation*: the monetary value of the damage by a (marginal) increase in atmospheric carbon can be interpreted as equivalent to the marginal value of carbon storage. Second, the costs of *damage avoidance* which a society incurs when lowering emissions – by investing either in less carbon intensive technology or in sequestration measures – may be used for valuation. And third of course, a valuation by *prices* realised in some early markets for carbon can be conducted. All these approaches will subsequently be described and applied to the carbon binding service of German forestry, and the suitability of these approaches to supplement national accounts will be discussed.

[15] Unit cost estimates in the literature are either per ton C or per ton CO_2. In the following text, we generally converted C based values to CO_2 based ones where necessary to avoid possible confusion, using a conversion factor of 3.67.

2.2 The damage valuation approach

2.2.1 Background

There is growing concern that rising greenhouse gas concentrations in the atmosphere could lead to a climate change which might develop severe environmental impacts world-wide, including an increment in the frequency of storms, droughts and floods, rising sea levels, accelerated rates of species loss, altered agricultural patterns, increased incidences of infectious diseases, and others. In so far as these impacts lead to a loss of life quality, they are costly. Under model assumptions of an equilibrating market which is guided by rational behaviour and full information of the participants, the damage cost associated with a marginal increase in the atmospheric carbon content equals the economic value of an additional carbon unit released into the atmosphere.

The literature on the potential impacts of global warming is wide and constantly growing (for a recent overview, see MCCARTHY et al. 2001), and some authors have already estimated the costs associated with (many of) these impacts. Cost estimates for a doubling of atmospheric CO_2 roughly lie in a range of 1.5 to 2.0 % of GDP for the world as a whole in older studies (FANKHAUSER 1993:88; MANNE et al. 1995; PEARCE et al. 1996), but estimates of 0.1 % of GDP as well as 4.8 % also have been published (MENDELSOHN et al. 1996; HOPE & MAUL 1996). A recent study by NORDHAUS & BOYER (2000) confirmed the early 1.5 % estimate. Contrary to this, TOL (forthcoming) found that global warming could also lead to positive net effects; he estimated a world wide aggregate benefit of 2.3 % of GDP under a doubled atmospheric CO_2 concentration, at least when the usual aggregation rule was applied (i.e. no different weights for poorer and richer people. For an overview, see TOL et al. 2000).

The wide range of estimates reported here already points to one of the central problems with such cost calculations: They need an enormous number of assumptions to bypass information gaps still existent today – about the meteorology of climate change itself, its impacts, their regional distribution, the various societies' reactions and adaptations to these impacts, and finally, the respective societies' valuations of all the changes initiated by the warming (e.g., human mortality risks). Various aggregation problems additionally appear – problems of regional aggregation, of aggregation across sectors and across time (discounting). As an example, TOL (forthcoming) showed that losses due to an increase in global mean temperature would mainly accrue to developing countries in Latin America, Asia and Africa; European and other OECD countries on the other hand might altogether gain from a limited global warming. Such distributive differences inevitably imply value judgements when it comes to aggregation, at least when an institution is missing which allows for a compensation of these differences.

2.2.2 Marginal valuations and application to forestry

The information problems described above apply to marginal cost estimates as well. Marginal costs (or at least, per-unit-costs of a "small" additional quantity of carbon released) have been estimated by various authors in the last decade. Table 21 presents some of the estimates (most of which are oriented at IPCC's 'IS92a' emission scenario). Most of the point estimates lie roughly between 1.4 and about 5.4 US$/t$CO_2$; higher values are generally due to lower discount rates and/or the use of expected values instead of "best guesses".

Table 21: Marginal Cost Estimates of CO_2 Emissions

study	model	cost [US$$_{1990}$/tCO$_2$]
AYRES & WALTER (1991)°		8.2–9.5
NORDHAUS (1991)°	DICE	2.0
PECK & TEISBERG (1991)°	CETA	3.3–3.8
CLINE (1992,1993)°	DICE	2.1–42.0
NORDHAUS (1994)°	DICE	1.9
FANKHAUSER (1995)°		6.2
MADDISON (1995)°		2.2
HOPE & MAUL (1996)	PAGE	1.4
PLAMBECK & HOPE (1996)*		–1.9
TOL (1999)*	FUND	2.5
TOL & DOWNING (2000)*		4.4

*Sources: °PEARCE et al. (1996); HOPE & MAUL (1996); *TOL et al. (2000) (modified). All converted from US$/tC to US$/tCO$_2$.*

Faced with the profuse amount of assumptions behind each of these estimates it is necessary to look at some measures of uncertainty associated with these values. Already the statistical confidence intervals, where reported, show that the results at best signify an order of magnitude rather than exact values. HOPE & MAUL (1996) and FANKHAUSER (1995) reported 90%-confidence intervals of 40%–160% and 30%–230%, respectively; the interval in NORDHAUS (1991) was even between 4% and 900% of the point estimate. TOL (1999) performed a detailed sensitivity analysis with the FUND model. Different assumptions about the discount rate clearly turned out to be most important; with a 0% discount rate, marginal costs per tonne carbon were up to 70-100 times higher than with a 10% discount rate. Another important influence came from the aggregation rule applied: Under "equity weighting" (see TOL 1999), world-wide marginal damages were three times higher than under simple summation. The assumption of a temperature rise of 1.5°C (instead of 2.5°C) roughly halved marginal costs, whereas an assumption of a 4.5°C temperature rise nearly doubled them. Other variations had a smaller influence (i.e. extension of the time horizon from 2100 to 2200, postponing emissions for 10 years, and variations in the underlying emission amount scenario).

Turning back to the point estimates, it seems that world-wide marginal damage costs around 1.4–5.4 US$/tCO$_2$ would be a guess which is mainly supported by the respective literature (cf. Table 21). Combining these point estimates with the quantity estimates developed above (in Table 20), the value of the carbon annually sequestered by German forests would have to be put between 76 and 292 million US$/year. With a marginal cost of 40 US$/tCO$_2$ (approximately the maximum value reported in Table 21), the carbon binding service would be worth about 2.2 billion US$/year (if on the other hand a limited warming would lead to benefits instead of costs – as cannot be excluded from the literature results presented above –, the carbon binding would be worthless, or of negative value).

2.2.3 Compatibility with National Accounting Principles

Using value estimates based on the damage cost approach for satellite accounts to the SNA would raise four major problems. The first of these is the uncertainty of the estimates due to the partly speculative character of the assumptions they are based on. The large range of damage estimates itself, as described above, makes the results of the damage valuation approach unreliable – at least for the time being.

A second problem has to do with possible misinterpretations of the marginal damage values, when these are related to SNA. A major part of these damages would accrue to non market goods which are not being recorded in national accounts today (for example, the value of a human life included in some damage estimates to account for altered mortality risks is alien to today's national accounting, since changes in 'human capital' are not reflected there). Hence the reference system of the cited damage values does not exactly fit.

A third problem is that although damages are usually not being included in national accounts, expenses for the elimination of damages are. This might lead to double counting if measures for damage elimination have been taken during the reporting period for which the valuation exercise has been done.

The fourth problem is a distributive one which is associated with world-wide damage aggregation. Relevant for a nation's accounting would be the damages of global warming which accrue to this country, rather than an average value for world-wide damages. As depicted above, damages would mainly emerge outside Europe; Europe as a whole (and hence at least most of its single countries) would suffer from below-average damages or would even benefit from global warming. If the latter was true, the value of carbon binding would be zero (or more precisely: less than zero), following the damage valuation approach.

2.3 The damage avoidance cost approach[16]

2.3.1 Background

In the presence of noticeable uncertainties about the possible damages due to climate change there are basically two options for a country's climate policy. The first is adopting some 'environmental (minimum) standard' approach which forces the economy to take measures for reducing atmospheric carbon load. The second is 'doing nothing'. The opportunity costs associated with reduction measures may be interpreted as the monetary value a society places on avoiding climate change induced damages. (Strictly speaking, these are 'costs of the climate protection policy' rather than 'the value of the carbon reduction service' itself: The concrete specification of the environmental (minimum) standard may be influenced by additional elements, e.g., by the risk aversion of a society, by the extent to which political institutions fail to transmit a society's preferences, by the efficiency of the political instruments chosen, by the additional influence of other political goals, or also by the bargaining power of a country in international climate negotiations).

The costs of reduction are quantity-dependent: Marginal costs increase with the amount of reduction. This complicates matters. Point estimates of costs are only valid for a specific amount of reduction, and cost functions rather than point estimates would be necessary for valuation in the absence of concretely specified reduction goals. The 'Kyoto protocol to the United Nation Framework Convention on Climate Change' contains such reduction goals to which point estimates of costs can be linked. However, these goals are not unique, but country specific. For the European Union as a whole, an 8 % emission reduction is envisioned as compared to the base year 1990. Austria is obligated to reduce emissions by 13 % to contribute its share to the Kyoto goal for the EU, whereas Germany is obligated to a 21 % reduction (burden sharing). Beyond that, Ger-

[16] sometimes also called "mitigation cost" or "abatement cost" approach in the literature.

many has committed itself internally to a 25 % reduction. The differences in marginal costs which already exist between economic sectors are being further amplified by such country specific quantitative goals. Hence the extent to which a trade-off between sectors as well as between countries will be allowed may significantly influence the 'price' a country will have to pay for reaching its reduction goal. Respective trade rules are still under development.

Basically two ways exist for reducing atmospheric carbon load, viz. avoiding emissions and sequestering carbon in sinks. Both possibilities are accepted by the Kyoto protocol and followers, although the accounting of sinks is meant to be only additional to domestic emission abatement activities. Both possibilities will be presented below.

2.3.2 Emission avoidance

The recent economic literature contains a multitude of studies presenting results of avoidance cost estimations as well as surveys about those. Among these studies there are great differences with regard to model type, time horizon, regional focus and assumed extent of emission trade. In particular the latter two are of great importance for the height of the emission avoidance costs. It is obvious that inter-sectoral and international emission trading leads to diminished marginal avoidance costs, for trading facilitates finding the least cost alternatives. This effect has to be taken into account when designing and implementing an emission trading system. Below, a few studies pointing out this result shall be introduced and discussed.

For one single state of Germany, Bavaria, different avoidance measures have been calculated using an engineering economic model (WAGNER et al., 2000). Avoidance costs for heat insulation in residential buildings totalled between 500 and 10,000 €/tCO_2 for cellar insulation and roof restoration, respectively. Replacement of out-dated white goods by more energy efficient ones resulted in a wide range between negative avoidance costs and 1,500 €/tCO_2, depending on the type of apparatus. Economic behaviour presumed, negative costs should not appear in an economic model. The existence of negative costs in reality may be attributed to market imperfections, i.e. incomplete information, hidden costs such as the risks associated with using new technologies, or it may be due to an incomparability of the goods exchanged against each other.

Estimations for the entire Federal Republic of Germany (HILLEBRAND et al., 1996) resulted in lower costs of emission avoidance. This may be due to two possible reasons: The use of a macroeconomic model which reduces total avoidance costs by energy tax revenues, and the greater regional unit which accounts for greater differences in the avoidance costs. HILLEBRAND et al. jointly assessed a large number of emission reduction measures which had been proposed by an inter-ministry panel; some of them have already come into force. For different sectors, avoidance costs varied between 200 (household) and a bit more than 400 €/tCO_2 (manufacturing industry). Another result was that despite the already large number of measures proposed by the inter-ministerial panel, additional measures like combined heat and power generation would be necessary to achieve the emission reduction targets. However, these comprehensive actions induce undesired effects. E.g. the necessary heat insulation measures in old buildings would generate a growth of building investments of more than 20 %. The consequences of such an economic growth impetus are price increases followed by growth losses, employment losses and a significant rise in the rate of inflation. Ensuring the macroeconomic targets, high employment, price stability, appropriate economic growth and foreign trade equilibrium, some measures may not be acceptable.

A lot of studies show directly the cost-cutting effect of emission trading by comparing marginal avoidance costs without trading to those with trading. Without trading, ZHANG (1999; cited in MOROZOVA & STUART 2001, p. 67) estimated domestic costs that range from 2 US$/t$CO_2$ in the EU to 85 US$/t$CO_2$ in Japan. If trading is allowed, the international price results in 3 US$/t$CO_2$. All these data are scenario forecasts for the year 2010. Other models, cited in IEA (2001), lead to similar results (Table 22). However, in all of these studies the lowest avoidance costs emerge in the United States of America. For Europe the marginal avoidance costs vary between 23 and 228 US$/t$CO_2$, with a median of about 49 US$/t$CO_2$. In the case of global trading the price would adjust to 8 US$/t$CO_2$ on average. IPCC provides a comprehensive survey on existing models resulting in mitigation cost estimates (IPCC, 2001; see Annex 3).

Table 22: Marginal avoidance costs in US$$_{2000}$/t$CO_2$

Model	**No trading US**	**No trading Europe**	**No trading Japan**	**Annex B trading**	**Global trading**
SGM	48			22	8
MERGE	81			34	24
G-Cubed	19	49	74	11	4
POLES	24	38-41	71	33	10
GTEM	111	228	222	36	
WorldScan	11	23	26	6	
GREEN	44	58	23	20	7
AIM	49	63	75	19	13
Average	48	77	82	24	8

Sources: SGM: SANDS et al. (1998), MERGE: MANNE and RICHELS (1998), G-Cubed: MCKIBBIN et al. (1998), POLES: CAPROS (1998), GTEM: TULPULE et al. (1998), WorldScan: BOLLEN et al. (1998), GREEN: VAN DEN MENSBRUGGHE (1998a), AIM: KAINUMA et al. (1998); all cited in IEA (2001)

MANTZOS (2000, p. 6 ff.) estimates marginal avoidance costs for the European Union under different scenarios. Starting from an extremely inflexible avoidance scenario and permitting stepwise more and more trading, the (average) marginal avoidance costs decrease steadily (Table 23); in the case of no trade (scenario 1) the marginal avoidance costs are averages across sectors and countries. With regard to the proposal for greenhouse gas emission allowance trading presented by the commission of the European communities (COM, 2001) scenario 4 is closest to the recent policy situation. It comes along with marginal avoidance costs of about 40 €/tCO_2.

Table 23: Marginal avoidance costs for the European Union under different scenarios [€/tCO_2]

Scenario	Marginal avoidance costs
1) Each sector within each EU member state reaches Kyoto target in 2010 separately	125.8
2) Each EU member state reaches Kyoto target in 2010 separately	54.3
3) EU-wide emission trading among energy supply sectors	45.3
4) EU-wide emission trading among energy supply and energy intensive sectors	43.3
5) EU-wide emission trading among all sectors	32.6

Source: MANTZOS (2000, p. 6 ff.)

2.3.3 Carbon Sequestration in Sinks

In addition to emission reduction, also sequestration measures can reduce atmospheric carbon loads. There are several potential sinks for carbon which could be used additionally to the ones already existing today. Forestry offers one of these. The two forestry options available are afforestation of former non-forested land, and enhancing the carbon stocks of already existing forests. Both options come along with different costs. For example, HUANG & KRONRAD (2001) calculated average costs of sequestering an additional tonne of carbon for loblolly pine stands in the USA. Using the FAUSTMANN formula, the costs were calculated as the difference between the soil expectation value of the economic optimal rotation and the soil expectation value of the carbon optimal rotation, the latter maximising the annual increment of sawtimber, which is regarded as a long-lived wood product. HUANG & KRONRAD's results indicated costs between 0.2 and 7.4 US$/t$CO_2$ for unstocked land, depending on site quality and interest rate; for lands already intensively managed the cost range was between 1.1 and 49.4 US$/t$CO_2$. Unfortunately, comparable calculations do not seem to exist today for Germany, although models are available which could provide the basis for such a calculation (see ROHNER & BÖSWALD 2001).

KOLSHUS (2001) provides a survey of cost estimates for carbon sequestration in sinks which are based on different methods and which cover various world regions. The studies in this review consider the carbon binding potential by forest plantation, forest management, and agroforestry measures. Altogether, the point estimates reported cover a broad range of costs which lies between less than one and more than 40 US$/t$CO_2$. Studies in individual developing countries of the tropics suggested lower costs than in the temperate zone. This matches results of IPCC which indicated regional average annual costs of about 2.2 US$/t$CO_2$ for tropical forestation and reduction of deforestation, increasing to about 7.6 US$/t$CO_2$ for forestation in other OECD countries than the USA (BROWN et al. 1996, after KOLSHUS 2001). More recent estimates of carbon sequestration costs for selected Activities Implemented Jointly and other LULUCF[17] projects range from 0.03 to 7.6 US$/t$CO_2$ (BROWN et al. 2000, after KOLSHUS 2001).

The interdependency of marginal costs and amount of carbon stored is captured by studies which apply cost functions rather than point estimates. As an example, KOLSHUS (2001, fig. 4.1) compared several regional cost curves for the USA. The study with the

[17] Land use, land-use change, and forestry activities

largest marginal cost estimates in this comparison (STAVINS 1999) indicated costs which increased from about 3.3 US$/t$CO_2$ (for a sequestration of 100 Mt/year) to about 13.6 US$/t$CO_2$ (for 300 Mt/year) and more than 32.7 US$/t$CO_2$ (for 500 Mt/year).

Sequestration possibilities are not restricted to forestry alone, albeit the forestry option is often considered being comparatively inexpensive. The forestry possibilities discussed so far are concentrated on storage in terrestrial vegetation; forest soils as well as wood products constitute additional carbon sinks which could be expanded to some degree in the future (furniture, buildings, paper products etc.). Beyond that, several further potential carbon sinks are being discussed which may prove cost efficient in the future, depending on the total amount of carbon to be stored as well as on technological development:

- soils of agricultural lands (croplands, grasslands, and rangelands, with emphasis on increasing long-lived soil carbon), or of other lands (biomass croplands, deserts and degraded lands, boreal wetlands and peatlands);

- several geologic formations (oil and gas reservoirs, unmineable coal seams, deep saline reservoirs);

- oceans (through chemical as well as biological bonding).

In agriculture, the largest potential carbon sink are not the plants, but the soils. The amount of carbon bound in the soils can be significantly influenced by the cropping system, e.g. through fallow reduction or abandonment, and by the intensity of tillage. As an example, marginal costs of soil carbon sequestration through such measures have been estimated between 3.3 and more than 130 US$/t$CO_2$ (12-500 US$/tC) for an incentive program to farmers in the US-American midlands, depending upon the type of contract or payment mechanism used, the amount of carbon sequestered, and the site-specific characteristics of the areas (ANTLE et al. 2001).

Using geologic formations as carbon sinks has as a precondition that carbon be captured at the emission sources by technical measures. Potential geologic sinks are oil, gas, coal, and saline reservoirs (USDOE 1999). First, production from an oil or natural gas reservoir can be enhanced in some cases by pumping CO_2 into the reservoir to push out the product; this represents an opportunity to sequester carbon at low net cost, due to the revenues from recovered oil/gas. About 32 million tons of CO_2 per year are already used by the USA for this purpose. Next, coal beds typically contain large amounts of methane-rich gas that is adsorbed onto the surface of the coal. Since CO_2 is roughly twice as adsorbing on coal as methane, it could be injected into the bed, thus displacing methane and remaining sequestered itself (instead of the current practice for recovering coal bed methane, viz. pumping water out of the reservoir). Similar to the by-product value gained from enhanced oil recovery, the recovered methane could provide a value-added revenue stream to the carbon sequestration process, thus possibly creating a low net cost option once this technology has become better understood and left the area of limited field tests to which it is still constrained today. Third, sequestration of CO_2 in deep saline formations might be of future interest at least for countries which have large capacities of saline formations at their disposal, although this option does not produce value-added by-products like the ones before, and many aspects of environmental acceptability and safety connected with it still need clarification. Today there exists already one commercial CO_2 geological sequestration facility, run by the Norwegian oil company Statoil which is injecting approximately one million tonnes per year of recovered CO_2 into the Utsira Sand, a saline formation under the sea associated with the

Sleipner West Heimdel gas reservoir. The amount being sequestered is equivalent to the output of a 150-megawatt coal-fired power plant (USDOE 1999).

Oceans are binding CO_2 by chemical solution as well as biologically, i.e. through the organisms they host. Since oceans cover most of the earth's surface, it is no wonder that technocratic approaches are striving to exploit the sequestration potential of oceans, too. The chemical approach is to directly inject CO_2 into deep areas of the ocean. The necessary technology exists, but possible environmental consequences as well as cost effectiveness considerations make this approach still questionable today (USDOE 1999). The biological approach to enhancing the rate of CO_2 absorption in the oceans involves fertilising surface waters with nutrients which are minimum factors today, especially with iron. The objective is to stimulate the growth of plankton, which are expected to consume greater amounts of carbon dioxide – in this respect the idea is basically the same as sequestering additional carbon in forests. Since phytoplankton is an early element of the aquatic food chain, this could also benefit the growth of fish populations. Both effects come along with severe ecological risks, but several demonstration experiments have already been conducted (SFC 2002). An American ocean research foundation recently has started a program for selling "Green Tags" (which are essentially bets, comparable to commodity-futures contracts) for such ocean based carbon sequestration projects, each "Green Tag" unit of 4 US$ representing one ton of CO_2 that will be sequestered in plankton during the foundation's early research and implementation of the concept (PLANKTOS 2002).

2.3.4 Compatibility with National Accounting Principles

The damage avoidance cost approach again suffers from various problems. With regard to the adoption of the above-mentioned estimates for a monetary valuation of carbon sequestration by forests some general aspects shall be discussed.

A first problem is the quantity dependence of emission avoidance as well as sequestration costs. Due to this dependence, the scenario used in any study eminently influences the amount of the estimated costs. The general frameworks of most studies are obviously oriented at the current climate policy, i. e. especially the Kyoto targets and the respective national commitments. Former studies primarily refer to the agreements reached in Kyoto. In the meantime, provisions have been adopted in Bonn and Marrakech that influence reduction commitments, too. Concerning emission trading each party shall maintain a "commitment period reserve" not open for trading. Certified emission reductions (CER) generated by sink projects in Non-Annex I Countries are limited to 1% of base year emissions of the respective party. Sink credits resulting from domestic forest management are accepted to a certain amount only. Hence, emission avoidance measures partly can be substituted by carbon sequestration measures. These newer restraints alter the conditions for generating and trading mitigation credits, and consequently, they change the respective market values, too. Furthermore, the USA as a big potential agent has left the carbon market; for other countries it is still unsure whether they will ratify the Kyoto protocol or not. Updated studies would be necessary to assess the impacts of these changes on national or international mitigation costs.

Following the principles of the System of National Accounting (SNA), investments in emission avoidance should be fully assigned to the year of implementation. However, the emission avoidance effects of these investments pertain to several years, in contrast to the (annual) carbon sequestration service of forests which is in question here. Hence depreciation values would be appropriate which however are not in line with the principles of SNA. Furthermore, many of the cost estimates are based on assumptions about interest rates to consider future investment costs and lower energy expenditures. This investment appraisal approach is not in line with the principles of SNA, too.

To a great extent, an accurate estimation of the avoided emissions is dependent on a precisely defined baseline, which means that future energy consumption development and energy saving measures not taken for climate protection reasons should be outlined and quantified as reference for scenario simulation. However, this information is hard to gain, especially on a world wide focus.

With regard to the adoption of avoidance costs for national accounting, one must be aware that the results of mitigation cost forecasts and national accounting can hardly be combined directly. While the former are ex-ante-predictions, national accounting is always an ex-post-view on an economy. It is an immanent problem of this two-sided perspective that measures not regarded in the baseline may be conducted in reality, so that their economic effects are already included in the national accounts. In this case the use of avoidance costs can lead to double counting. This can be deemed as the major shortcoming of the avoidance cost approach.

Calculation of sequestration costs in forests is faced with similar problems as described above. From a theoretical point of view it would be in accordance with the system of National Accounting to offset an investment in carbon sequestration (e.g. enhancing the growing stock) by its opportunity costs, which are the revenues otherwise accruing to the forest enterprises and showing up in the production account. In fact however, many private and most of public forest owners pursue social targets additionally to their private ones; they invest in protective and recreation functions of forests which no market rewards today (DAHM et al. 1998). Beside the social targets, a bulk of competing private goals is routinely being discussed for German forest owners (SPEIDEL 1972). Among these are prestige goals, game hunting, money savings, and liquidity goals; also taxation reasons influence forest management goals. Carbon sequestration itself is an explicit goal at least for some public forest enterprises. Since many of the different goals listed here would lead to identical silvicultural measures, it is not possible to separate the carbon sequestration part of a forest investment from other goals. Hence, the opportunity costs of carbon sequestration can not be specified exactly.

An additional problem results from the business economic approach of most of the carbon sequestration cost estimates. Operating with net present values is not suitable for National Accounting since only transactions within the current year should be taken into account to keep consistency with the system of National Accounting.

Given the bulk of problems described above, the damage avoidance cost approach does not seem to be perfectly suited for a direct valuation of the carbon binding service of forests in the framework of national accounting. However, the model based avoidance cost forecasts can be compared with emerging market prices, which will be presented next.

2.4 Emerging market prices

2.4.1 Background

A market for greenhouse gas (GHG) emissions has started to emerge over the past five years. This market is based on the limitations of GHG emissions which are a consequence of the already mentioned international negotiations following the United Nations Framework Convention on Climate Change (UNFCCC) of 1992, especially the Kyoto protocol of 1997. The Protocol has not yet entered into force, and the process of developing institutions necessary to bring the Protocol into force is still ongoing. As yet, only few national governments have imposed legal limitations on domestic GHG emissions or established binding trading rules. European Countries which have recently developed national regulatory programs involving some possibility for trading are the United Kingdom and Denmark; however, the details of these programs are different from each other. Thus, the international GHG market is evolving under a framework which is still rather loosely constructed. To date, it has evolved from a variety of mostly project-based emission trading programs which have been voluntary in nature and which collectively serve as precursors to formal GHG regulation (ROSENZWEIG et al. 2002). In anticipation of possible governmental regulations, also some private firms have implemented internal emission trading prototypes to gain experience with trading and to detect possible problems.

Emission trading is one of the flexible mechanisms provided by the Kyoto-Protocol to help its parties in achieving the emission reduction target. In principle, there are two different emission trading schemes:

- One possibility ("cap and trade") is characterised by a global cap; initially emission permits are being allocated to different sectors or enterprises, and only these allocated permits are being traded afterwards. Emission permits may be allocated either freely, by referring to some historic point in time (grandfathering), or by an auction mechanism, the latter giving the opportunity to distribute permits most efficiently. Surplus permits can be banked to subsequent years in this scheme.

- The second scheme is referred to mitigation projects (sequestration or emission avoidance) and called "offset". Offset schemes require valid baseline scenarios, the proof of additionality, securing permanence, leakage assessment and clarification of property rights.

Most of the current national and enterprise trading programs follow the "cap and trade" scheme, however some are open for credits from emission reduction or sequestration projects. Free allocation, partly with some share of auctioned permits, is preferred in all of the trading programs. A comprehensive survey on existing trading programs is provided by HAITES & MULLINS (2001, p. 36).

Basically two ways exist to demonstrate market type carbon values: One is to use model based price forecasts, the other is to refer to prices which have already been effectuated in the real (prototype) markets established so far. Since model forecasts rely heavily on assumptions about avoidance costs which have already been described in the previous chapter, we will confine ourselves to realised prices here. Both approaches are closely connected: Ideally, market prices would reflect marginal avoidance costs under the respective conditions (i. e. consistence according to trading among countries and sectors). Differences between ex-ante model results and ex-post market prices can appear due to imperfect information concerning the cheapest avoidance options available, or they can be interpreted as surcharges or discounts for uncertainty, for example referring to the political situation in host countries. Additionally, there are several factors which need not necessarily be included in model estimates, but which can also influence emission allowance market prices, like changes in national energy policies (e.g. the establishment of a new tax system), or alterations in the approval rules for avoidance measures. Price differentials between trades can be explained by differences in the features of the reductions such as their type and vintage, geographical location, and the details of the monitoring and verification procedures. Other factors that affect reductions' commercial value include contractual liability provisions, seller creditworthiness, and the like.

2.4.2 Realised prices

As yet emission markets are still developing. Nevertheless, some transactions could already be observed in the past (see Table 24). It seems that emission markets converge to regular bond markets, as in the meantime emissions are being traded daily at the London stock exchange (REUTERS, 2002 b).

Table 24: Published carbon dioxide market transactions since 1996 (only listed if quantities and prices are available)

year	description of the transaction	quantity [t CO_2 e]	price [US$/t$CO_2$ e]
1996	Arizona Public Service acquires 2.5 Mio t CO_2 from Niagara Mohawk Energy Company	2,500,000	2.70
1998	Canadian Suncor Energy acquires 100,000 t CO_2 and a 10 Mio. t option from Niagara Mohawk	10,100,000	0.80
1999	BP internal allowance trade – pilot phase (35 transactions)	361,000	10-25
2001	BP internal allowance trade	17,000,000	7
2001	ERUPT (emission reduction units procurement tender; Dutch program with government as only buyer), purchases of credits from Poland and Romania according to JI	4,000,000	8
2001	Elsam (DK) sells CO_2-credits to Entergy (USA)	10,000	< 4.80
2001	Elsam (DK) sells CO_2-credits to Germany's utility giant E.ON	100,000	< 4.80
2001	Energy E2 (Denmark) sells CO_2-credits to E.ON	50,000	< 4.80
2002	April 10th: opening of Britain's spot market in greenhouse gas emission trading 1st deal by BP (1000 credits)		4.30-10 7.20
2002	Britain's spot market in greenhouse gas emission trading, recent price for typical transactions	5-15,000	9
2002	Summary of the expressions of interest in the first submission period according to the ERUPT program (all proposed projects are CDM-projects)	47,000-8,000,000 (per proj.)	3-5 (€)

CO_2 e: Carbon dioxide equivalent; JI: Joint Implementation; CDM: Clean Development Mechanism. Sources: SEGALEN (2002), REUTERS (2001, 2002 a, b), VARILEK et al. (2001), ANONYMUS (2002), GRÜTTER (2002), BP (2001)

The price span reflected by Table 24 ranges from a little less than 1 to 10 €/tCO_2e (which is approximately the same order of magnitude in US$); higher prices of up to

25 €/tCO_2e have been realised in the 1999 pilot phase of the BP internal trade. An average price might be assumed at approximately 5 €/tCO_2e, although the recent development at the London stock exchange seems to tend towards somewhat higher average prices.

This average also coincides well with price *expectations* of market participants, as surveyed by NATSOURCE (2002). According to this investigation, a price of just over 5 US$/$CO_2$e on average was expected for the pre-Kyoto period (reference date June 30, 2005) in interviews with representatives of 35 companies with operations in several industrialised countries. For the midpoint of the Kyoto period (June 30, 2010), the average price expectation was just below 11 US$/$CO_2$e.

When interpreting the table it has to be noted that most GHG trades effectuated so far have been voluntary, involving commodities and trade modalities defined by the trades' participants themselves. Since there does not exist any guarantee that these transactions will be accepted for future emission reductions (although this might be possible), these trades may have been influenced by some speculative motivation. A further point worth noting is that the transactions listed above may not be representative for all trades which have been concluded so far. ROSENZWEIG et al. (2002) estimated that since 1996, approximately 65 trades with a minimum quantity of 1,000 t CO_2 equivalents have occurred worldwide, including trades of reductions as well as financial derivatives based on reductions (smaller trades and internal corporate trades are not included in this figure). Turning to the value of the trades, it has to be stressed that many traders are reluctant to publish prices. It cannot be excluded that those prices which are indeed being published suffer from some bias in one or the other direction, but it seems impossible to speculate about the direction of this bias.

2.4.3 Compatibility with National Accounting Principles

It is a basic convention within national product calculation that transactions should be assessed applying market prices whenever possible (FRENKEL & JOHN 1993). Ideally, market prices reveal the real preferences of the operating subjects, reflecting the appreciation of a certain good by the consumers altogether. However, market prices may oscillate to a considerable extent which is disadvantageous for time series analysis.

Valuing the carbon sequestration service of forests via market prices, and including these in national accounts may become possible in two ways in the future, depending on the basic decision whether property rights for forestry sink credits (resulting from carbon sequestration additional to a defined baseline) will be allocated to forest owners or not. If these property rights will be allocated, revenues resulting from trades with such credits will appear automatically in national accounts. If on the other hand property rights concerning sink credits will not be allocated, a valuation of carbon sequestration by forests via market prices can be done only indirectly, e.g. in a satellite account. Assuming the European forest sector being a price taker at an international emission permit market, real market prices can be applied for valuation of the carbon sequestration service. This can be done even today, being aware that for the time being, published market prices are not too reliable due to the low number of transactions, and the problems associated with their representativity as described above.

3 Conclusions and application to the forests of Germany

The estimates of physical carbon sequestration by German forests provided in chapter 1 resulted in an annual net change of carbon stocks amounting to 14.9 MtC/a (or 54.7 $MtCO_2$/a, using a conversion factor of 3.67); total carbon stocks were estimated at 1,081 MtC (4 $MtCO_2$) in the wood biomass, or 2,249 MtC (8,254 $MtCO_2$) including humus layer and soils. Combining these quantity estimates with the price estimates presented above, the annual carbon sequestration service by German forests would have to be put in an order of magnitude between 55 Mio. and 547 Mio. €/a at prices between 1 and 10 €/tCO_2; the mean price estimate of 5 €/tCO_2 would accordingly give a value of about 270 Mio. €/year.

Model estimates of avoidance costs confirmed this order of magnitude if they assumed that global trade was permitted; for this case marginal costs close to 8 €/tCO_2 were reported. However, if trade was restricted to the EU only, resulting costs were four times higher; under a no-trade assumption, costs were even 15 times higher and would result in a value above the order of magnitude reported here. Costs for additional sequestration by forestry measures have not been available for Germany; calculation results for other countries altogether showed that forestry measures can contribute significantly to an efficient mix of measures aimed at abating global warming. Measures in temperate regions turned out to be much more expensive than in tropical ones. This emphasises the importance which trade (and other flexible instruments, like Joint Implementation) may have on carbon sequestration values.

Reported damage cost estimates were, on global average, in the same order of magnitude like market prices for CO_2, but turned out to be rather uncertain. Further problems with this approach were that they relied heavily on distributional assumptions (it may be recalled that e.g. for European countries, even negative damage estimates have been reported), and that they refer to value elements which are in many cases far from being reflected in the market price system at which national accounting is based (like money values for human lives, among others). Therefore a comparison to the results of the market price as well as the avoidance cost approach does not seem to be very fruitful for the present purpose of valuing forestry's sequestration service in the context of national accounting.

Turning back to the price based valuation results, it is interesting to compare these to the value of other goods and services supplied by forestry. The gross added value of German forestry was 1.31 Billion € in 1998 (STBA 2001). This means that if there was a global market for carbon storage recognising also sequestration by forests, carbon storage would attribute a rather significant proportion of some 20 % to the gross added value of forestry in Germany. Not much is known about the value of non-market services of forests in this country, recreation being the only service already valued at aggregate level as yet. A recent study estimated consumers' surplus for forestry recreation at 2.55 Billion €/a for Germany as a whole (ELSASSER 2001), or roughly one order of magnitude above the presented carbon values.

However, in all these comparisons it has to be pointed out that market values for carbon sequestration are highly dependent on the institutional framework of the prospective market, and especially on political decisions about the question of which countries and which economic sectors will be allowed to trade with each other. As has been shown, trade restrictions would increase costs noticeably. Since market prices for carbon sequestration are strongly dependent on opportunity costs, prices could end up far higher than under a global trade assumption. Under a restrictive framework for trade, the aggregate value for carbon sequestration by forests could hence equal or even exceed the value of the wood production or of the recreation service in Germany. Under these circumstances, some portion of the carbon price would however have to be interpreted as a fee for institutional inefficiency.

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Annexes

Annex 1: Yield tables used for updating the inventory database

Yield Table	Species Group	Applied to the following Laender (abbreviations)
Rotbuche, mäßige Durchforstung, (SCHOBER 1967)	beach	BW BY HE NI NW RP SL SH
Rotbuche, mittlere Stammzahlhaltung, (DITTMAR, KNAPP, LEMBCKE 1983)	beach	BB MV SN ST TH
Douglasie, mäßige Durchforstung, (BERGEL 1985)	douglas fir	BW BY HE NI NW RP SL SH
Douglasie, mäßige Durchforstung, (SCHOBER 1956)	douglas fir	BB MV ST TH
Douglasie, starke Durchforstung, (BERGEL 1985)	douglas fir	SN
Douglasie, mäßige Durchforstung, (SCHOBER 1956)	fir	BB
Douglasie, starke Durchforstung, (BERGEL 1985)	fir	SN
Fichte, Bonitätssystem S, (WENK, GEROLD, RÖMISCH 1984)	fir	MV ST
Tanne, mäßige Durchforstung, (HAUSSER 1956)	fir	BW BY HE NI NW RP SL SH TH
Esche, schwache Durchforstung, (WIMMENAUER 1919)	long rotation broadleaves	BW BY BB HE MV NI NW RP SL SN ST SH TH
Europ. Lärche, mäßige Durchforstung, (SCHOBER 1946)	larch	BW BY BB HE MV NI NW RP SL SN ST SH TH
Eiche, Hochdurchforstung, (ERTELD 1961)	oak	BB MV SN ST TH
Eiche, mäßige Durchforstung, (JÜTTNER 1955)	oak	BW BY HE NI NW RP SL SH
Kiefer, mäßige Durchforstung, (WIEDEMANN 1943)	pine	BW BY HE NI NW RP SL SH
Kiefer, mittleres Ertragsniveau, (DITTMAR, KNAPP, LEMBCKE 1975)	pine	BB MV SN ST TH
Birke, (SCHWAPPACH 1903/29)	short rotation broadleaves	BW BY BB HE NI NW RP SL ST SH
Schwarzerle, starke Durchforstung, (MITSCHERLICH 1945)	Short rotation broadleaves	MV SN TH
Fichte, mäßige Durchforstung, (WIEDEMANN 1936/42)	spruce	BW BY HE NI NW RP SL SH
Fichte, Bonitätssystem S (WENK, GEROLD, RÖMISCH 1984)	spruce	BB MV SN ST TH

BW	Baden-Württemberg
BY	Bayern
BB	Brandenburg
HE	Hessen
MV	Mecklenburg-Vorpommern
NI	Niedersachsen
NW	Nordrhein-Westfalen
RP	Rheinland-Pfalz
SL	Saarland
SN	Sachsen
ST	Sachsen-Anhalt
SH	Schleswig-Holstein
TH	Thüringen

Annex 2: Literature sources used to estimate root biomass from aboveground biomass

genus	data points	country	source	quoted from
Picea	1	USA	ARTHUR & FAHEY 1992	VOGT et al. 1996
	3	CZ	CERNY 1990	NABUURS & MOHREN 1993
	1	B	DEVILLEZ et al. 1973a in SANT-ANTONIO et al. 1977	KBA database
	1	RUS	DYLIS 1971	CBHB database
	3	D	ELLENBERG et al. 1986	source
	3	F	GOASTER et al. 1991	VOGT et al. 1996
	3	USA	GORDON	CBHB database
	1	DK	HOLSTENER-JORGENSEN 1958	RÖHRIG 1966
	1	B	KESTEMONT 1982	NABUURS & MOHREN 1993
	15	BLR	LAKIDA et al. 1995	KBA database
	1	S	NIHLGARD	CBHB database
Abies	6	CDN	BASKERVILLE 1966	KBA database
	3	USA	GRIER et al. 1981	KBA database
	1	USA	VOGT et al. 1983, 1990; HAR-MON et al. 1986; EDMONDS 1987 (all in VOGT 1991)	KBA database
	1	USA	VOGT et al. 1987	KBA database
	1	CZ	VYSKOT 1976 *1 in CANNELL 1982	KBA database
Pseudotsuga	1	USA	FOGEL & HUNT 1979, 1983	VOGT et al. 1996
	1	USA	GESSEL & SOLLINS 1981	CAIRNS et al. (1997)
	5	USA	GRIER et al 1977; SANTANTO-NIO & HERMAN 1977; SOLLINS et al. 1980	CBHB database
	6	USA	HEILMAN & GESSEL 1963 in SANTANTONIO et al. 1977	KBA database
	2	USA	KEYES & GRIER 1981	KBA database
	2	USA	KEYES 1979; EDMONDS 1980, 1987; VOGT et al. 1980, 1986, 1987a,b; KEYES & GRIER 1981; VOGT, unpublished (all in VOGT 1991)	KBA database
	5	CDN	KURZ 1989	KBA database
	1	USA	TURNER 1975	VOGT et al. 1996
	10	USA	VOGT 1987	VOGT et al. 1996
	2	USA	VOGT et al. 1987, VOGT 1991, EDMONDS 1980; EDMONDS 1987; VOGT et al 1983	CBHB database
	1	USA	VOGT et al. 1990 in VOGT 1991	KBA database
Pinus	2	S	AXELSSON & BRAKENHIELM 1980; LINDER & AXELSSON 1982	VOGT et al. 1996
	4	CDN	COMEAU & KIMMINS 1989	CBHB database
	1	USA	CROMACK 1973; MALKONEN 1975; SWANK & CROSSLEY 1988	VOGT et al. 1996
	1	USA	HARRIS et al 1977	CAIRNS et al. (1997)
	1	USA	KINERSON et al 1977; RALSTON et al.	CAIRNS et al. (1997)
	87	BLR	LAKIDA et al. 1995	KBA database
	3	CDN	MACLEAN 1978 in CANNELL 1982	KBA database
	11	GB	OVINGTON 1957 in SANTANTO-NIO et al. 1977	KBA database
	1	GB	OVINGTON & MADGWICK 1959 a in SANTANTONIO et al. 1977	KBA database

genus	data points	country	source	quoted from
	1	GB	OVINGTON et al. 1967 in SANTANTONIO et al. 1977	KBA database
	1	E	PUIGDEFABREGAS	CAIRNS et al. (1997)
	1	USA	RALSTON 1973, HARRIS et al. (in press) in SANTANTONIO et al. 1977	KBA database
	1	J	SATOO	CBHB database
	1	USA	WELCH & KLEMMEDSON 1975	VOGT et al. 1996
	1	USA	WESTMAN & WHITTAKER 1975	CBHB database
	1	NZ	WILL 1966 in SANTANTONIO et al. 1977	KBA database
Fagus	1	B	DEVILLEZ et al. 1973b in SANTANTONIO et al. 1977	KBA database
	2	B	DUVIGNEAUD & KESTEMONT 1977	NABUURS & MOHREN 1993
	1	? (Central Europe)	EBERMEYER 1876, WETZEL 1957 DUVIGNEAUD 1962 (in RODIN & BASILEVICH 1967) in SANTANTONIO et al. 1977	KBA database
	1	D	ELLENBERG	CAIRNS et al. (1997)
	3	D	ELLENBERG et al. 1986	source
	3	BG	GARELKOV 1973 in SANTANTONIO et al. 1977	KBA database
	1	DK	HOLSTENER-JORGENSEN 1958	RÖHRIG 1966
	2	DK	MOLLER et al. 1954 in SANTANTONIO et al. 1977	KBA database
	3	S	NIHLGARD et al. 1981 in CANNELL 1982	KBA database
	1	J	SHIDEI	CAIRNS et al. (1997)
	1	DK	THAMDRUP	CAIRNS et al. (1997)
	3	USA	WHITTAKER et al. 1974 in SANTANTONIO et al. 1977	KBA database
Quercus	1	B	COLE & RAPP 1981; VOGT et al. 1986	VOGT et al. 1996
	1	USA	CROMACK 1973; MCGINTY 1976; SWANK & CROSSLEY 1988	VOGT et al. 1996
	1	B	DUVIGNEAUD & GALOUX	CAIRNS et al. (1997)
	1	B	DUVIGNEAUD 1971	NABUURS & MOHREN 1993
	5	B	DUVIGNEAUD et al. 1971 in SANTANTONIO et al. 1977	KBA database
	3	B	DUVIGNEAUD et al. 1971	NABUURS & MOHREN 1993
	1	DK	HOLSTENER-JORGENSEN 1958	RÖHRIG 1966
	1	H	JAKUCS	CAIRNS et al. (1997)
	4	BLR	LAKIDA et al. 1995	KBA database
	1	F	LOISSANT	CAIRNS et al. (1997)
	1	USA	LOUCKS & LAWSON	CAIRNS et al. (1997)
	1	PL	MEDWECKA-KORNAS & BANDOLO-CIOLCZYK	CAIRNS et al. (1997)
	1	USA	OVINGTON et al. 1963 in SANTANTONIO et al. 1977	KBA database
	1	NL	van der DRIFT 1991	CAIRNS et al. (1997)
	1	CZ	VYSKOT 1976	CBHB database
	1	CZ	VYSKOT, M. 1976 *1 in CANNELL 1982	KBA database
	1	USA	WHITTAKER & WOODWELL 1969 in SANTANTONIO et al. 1977	KBA database
	1	USA	YIN et al. 1989	VOGT et al. 1996

genus	data points	country	source	quoted from
srb: *Betula*	3	GB	OVINGTON & MADGWICK 1959 b in SANTANTONIO et al. 1977	KBA database
	3	RUS	SMIRNOVA & GORODENTSEVA 1958	CBHB database
	1	USA	YOUNG, H.E. 1973 in CANNELL 1982	KBA database
srb: alnus	8	LT	LAKIDA et al. 1995	KBA database
	1	USA	TURNER 1975	VOGT et al. 1996
	1	USA	TURNER et al. 1976; ZAVITOV-SKI & STEVENS 1972	CBHB database
	2	USA	YOUNG, H.E. 1972 in CANNELL 1982	KBA database
	1	USA	ZAVITKOVSKI & STEVENS 1972 in SANTANTONIO et al. 1977	KBA database
	4	USA	ZAVITKOVSKI et al. 1976 in CANNELL 1982	KBA database
srb: *Populus*	1	TJ	MOLOTOVSKY	CBHB database
	3	USA	RUARK & BOCKHEIM 1987	VOGT et al. 1996

Database available from the authors upon request.

CBHB database: Database used in CAIRNS et al., 1997 (available by courtesy of M. CAIRNS and co-authors)

KBA database: Database used in KURZ et al., 1996 (available by courtesy of M. APPS and co-authors)

Annex 3: List of models used for mitigation cost estimates in different regions

Model	**Region**	**Reference**
ABARE-GTEM	USA/EU/Japan/CANZ	In: WEYANT, OLAVSON, 1999
ADAM	Denmark	ANDERSEN et al., 1998
AIM	USA/EU/Japan/CANZ	In: WEYANT, OLAVSON, 1999
	Japan	KAINUMA et al., 1999; KAINUMA et al., 2000
	China	JIANG et al., 1998
CETA	USA/EU/Japan/CANZ	In: WEYANT, OLAVSON, 1999
E3-ME	UK/EU/World	BARKER 1997, 1998a, 1998b, 1998c, 1999
ELEFANT	Denmark	DANISH ECONOMIC COUNCIL, 1997; HAUCH, 1999
ECOSMEC	Denmark	GORTZ et al., 1999
ERIS		KYPREOS et al., 2000
G-Cubed	USA/EU/Japan/CANZ	In: WEYANT, OLAVSON, 1999
GEM-E3	EU	CAPROS et al., 1999
GEM-E3	Sweden	NILSSON, 1999
GemWTrap	France/World	BERNARD and VIELLE, 1999a, 1999b, 1999c
GESMEC	Denmark	FRANDSEN et al., 1995
GRAPE	USA/EU/Japan/CANZ	In: WEYANT, OLAVSON, 1999
IMACLIM	France	HOURCADE et al., 2000a
IPSEP	EU	KRAUSE et al., 1999
ISTUM	Canada	JACCARD et al., 1996; BAILIE et al., 1998
MARKAL	World	KYPREOS and BARETTO, 1999
	Canada	LOULOU and KANUDIA, 1998, 1999a and 1999b; LOULOU et al., 2000
	Ontario (Canada)	LOULOU and LAVIGNE, 1996
	Quebec, Ontario, Alberta	KANUDIA and LOULOU, 1998b; KANUDIA and LOULOU, 1998a; LOULOU et al., 1998
	Canada, USA, India	KANUDIA and LOULOU, 1998b
	EU	GIELEN, 1999; SEEBREGTS et al., 1999a, 1999b; YBEMA et al., 1999
	Italy	CONTALDI and TOSATO, 1999
	Japan	SATO et al., 1999
	India	SHUKLA, 1996
MARKAL-MACRO	World	KYPREOS, 1998
	USA	INTERAGENCY ANALYTICAL TEAM, 1997
MARKAL-MATTER	EU	GIELEN et al., 1999b, 1999c
MARKAL and EFOM	EU	GIELEN et al., 1999a; KRAM, 1999a, 1999b
	Belgium, Germany, Netherlands, Switzer-land	BAHN *et al.*, 1998
	Switzerland, Colombia	BAHN *et al.*, 1999a
	Denmark, Norway, Sweden	LARSSON *et al.*, 1998
	Denmark, Norway, Sweden Finland	UNGER and ALM, 1999
MARKAL Sto-chastic	Quebec	KANUDIA and LOULOU, 1998a
	Netherlands	YBEMA et al., 1998
	Switzerland	BAHN et al., 1996
MEGERES	France	BEAUMAIS and SCHUBERT, 1994
MERGE3	USA/EU/Japan/CANZ	In: WEYANT, OLAVSON, 1999
MESSAGE	World	MESSNER, 1995
MISO and IKARUS	Germany	JOCHEM, 1998
MIT-EPPA	USA/EU/Japan/CANZ	In: WEYANT. 1999
MobiDK	Denmark	JENSEN, 1998

Model	**Region**	**Reference**
MS-MRT	USA/EU/Japan/CANZ	In: WYANT, 1999
MSG	Norway	BRENDEMOEN and VENNEMO, 1994
MSG-EE	Norway	GLOMSROD et al., 1992; ALFSEN et al., 1995; AASNESS et al., 1996; JOHNSEN et al., 1996
MSG-6	Norway	BYE, 2000
MSG and MODAG	Norway	AASERUD, 1996
NEMS + E-E	USA	BROWN et al., 1998; KOOMEY et al., 1998; KYDES, 1999
Oxford	USA/EU/Japan/CANZ	In: WEYANT, OLAVSON, 1999
POLES	USA/Canada, FSA, Japan, EU, Australia, New Zealand	CRIQUI and KOUVARITAKIS, 1997; CRIQUI et al., 1999
PRIMES	Western Europe	CAPROS et al., 1999a
RICE	USA/EU/Japan/CANZ	In: WEYANT, OLAVSON, 1999
SGM	USA/EU/Japan/CANZ	In: WEYANT, OLAVSON, 1999
SPIT	UK	SYMONS et al., 1994
SPIT	Ireland	O‘ DONOGHUE, 1997
World Scan	USA/EU/Japan/CANZ	In: WEYANT, OLAVSON, 1999

CANZ: Other OECD countries (Canada, Australia, and New Zealand); FSU: Former Soviet Union.
Source: IPCC, 2001