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Carbon Fixation through Forestation Activities.

A study of the carbon sequestering potential of selected forest types,
commissioned by the Foundation Face

G.J. Nabuurs & G.M.J. Mohren

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FOREWORD

The Face Foundation commissioned the Institute for Forestry and Nature Research (IBN-DLO), in Wageningen the Netherlands, to carry out a study into the fixation of carbondioxide by forest ecosystems. In 1991 the Face Foundation has been founded by the Dutch Electricity Generating Board (Sep) with the aim to fix CO₂ by means of planting of new forest. Face is an acronym for **F**orests **A**bsorbing **C**arbondioxide **E**mission.

In 1991 there were no usable data or methods available against which the assignment could be reviewed. This despite the worldwide interest in this mechanism of establishing new forests as a means of curbing the CO₂ level in the atmosphere.

One of the Foundation's first activities was to initiate a study to develop a methodology for calculating the CO₂ fixation capacity of forest ecosystems.

This report presents the results of this study. It covers the CO₂-fixation of 16 different foresttypes. The study also provides some understanding of the fixation spectrum of a forest system. Finally a method is presented to calculate the sequestration capacity of other foresttypes.

The Face Foundation presently has computer software that calculates the cost-effectiveness of the Foundation's current and future investments in the various regions of the world.

The research staff at IBN-DLO was supported by a supervisory committee consisting of representatives from the Agricultural University in Wageningen (AUW), the Ministry of Housing, Physical Planning and Environment and the Ministry of Agriculture, Nature Conservation and Fisheries and the Face Foundation. The Institute for Terrestrial Ecology (ITE) in Edinburgh was responsible for the quality control.

A workshop, attended by international experts, was held in the spring of 1993. The workshop expressed its appreciation of the thoroughness of the study and of its results.

I as well, wish to express my appreciation and I would like to thank the supervisory committee for the expert and critical way in which they have monitored and modified the study.

Drs. E.H.T.M. Nijpels

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19 August 1993

Our Ref

**SCIENTIFIC REVIEW OF THE REPORT "CARBON FIXATION THROUGH FORESTATION
ACTIVITIES" BY G J NABUURS AND G M J MOHREN**

After detailed review of its contents, I hereby state that the report on "Carbon fixation through forestation activities" by G J Nabuurs and G M J Mohren is scientifically sound, and that the results presented in the report are up to date and in agreement with present scientific information and thinking in this field.

The analysis carried out in this report correctly uses published literature, and both the methods used and the results obtained are fully in agreement with comparable analyses carried out elsewhere.

The work gives estimates of carbon stocks and carbon flows in selected forest ecosystems that are reliable in so far as the data published in the literature are correct. The report provides a good overview of the possibilities, limitations and uncertainties associated with carbon storage in forest ecosystems.

Yours sincerely

Melvin G R Cannell FRSE
Head of Station, ITE Edinburgh

Natural Environment Research Council

ACKNOWLEDGEMENTS

This study gives an assessment of the potential for storage of atmospheric carbon in selected forest ecosystems around the world. The study was funded by the Face Foundation, and carried out by the Institute for Forestry and Nature Research (IBN-DLO) in Wageningen between July 1992 and March 1993. The study was carried out under supervision of an expert panel appointed by the Face Foundation. A draft report was reviewed externally, and the final version has been revised according to the reviewers suggestions. Appendix A contains a list of persons involved in the project. The authors wish to thank the project's supervisory group, and the external reviewers for their comments and additions. We also wish to thank ms. C.G. van Eijk Bos for assisting in interpreting the growth and yield data for tropical rainforest, and dr. H. van der Voet for carrying out an uncertainty analysis of the model CO2FIX and the parameter values used to describe the selected forest types.

Wageningen, September 1993,

G.J. Nabuurs & G.M.J. Mohren

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SUMMARY

The biosphere plays an important role in the regulation of the carbon cycle, and forests are important as they contain a relatively large and stable storage pool of atmospheric carbon. Through photosynthetic assimilation of carbon in the leaves or needles, biomass is built up in compartments such as the stem, branches, foliage and roots, and is thus removed from the atmosphere. In forest ecosystems, part of this carbon accumulates during the development of the ecosystem when the living biomass and dead organic material accumulate. In young and fast growing forests, this rate of accumulation is relatively rapid. In due time, part of this carbon is allocated to the litter, which subsequently decomposes or augments the stable humus in the soil.

In managed production forests, part of the carbon in the stems is harvested and used in some kind of product. After some time, depending on the type of product, decomposition occurs and the carbon is released into the atmosphere. Storage in forests thus has a temporary character, but by means of their large amount of biomass accumulated over time, forests permanently withdraw a certain amount of carbon from the atmosphere. When this total system of living biomass, litter, soil stable humus and forest products has reached its equilibrium, the net annual storage rate is zero, but the maximum amount of carbon is withdrawn from the atmosphere.

The carbon sequestering potential of forest ecosystems mainly consists of the build-up of this equilibrium biomass after afforestation. When the equilibrium biomass in a mature stand is reached, further carbon assimilation is counter-balanced by equivalent biomass decomposition, and the carbon storing potential is used up.

This report presents the results of a study on the carbon storing capacity of 16 global forest types. Unless otherwise indicated, three productivity levels were distinguished for each forest type. Productivity is described according to the mean annual volume increment at the end of a rotation (I_m in $m^3 ha^{-1} yr^{-1}$). The forest types have been chosen according to criteria of expected high carbon sequestering capacity and probability of establishment. They are:

- 1: Regrowing, **heavily logged evergreen** tropical lowland Dipterocarp rainforest in three site classes with I_m values over the regrowing period of 11.7, 14.1 and 18.7 $m^3 ha^{-1} yr^{-1}$. The regrowing forest is heavily logged every 70 years, as a result of which the standing biomass decreases by 80%. The assessment starts with the logged-over situation.
 - 2: Regrowing, **selectively logged evergreen** tropical lowland Dipterocarp rainforest in three site classes with I_m values over the regrowing period of 12.4, 15.8 and 18.1 $m^3 ha^{-1} yr^{-1}$. The regrowing forest is selectively logged every 70 years, as a result of which the standing biomass decreases by 50%. The assessment starts with logged-over situation.
 - 3: Regrowing, **heavily logged semi-evergreen** tropical lowland rainforest in one site class with an I_m over the regrowing period of 7.0 $m^3 ha^{-1} yr^{-1}$.
-

The regrowing forest is heavily logged every 70 years, as a result of which the standing biomass decreases by 80%. The assessment starts with the logged-over situation.

- 4: Regrowing, **selectively logged semi-evergreen** tropical lowland rainforest in one site class with an I_m over the regrowing period of $10.5 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. The regrowing forest is selectively logged every 70 years, as a result which the standing biomass decreases by 50%. The assessment starts with the logged-over situation.
 - 5: **Afforestation of tropical wastelands** in one site class starting with a pioneer afforestation consisting of *Albizia* spp., which after 10 years is underplanted with *Dipterocarps* (*Shorea* spp.). Next a selective cut is applied every 70 years, through which the standing volume decreases by 50%. The I_m is $9.3 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 6: **Recovering heavily logged evergreen** tropical lowland *Dipterocarp* rainforest on a moderate site, on which the regrowth is hampered by the **vigorous growth of lianas**. The assessment starts with logged-over rain forest, and the I_m is $8.4 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. A cutting cycle of 140 years is applied, and the standing biomass decreases by 60% at logging.
 - 7: Norway spruce (*Picea abies*) stands in **montane central Europe** in three site classes in rotations of 120 years with I_m values of 5.8, 9.3 and $14.2 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 8: Mixed deciduous stands of pedunculate oak (*Quercus robur*) and beech (*Fagus sylvatica*) in central Europe in three site classes in rotations of 150 years, with I_m values of 3.5, 5.4 and $8.1 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 9: Douglas-fir (*Pseudotsuga menziesii*) stands in the northwest of the USA in three site classes in rotations of 100 years with I_m values of 11.5, 14.9 and $18.6 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 10: Norway spruce (*Picea abies*) stands in the **Boreonemoral zone** of Russia, in three site classes in rotations of 100 years with I_m values of 3.2, 4.6 and $6.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 11: Industrial plantations of **poplar** (*Populus x euramericana*) on former agricultural land in three site classes in rotations of 45 years with I_m values of 5.5, 10.4 and 13.2 and on one site in a rotation of 20 years with an I_m value of $19.2 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 12: Industrial plantations of **black locust** (*Robinia pseudoacacia*) on former agricultural land in three site classes in rotations of 50 years with I_m values of 5.8, 8.9 and $12.1 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 13: Industrial plantations of **radiata pine** (*Pinus radiata*) in three site classes in New Zealand and Australia in rotations of 40 years with I_m values of 17.5, 22.2 and $27.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 14: Industrial plantations of **Caribbean pine** (*Pinus caribaea*) in three site classes in Brazil and Venezuela in rotations of 25 years with I_m values of 13.9, 19.6 and $23.8 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 15: Industrial plantations of **loblolly pine** (*Pinus taeda*) in three site classes in the southeast of the USA in rotations of 30 years with I_m values of 6.2, 9.7 and $13.6 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 16: Industrial plantations of **slash pine** (*Pinus elliottii*) in three site classes in Brazil in rotations of 30 years with I_m values of 17.2, 26.0 and $34.8 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
-

The carbon storage potential of these forest ecosystems has been established with the help of a dynamic model (CO2FIX), which describes the carbon cycle from annual growth and loss rates of the main biomass compartments of the forest ecosystem, in combination with accumulation and turnover of soil organic matter. The input variables characterizing forest type and site conditions consist of rotation length, current volume increment, allocation of Net Primary Production (NPP) to stem, branches, foliage and roots, basic wood density, carbon content of living biomass (50%) and stable soil humus (58%), turnover rate of foliage, branches and roots, natural mortality of the tree stand, residence time of harvested products, humification rates of litter, residence time of litter and stable soil humus, initial values for dead wood, litter and stable soil humus and a thinning regime together with a specified allocation to the product groups. The input parameter values were derived from yield tables, biomass measurements and other literature sources. The model produces an annual output of stocks and fluxes of carbon in the various biomass compartments and in the soil.

The carbon sequestering capacity of forest ecosystems can be evaluated by several criteria that fall into two broad categories.

- 1) The long-term average stock of carbon in the living biomass and in the forest products. This is calculated as the average of the stock of carbon in these two compartments over a long period of time (eg. multiple rotations). Forests which are managed in long rotations with a moderate growth, but which accumulate a large amount of living biomass, score relatively high on this criterion.
- 2) The average net annual carbon flux during the first rotation. This is calculated as the average of the annual net carbon flux in the total system of living biomass, litter, dead wood, stable soil humus and wood products. The net carbon flux is calculated as carbon accumulation through growth minus carbon release through decomposition. Short rotation plantations with a high growth rate score relatively high on this criterion during the first rotation. Because product decomposition is included in the calculation, long-term average net carbon flux becomes zero during multiple rotation.

Certain forest types such as the boreal forests, contain a rather small amount of carbon in the living biomass. To evaluate these forest types correctly, the stock of carbon in the soil organic matter (forest floor litter, dead wood and stable humus) should be taken into account as well. In temperate and boreal forests, the total amount of carbon in dead organic material in the soil is larger than the stock of carbon in the living biomass. However, the rate of accumulation of soil carbon is much lower than in the biomass after forestation, the difference typically being one or two orders of magnitude.

In the analysis as presented here, forest types are only evaluated according to their carbon sequestering capacity. For this it is assumed that site conditions are stable, that productivity levels are sustainable and that no additional disturbances (eg. pollution, global climate change) occur. When planning large-scale afforestations, other important criteria may have to be taken into account as well, such as ecological diversity, scenic beauty and the effect of

the plantation on the long term productivity of the soil.

The results concerning stocks of carbon are always presented in Mg C ha^{-1} (Mega gram = 10^6 gram carbon per hectare = ton carbon per hectare) and the results concerning the fluxes are presented in $\text{Mg C ha}^{-1}\text{yr}^{-1}$. To convert from pure carbon to carbon dioxide the values should be multiplied by $44/12 = 3.67$.

The results are summarized in Figure S.1 and in Table S.1.

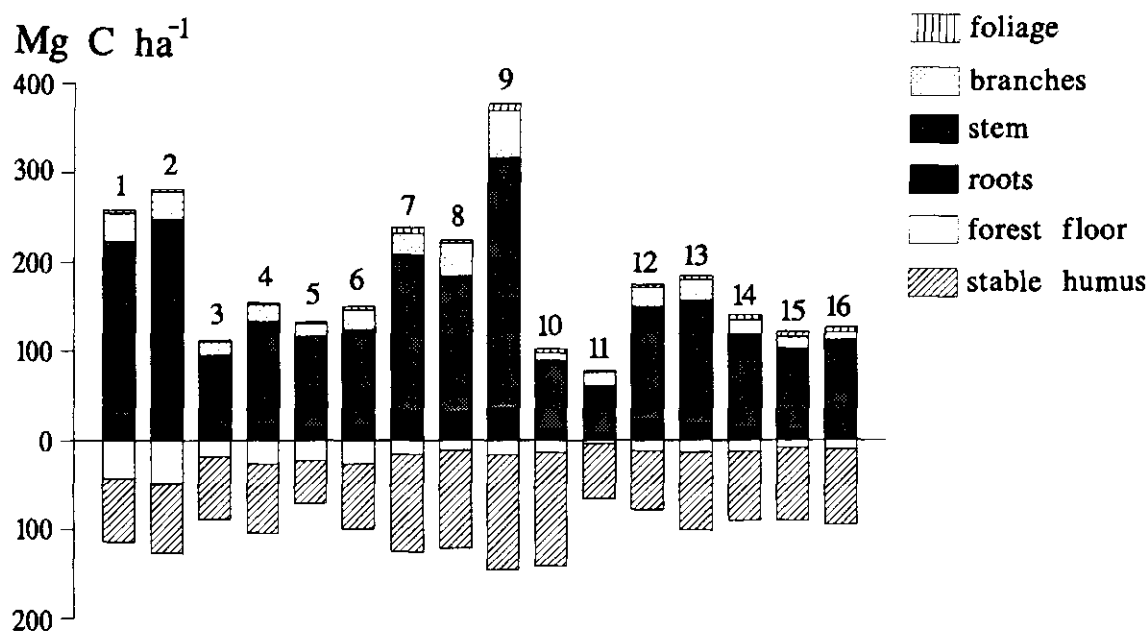


Fig. S.1 Carbon content per compartment in each forest type, at the end of the rotation, for good growing conditions. Explanation of the forest types:

- 1: Regrown, **heavily logged evergreen** tropical lowland Dipterocarp rainforest. The regrowing forest is logged heavily every 70 years.
- 2: Regrown, **selectively logged evergreen** tropical lowland Dipterocarp rainforest. The regrowing forest is logged selectively every 70 years.
- 3: Regrown, **heavily logged semi-evergreen** tropical lowland rainforest. The regrowing forest is logged heavily every 70 years.
- 4: Regrown, **selectively logged semi-evergreen** tropical lowland rainforest. The regrowing forest is logged selectively every 70 years.
- 5: Afforestation of tropical wasteland starting with *Albizia* spp. as a pioneer, which after 10 years is underplanted with Dipterocarps (*Shorea* spp.), which in turn is selectively logged every 70 years.
- 6: Regrown heavily logged evergreen tropical lowland Dipterocarp rainforest on a moderate site, with regrowth hampered by **vigorous growth of lianas**.
- 7: **Norway spruce** (*P. abies*) stand in **montane central Europe** at an age of 120 years.
- 8: **Mixed deciduous** stand of pedunculate oak (*Q. robur*) and beech (*F. sylvatica*) in central Europe at an age of 150 years.

- 9: **Douglas-fir** (*P. menziesii*) stand in the Pacific northwest of the USA at an age of 100 years.
- 10: **Norway spruce** (*P. abies*) stand in the **Boreonemoral zone** of Russia at an age of 100 years.
- 11: Industrial plantation of **poplar** (*P. x euramericana*) on former agricultural land at an age of 45 years.
- 12: Industrial plantation of **black locust** (*R. pseudoacacia*) on former agricultural land at an age of 50 years.
- 13: Industrial plantation of **radiata pine** (*P. radiata*) in New Zealand and Australia at an age of 40 years.
- 14: Industrial plantation of **Caribbean pine** (*P. caribaea*) in Brazil and Venezuela at an age of 25 years.
- 15: Industrial plantation of **loblolly pine** (*P. taeda*) in the southeast of the USA at an age of 30 years.
- 16: Industrial plantation of **slash pine** (*P. elliotii*) in Brazil at an age of 30 years.

It is clear from Figure S.1, that the bulk of carbon is usually stored in the stem wood and that the other biomass compartments (branches, foliage and roots) are of lesser importance. The amount in the forest undergrowth is not presented separately, as it appeared from literature data that this amount was usually only 1-2% of the entire ecosystem in closed forest ecosystems. The amount of biomass in plants other than trees is implicitly included in the estimate of foliage and branch biomass.

Douglas-fir stands in the Pacific northwest of the USA (no. 9) store by far the largest amount of carbon in the living biomass, followed by the long rotation mixed deciduous and spruce stands in central Europe and the regrowing selectively logged evergreen lowland tropical rainforests.

In most forest types the amount of carbon in the forest floor litter and the stable humus in the mineral soil is of considerable importance. The relatively large amount of carbon in the forest floor of the tropical forest types (type 1 to 6) consists mainly of the fairly large amount of dead wood caused by natural mortality, assumed to occur in these forest types. In the other forest types, which are subject to regular silvicultural management, no natural mortality is assumed.

The amount of carbon in the forest floor and stable humus relative to the amount in the living biomass is the most important in the boreal forest type (no. 10). In this forest type there is 60% more carbon in the soil than in the living biomass. Only under Douglas-fir in the Pacific northwest of the US, is more carbon stored in the soil organic matter.

When comparing the individual results in Table S.1, it becomes clear that a forest types may perform very well according to one criterion, but rather poorly according to another. The selectively logged tropical evergreen rainforest best satisfies the criterion, "long-term average stock of carbon in the living biomass and products" with 206 Mg C ha^{-1} , followed by Douglas-fir in the Pacific northwest of the USA. Selective logging systems in the tropical rainforests result in a much larger stock of carbon in the new equilibrium situation than the system with heavy logging. When compared to untouched virgin rainforest

all logging systems result in a decrease in the average long-term stock of carbon in the system.

As expected, the industrial short rotation forest types show relatively small stocks at the time of harvest, combined with high net fluxes during the rotation. Thus, the short rotation forest types perform very well according to the criterion net annual fixation during the first rotation. Highest net annual carbon fixation in the first rotation is achieved with Caribbean pine in Brazil with a storage rate of $5.12 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. The value given in column 2, is however, only valid for the first rotation. As explained before, net carbon flux tends to zero in the long term.

Table S.1 Summarized presentation of the carbon sequestering potential of the selected forest types (moderate production levels) according to the main evaluation criteria.

- 1: Long-term average amount of carbon (after 300 years) in the living biomass and the forest products (stems, branches, foliage, roots, undergrowth and products) (Mg C ha^{-1}).
- 2: Average net annual carbon flux over the first rotation ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$) (accumulation through photosynthesis minus decomposition of stable humus, litter, dead wood, logging slash and products).
- 3: Long-term average amount of carbon (after 300 years) in the soil organic matter (i.e. litter, dead wood and stable soil humus) (Mg C ha^{-1}).
- 4: Area technically suitable and socially available for this forest type, based on estimates by Winjum et al. (1992) after Howlett & Sargent (1991), Brown et al. (1992) & Birdsey (1990) (in 10^6 ha).

Forest type:	1	2	3	4
1. Heavily logged evergreen rainforest	144	2.40	92	5.0
2. Selectively logged evergr. rainforest	207	2.85	102	2.0
3. Heavily logged semi-evergreen rainforest	76	1.07	76	5.0
4. Selectively logged semi-evergr. rainforest	151	2.03	98	2.0
5. Afforestation of wasteland	121	1.69	67	30.0
6. Logged rainforest hampered by lianas	125	0.79	92	20.0
7. Norway spruce in central Europe	137	2.02	117	0.3
8. Mixed deciduous in central Europe	110	1.35	105	0.2
9. Douglas-fir in northwest USA	196	3.43	143	0.1
10. Norway spruce in boreal zone of Russia	53	1.03	139	30.0
11. Poplar on former agricultural land	62	2.23	75	0.2
12. Black locust on former agricultural land	111	3.35	84	0.1
13. Radiata pine in N. Zealand and Australia	126	4.54	97	0.3
14. Caribbean pine in Brazil and Venezuela	89	5.12	90	0.5
15. Loblolly pine in southeast USA	59	3.21	81	0.2
16. Slash pine in Brazil	111	3.88	80	0.3

The stock of carbon in the soil organic matter is largest under Douglas-fir followed by the boreal forests and the temperate forests in a long rotation. Limited amounts are mainly found in tropical wasteland and former agricultural land.

The fourth column in Table S.1. is added in order to provide some idea of the relevance and the afforestation potential for each forest type considered here. Some forest types perform very well per hectare, according to the long-term average stock of carbon, but in case of a limited available area, the contribution to the overall sequestration of carbon from the atmosphere will still be limited. It is expected that especially in the tropics and in the boreal zone with less intensive land-use (e.g. indicated by abundance of waste lands and left-over logged forest) afforestations can be carried out more easily than in for example Europe or the Pacific northwest of the USA, where possibility for changes in land-use may be small. For the pine plantations, the estimate in the last column is based on the present-day area.

All results are based on the assumption that site factors remain constant during the simulation period. Possible effects of climate change, acidification or declining soil fertility are not taken into account. The analysis of carbon sequestering potential depends largely on availability of growth and yield data. The results for forest types for which well established growth and yield tables are available, are very reliable. When growth rates are uncertain, the estimate for carbon sequestration is uncertain also. Allocation to the other biomass compartments (branches, foliage and roots) is done on the basis of available biomass measurements. No reliable yield tables exist for the tropical forest types (nrs. 1 to 6) and rather scattered data on regrowth or growth were used instead. Thus the results for these forest types are more uncertain, and should be updated as soon as more information on growth and productivity becomes available. More data of this type are expected to come available in the near future.

The amounts in the forest floor and the stable soil humus were based on extensive data in literature for each climatic region. The simulations were fitted by hand to reproduce existing inventory data. It was assumed that during the simulation period, there was no major decrease or build-up of the stock of stable humus in the mineral soil. Only on former agricultural land, where the stock of stable humus has declined through intensive ploughing etc., some accumulation of stable humus in the mineral soil can be expected to occur. Typically, the rate of accumulation of accumulation can be expected to be one order of magnitude less than the rate of carbon accumulation in the living biomass.

Concluding it can be stated that based on the most important criterion, "long-term average stock of carbon in the biomass and products" selectively logged lowland evergreen tropical rainforest and Douglas-fir forest in the USA sequester the largest amount of carbon. Both may achieve carbon stocks of some 200 Mg C ha^{-1} .

1. INTRODUCTION

1.1. Principles of carbon sequestration in forest ecosystems

Forest ecosystems may contain large amounts of carbon, both in the living biomass and in the dead organic material on the forest floor and in the soil (Olson et al. 1983, Post et al. 1982, Bouwman 1990). Through accumulation of biomass and, possibly, through an increase in dead organic material in the soil, a growing forest absorbs carbon from the atmosphere through photosynthesis and assimilation of carbon dioxide. The biosphere plays an important role in the regulation of the carbon cycle (Goudriaan 1987 & 1992), and the vegetation is a considerable pool of atmospheric carbon (Ajtay et al. 1977, Birdsey 1990, Bolin et al. 1986, Brown & Lugo 1986, Cannell et al. 1992, Cole & Rapp 1981, DeAngelis et al. 1981, Detweiler & Hall 1988, Freedman et al. 1992, Houghton et al. 1984, Kauppi et al. 1992, Lieth 1975, Lugo & Brown 1992, Milleman & Boden 1985, Olson et al. 1983, Reichle 1981, Trexler 1991, Vitousek 1991, Whittaker & Likens 1973, Woodwell 1984, Woodwell et al. 1978).

When new forest is established, e.g. on former agricultural land, the biomass within the ecosystem increases and carbon from the atmosphere accumulates in the vegetation (Wolf & Janssen 1991, Wiersum & Ketner 1989). In the developing forest soil the amount of stable organic matter may also increase because the soil is disturbed relatively little compared with the previous agricultural land use (Johnson 1992, Minderman 1968, Ovington 1954). The amount of living biomass accumulating peaks as growth gradually decreases when the forest ages, and litter loss and decomposition processes increase (Ovington 1965). In a mature, natural forest at equilibrium with the environment, net primary production (NPP) equals decomposition and, on average, the net carbon exchange with the atmosphere is zero. This means that the sequestering of carbon in forests should be considered a temporary phenomenon. However, as a consequence of the build-up of biomass and organic matter in the soil, a certain amount of carbon is permanently withdrawn from the atmosphere, by being incorporated in the organic material within the ecosystem.

To understand and quantify the role of forest ecosystems in the carbon cycle it is necessary to quantify both the net annual carbon fluxes and the total carbon content of representative forest ecosystems, thereby including the carbon fluxes and stocks in the soil. Only by considering both these criteria, is it possible to evaluate the feasibility of afforestation as a means to sequester and store atmospheric carbon. The carbon sequestering potential of the main forest types in The Netherlands was estimated earlier, using existing biomass data and yield tables in combination with the CO₂FIX model (Mohren & Klein Goldewijk 1990a & 1990b, Nabuurs & Mohren 1993). Similar analyses have been carried out in the United Kingdom (Dewar & Cannell 1992), Europe (Cannell et al. 1992, Kauppi et al. 1992, Kauppi & Tomppo 1993) and a selection of other countries (Dixon et al. 1991).

1.2. Method

Figure 1.1 gives an elementary representation of carbon fluxes and carbon storage compartments in a forest. Carbon is taken up as carbondioxide by means of photosynthesis. Part of the assimilates formed during canopy assimilation of carbon dioxide are used in respiratory processes, and lost to the atmosphere again as carbon dioxide. In the model photosynthesis and respiration are not considered explicitly, but instead the resulting increment rates are estimated from stem volume increments given in yield tables (Appendix D). Different site classes were used to account for the range of production levels. The production level of a certain forest (and thus its carbon sequestering potential) can be determined with the help of Appendix J. Stem volume increment is easily converted to stem biomass increment and carbon accumulation, using well-known values for basic density (dry weight per unit of fresh volume, usually expressed as kg per m³, see Appendix C), and assuming 50% pure carbon in oven-dry structural biomass (Ajtay et al. 1977).

The allocation to various organic compartments (i.e. branches, foliage and roots; appendix E) relative to stem dry weight increment and their characteristic turnover rates (Appendix F) can be taken into account too. The problem of allocation of net primary production to the different biomass compartments has long been recognized (Dewar & Cannell 1992, Johnson & Sharpe 1983, Santantonio 1989, Santantonio et al. 1977). The amount of biomass in the varying compartments is determined not only by allocation, but also by the turnover time of the organs. In this study the estimation of turnover time has been kept rather simple, distinguishing between deciduous species with a leaf life-span of one year, and conifers with average needle lifespan of three years.

By incorporating a harvesting schedule, that accounts for various product uses (Appendix I) such as paper, fuelwood, packing wood, particle board or saw timber, the subsequent release of carbon to the atmosphere through product decomposition can be analysed as well, provided some assumption can be made about average residence time of carbon in the product classes (Appendix G).

As well as accumulating in the living biomass, carbon also accumulates in the litter layer and in stable humus in the mineral soil (Schlesinger 1984, Vogt et al. 1986). The turnover time chosen for foliage, branches and roots, determines the litter input. Thus, by using residence times of carbon in litter and humus (Appendix H) that agree with general descriptions of the dynamics of soil organic matter, feasible results for stocks of carbon in humus and litter were achieved. This ensured that the whole system of production, allocation, turnover time, decomposition, humification and initial carbon stocks is interrelated and parameter values could only be set in combination and in accordance with literature, other climates and forest types.

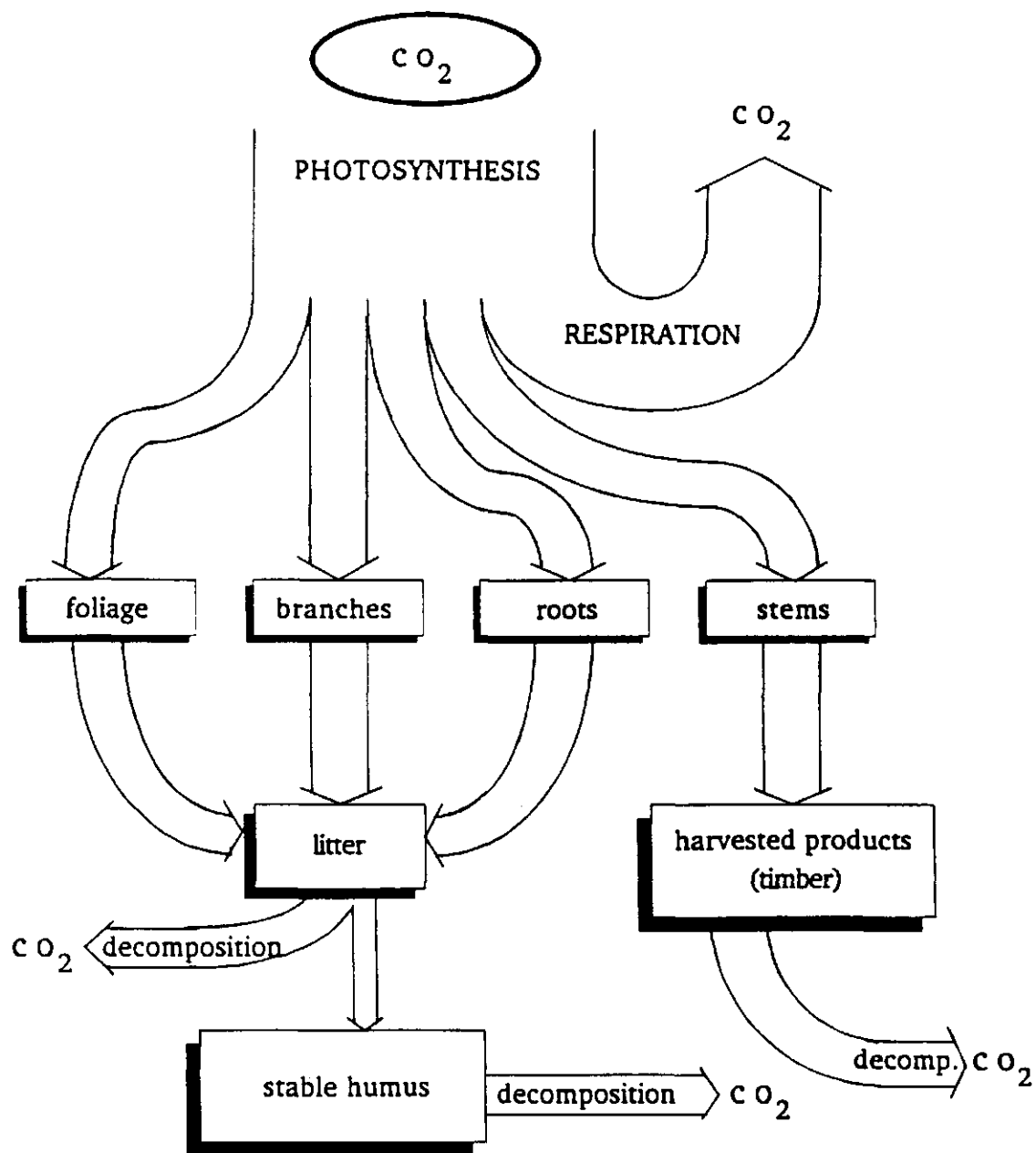


Fig. 1.1 A simplified diagram of fluxes and stocks of carbon in a forest ecosystem. For further explanation, see text § 1.2.

The simulation model CO2FIX described by Mohren & Klein Goldewijk (1990a & 1990b) was used for the calculations, augmented by published data on growth rates and amounts of biomass in the various forest types (datafiles in Mohren & Nabuurs, 1993). The model describes the carbon cycle from annual growth and loss rates of the main biomass compartments of the forest ecosystem, in combination with accumulation and turnover of soil organic matter. The input variables characterizing forest type and site conditions consist of rotation length, current volume increment, allocation of Net Primary Production (NPP) to stem, branches, foliage and roots, basic wood density, carbon content of living biomass (50%) and stable humus (58%), turnover rate of foliage, branches and roots, natural mortality of the tree stand, residence time of harvested products, humification rates of litter, residence time of litter and stable soil humus, initial values for dead wood, litter and stable soil humus and a thinning regime together with a specified allocation to the product groups. The input parameter values were derived from yield tables, biomass measurements and other literature sources (e.g. Cannell 1982, Kimmins et al. 1985, De Vries et al. 1990). The model produces an annual output of stocks and fluxes of carbon in the various biomass compartments and in the soil.

The calculation procedure in CO2FIX is comparable to the analysis of Dewar (1991, see also Dewar & Cannell 1992, and Cannell et al. 1992). Basically, a carbon accounting procedure is used, in which stem volume increment from yield tables is used to drive carbon accumulation in the entire living biomass through proportionality coefficients derived from biomass measurements. Using a simulation model that runs with timesteps of one year, a dynamic description of carbon in the various biomass components is obtained, with the possibility to adjust rotation age, thinning, product use, etc. according to the species and silvicultural system under study. Data files have been specified for all forest types and productivity levels considered (Mohren & Nabuurs, 1993).

The literature data useful for such an analysis fall into two broad categories: data on stem volume accumulation, usually obtained from long-term permanent field plots in even-aged mono-species stands, and data on ecosystem biomass and primary production, usually obtained in relatively short-term ecosystem research. Growth and yield data from monitoring permanent plots are usually fairly accurate and relatively easy to extrapolate, but are mostly limited to the stem volume of commercially grown species only, and for a limited number of silvicultural systems. Also, stem volume is only one of the biomass compartments that constitute the total ecosystem carbon content. Detailed information on total forest biomass and organic matter content is rather scarce, and although accurate for a particular forest ecosystem, more difficult to extrapolate to other site conditions and productivity levels.

1.3. Criteria to evaluate the carbon sequestering potential.

Nine criteria were selected and calculated for each forest type to evaluate the capacity of carbon fixation and -storage of the forest types considered.

- 1) Total stock of carbon at the end of the rotation in biomass and products (expressed in Mg C ha^{-1} ; represented by the value at the end of the rotation on the thick line in Figure 1.2B);
 - 2) Total stock of carbon at the end of the rotation in the soil organic matter i.e. litter, dead wood and stable humus (expressed in Mg C ha^{-1} ; represented by the value at the end of the rotation on the belowground thick line in Figure 1.2A);
 - 3) Total stock of carbon at the end of the rotation in biomass, products and in soil organic matter (expressed in Mg C ha^{-1} ; represented by the value at the end of the rotation on the thick line in Figure 1.2B and the belowground thick line in Figure 1.2A);
 - 4) Long-term average stock of carbon in the biomass and the forest products (expressed in Mg C ha^{-1} ; represented by the upper dashed line in Figure 1.2B);
 - 5) Long-term average stock of carbon in the forest products (expressed in Mg C ha^{-1} ; represented by the lower dashed line in Figure 1.2B);
 - 6) Long-term average stock of carbon in the soil organic matter i.e. litter, dead wood and stable humus (expressed as Mg C ha^{-1} ; represented by the proceeding average of the belowground thick line in Figure 1.2A);
 - 7) Long-term average stock of carbon in the total system of biomass, forest products and soil organic matter (expressed in Mg C ha^{-1} , calculated by adding up the proceeding averages of biomass, products and soil organic matter) .
 - 8) Net accumulated amount of carbon over the first 100 years after afforestation (expressed in Mg C ha^{-1} ; represented by the value of the above- and belowground thick line at $T = 100 \text{ yr}$ minus the initial values in Figure 1.2A);
 - 9) Proceeding average of the net annual carbon flux (accumulation minus decomposition of litter, stable humus, logging slash and products, expressed in $\text{Mg C ha}^{-1} \text{ yr}^{-1}$) (represented by the dashed line in Figure 1.3). The average is calculated at some arbitrary point in time, i.e. at the end of the first rotation. Obviously, the long-term average tends towards zero during multiple rotations when equilibrium is reached and no more additional carbon is added.
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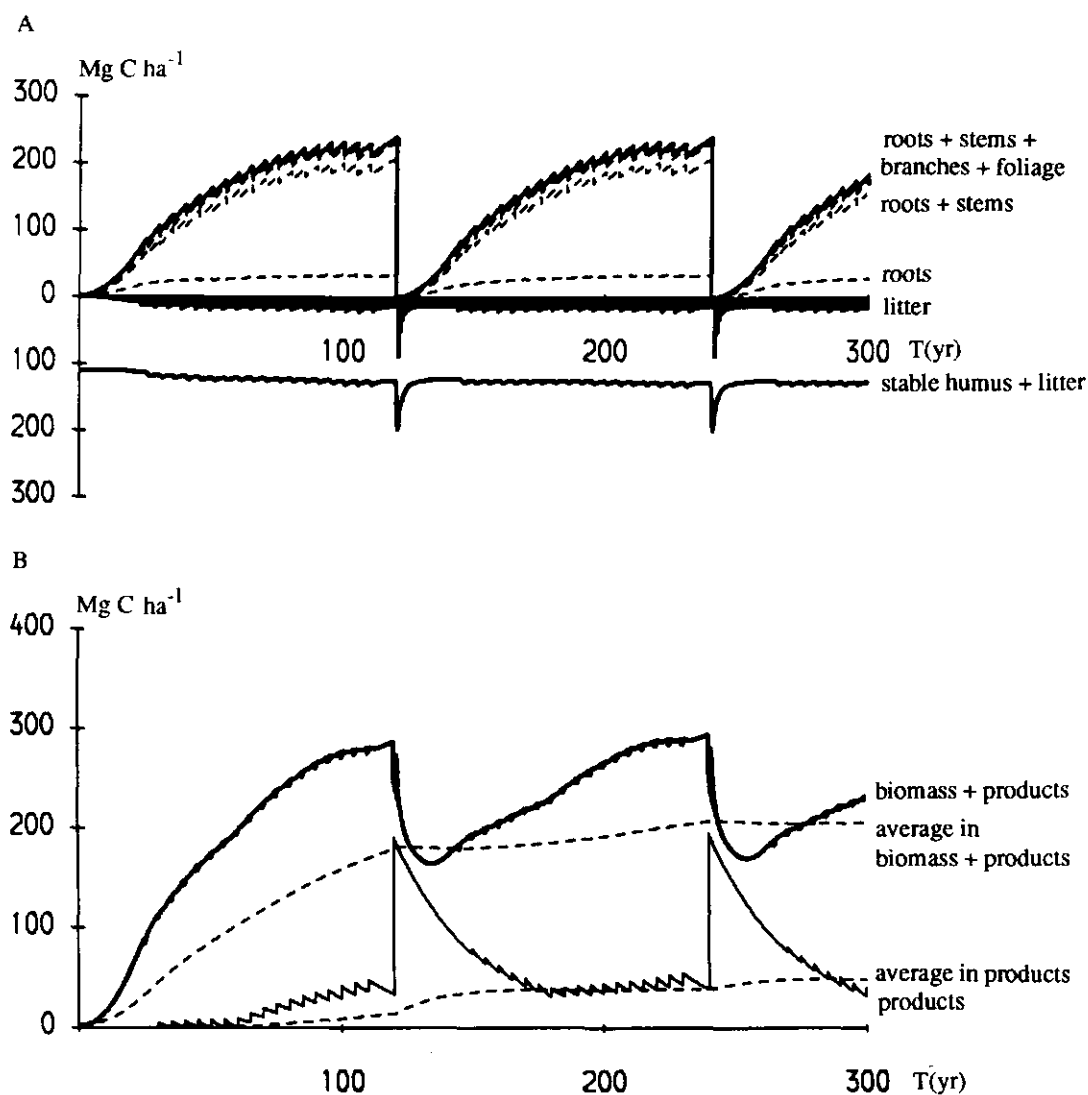


Fig. 1.2 Sample representation of carbon stocks during stand development.

A: Carbon stocks in the main aboveground biomass compartments (foliage, branches, stems and roots) and the belowground compartments (litter + stable humus); Mg C ha⁻¹; B: Total carbon stocks since stand establishment in biomass and products together (thick line) and carbon stocks in the harvested forest products (thin line), for successive rotations. Upper dashed line: long-term proceeding average value for total carbon stock in biomass and products, and lower dashed line: long-term proceeding average value for carbon stock in products. All values in Mg C ha⁻¹. Fig. 1.2 en fig 1.3

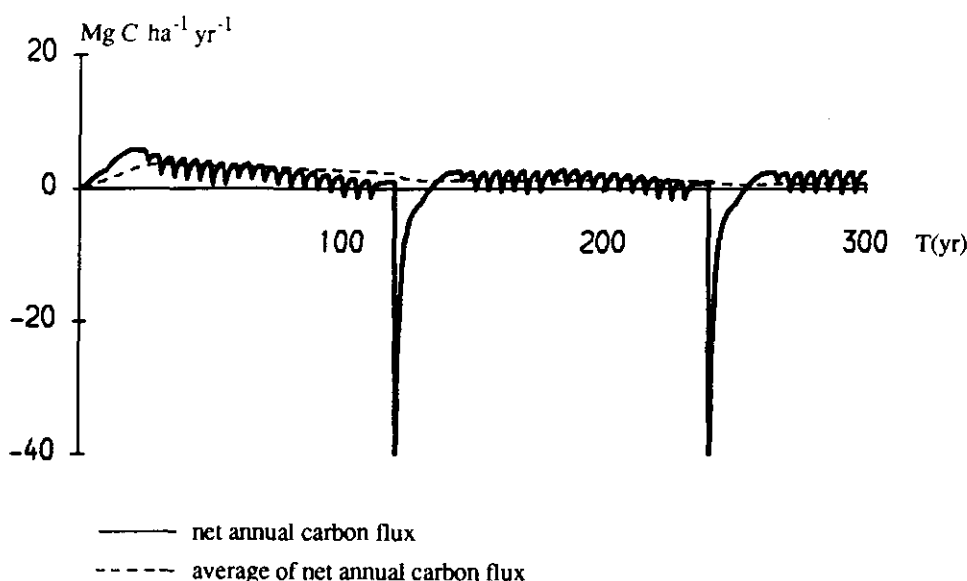


Fig. 1.3 Sample representation of net annual carbon fluxes, ($\text{Mg C ha}^{-1} \text{yr}^{-1}$), resulting from carbon accumulation in the biomass and products and decomposition of soil organic material and forest products for successive rotations corresponding to the biomass build-up presented in Figure 1.2. Thick line: carbon flux on annual basis. Dashed line: long-term average for net carbon flux.

Depending on the objective of the evaluation, one or more of these criteria can be selected. For example, for maximization of long-term, sustainable storage of carbon, the long-term average stock of carbon (criterion 4) is most appropriate, as this represents the final contribution to permanent carbon storage in the forest ecosystem and its products. If the speed of carbon fixation is relevant, it is most appropriate to look at average net annual carbon fixation over the first rotation. Short rotation plantations may seem to do particularly well in this case, but this storage rate strongly declines during following rotations, because the average stock in the total system does not increase further.

The average stock of carbon in the soil organic matter (litter, dead wood and stable humus) is of great importance for particular forest types such as the boreal forests.

1.4. Forest types considered

This report considers a number of forest ecosystems worldwide, ranging from tropical lowland evergreen rainforest to boreal spruce ecosystems, in order to assess and quantify the feasibility of carbon fixation through forestation activities worldwide. The aim is to obtain an overview based on existing information on forest ecosystem biomass and carbon assimilation and growth, that enables a worldwide comparison of forest types in relation to climate and soil. Three production levels related to site conditions are considered.

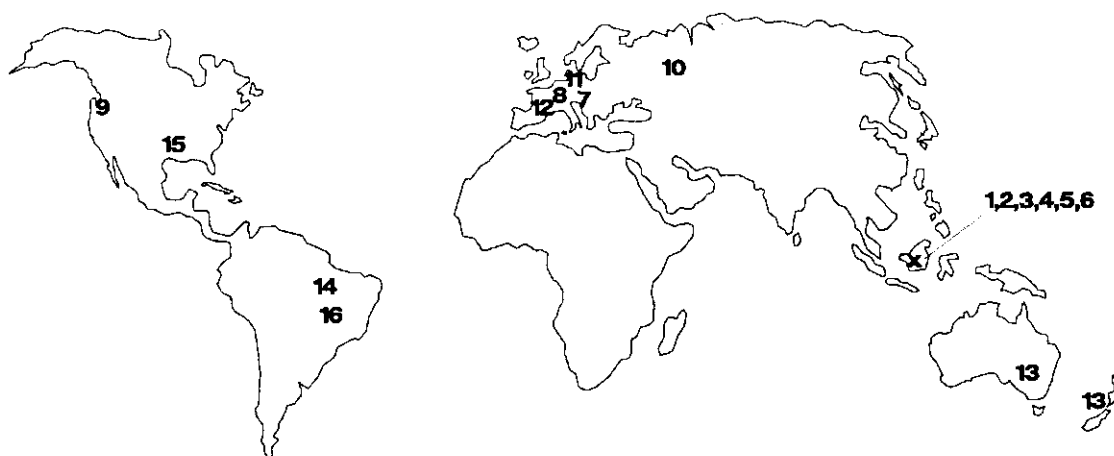


Fig. 1.4 Location of the selected forest types.

1. Heavily logged evergreen rainforest
2. Selectively logged evergreen rainforest
3. Heavily logged semi-evergreen rainforest
4. Selectively logged semi-evergreen rainforest
5. Afforestation of wasteland with Albizia
6. Heavily logged evergreen rainforest hampered by lianas
7. Norway spruce in montane Central Europe
8. Mixed deciduous forest in Central Europe
9. Douglas-fir in Pacific Northwest USA
10. Norway spruce in Boreonemoral zone of Russia
11. Poplar on former agricultural land in Europe
12. Black locust on former agricultural land in Europe
13. Radiata pine in New Zealand and Australia
14. Caribbean pine in Brazil and Venezuela
15. Loblolly pine in Southeast USA
16. Slash pine in Brazil

Taking into account the availability of biomass data and genuine stem volume growth and yield information, as well as the potential for afforestation and relevance for local forestry, the following forest ecosystem types were selected:

- 1: Regrowing, **heavily logged evergreen** tropical lowland Dipterocarp rainforest in three site classes with I_m values over the regrowing period of 11.7, 14.1 and 18.7 $\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$. The regrowing forest is heavily logged every 70 years, as a result of which the standing biomass decreases by 80%. The assessment starts with the logged-over situation.
- 2: Regrowing, **selectively logged evergreen** tropical lowland Dipterocarp rainforest in three site classes with I_m values over the regrowing period of 12.4, 15.8 and 18.1 $\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$. The regrowing forest is selectively logged every 70 years, as a result of which the standing biomass decreases by 50%. The assessment starts with logged-over situation.
- 3: Regrowing, **heavily logged semi-evergreen** tropical lowland rainforest in one site class with an I_m over the regrowing period of 7.0 $\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$. The regrowing forest is heavily logged every 70 years, as a result of which the standing biomass decreases by 80%. The assessment starts with the logged-over situation.

- 4: Regrowing, **selectively logged semi-evergreen** tropical lowland rainforest in one site class with an I_m over the regrowing period of $10.5 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. The regrowing forest is selectively logged every 70 years, as a result which the standing biomass decreases by 50%. The assessment starts with the logged-over situation.
 - 5: **Afforestation of tropical wastelands** in one site class starting with a pioneer afforestation consisting of *Albizia* spp., which after 10 years is underplanted with *Dipterocarps* (*Shorea* spp.). Next a selective cut is applied every 70 years, through which the standing volume decreases by 50%. The I_m is $9.3 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 6: Recovering **heavily logged evergreen** tropical lowland *Dipterocarp* rainforest on a moderate site, on which the regrowth is hampered by the **vigorous growth of lianas**. The assessment starts with logged-over rain forest, and the I_m is $8.4 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. A cutting cycle of 140 years is applied, and the standing biomass decreases by 60% at logging.
 - 7: **Norway spruce** (*Picea abies*) stands in **montane central Europe** in three site classes in rotations of 120 years with I_m values of 5.8, 9.3 and $14.2 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 8: **Mixed deciduous** stands of pedunculate oak (*Quercus robur*) and beech (*Fagus sylvatica*) in central Europe in three site classes in rotations of 150 years, with I_m values of 3.5, 5.4 and $8.1 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 9: **Douglas-fir** (*Pseudotsuga menziesii*) stands in the Pacific northwest of the USA in three site classes in rotations of 100 years with I_m values of 11.5, 14.9 and $18.6 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 10: **Norway spruce** (*Picea abies*) stands in the **Boreonemoral zone** of Russia, in three site classes in rotations of 100 years with I_m values of 3.2, 4.6 and $6.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 11: Industrial plantations of **poplar** (*Populus x euramericana*) on former agricultural land in three site classes in rotations of 45 years with I_m values of 5.5, 10.4 and 13.2 and on one site in a rotation of 20 years with an I_m value of $19.2 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 12: Industrial plantations of **black locust** (*Robinia pseudoacacia*) on former agricultural land in three site classes in rotations of 50 years with I_m values of 5.8, 8.9 and $12.1 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 13: Industrial plantations of **radiata pine** (*Pinus radiata*) in three site classes in New Zealand and Australia in rotations of 40 years with I_m values of 17.5, 22.2 and $27.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 14: Industrial plantations of **Caribbean pine** (*Pinus caribaea*) in three site classes in Brazil and Venezuela in rotations of 25 years with I_m values of 13.9, 19.6 and $23.8 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 15: Industrial plantations of **loblolly pine** (*Pinus taeda*) in three site classes in the southeast of the USA in rotations of 30 years with I_m values of 6.2, 9.7 and $13.6 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
 - 16: Industrial plantations of **slash pine** (*Pinus elliottii*) in three site classes in Brazil in rotations of 30 years with I_m values of 17.2, 26.0 and $34.8 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
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2. TROPICAL RAINFORESTS

2.1. Introduction

Warm and cool as well as humid and dry climates occur between the tropics of Cancer and Capricorn. A large range of tropical forest types has developed in response to these climates and the geomorphological and pedological conditions in the American, African and Asian tropics (Lieth & Werger 1989). Although vast areas of untouched rainforest still exist, a major part of the tropical rainforest is threatened with destruction within a couple of decades (Kartawinata et al. 1989, Kartawinata & Vayda 1984). In order to preserve vast areas of the virgin rainforest it is of great importance to establish strict forest reserves, to develop sustainable selective silvicultural systems (Korsgaard 1985) and to reforest wasteland.

In this chapter the forest types of Kalimantan, Indonesia, are described in more detail, after a general description of tropical forests. The parameters of the *Dipterocarp* evergreen rainforest and the semi-evergreen rainforests used as model input, such as site conditions, biomass and production rates, are described in more detail and carbon sequestering potential of several silvicultural systems in these forests is determined.

2.1.1. Climate and tropical forest types

The tropical atmosphere is an important part of the global atmospheric circulation because of the intensive circulation of heat and water vapour. Air masses heat up in the the equatorial zone and rise to the tropopause. At the tropopause, the air masses move towards the poles. The resultant cooling causes the air masses to descend at subtropical latitudes. Air masses from both hemispheres collide at the equator, forming the Intertropical Convergence Zone (see Figure 2.1). On the continents, the Intertropical Convergence Zone shifts seasonally towards the north or the south, and monsoon-like westerly winds may develop in different intensities near the equator. These winds are of special importance for the occurrence of rainfall in the equatorial forest belt.

In the tropical rainforests near the equator the mean annual precipitation is 3000 mm. In Africa and South America this amount rapidly decreases because of a dry season towards the tropics of Cancer and Capricorn. Near the marginal tropical and subtropical dry belt the world's lowest rainfall totals occur. In Southeast Asia the temporary shortage in precipitation is far less pronounced because of the monsoon (see Figure 2.2). As a result, in the rainforests of the monsoon area the amount of summer rainfall can be extremely high, but winter rainfall may be rather low.

Climatic types of the tropical rainforest can be distinguished (Lauer 1989) on the basis of the annual cycle of the water budget of the tropical region: the equatorial, the tropical, the marginal tropical, the tropical montane and the edaphic humic type. Only the first three types are of importance in this study.

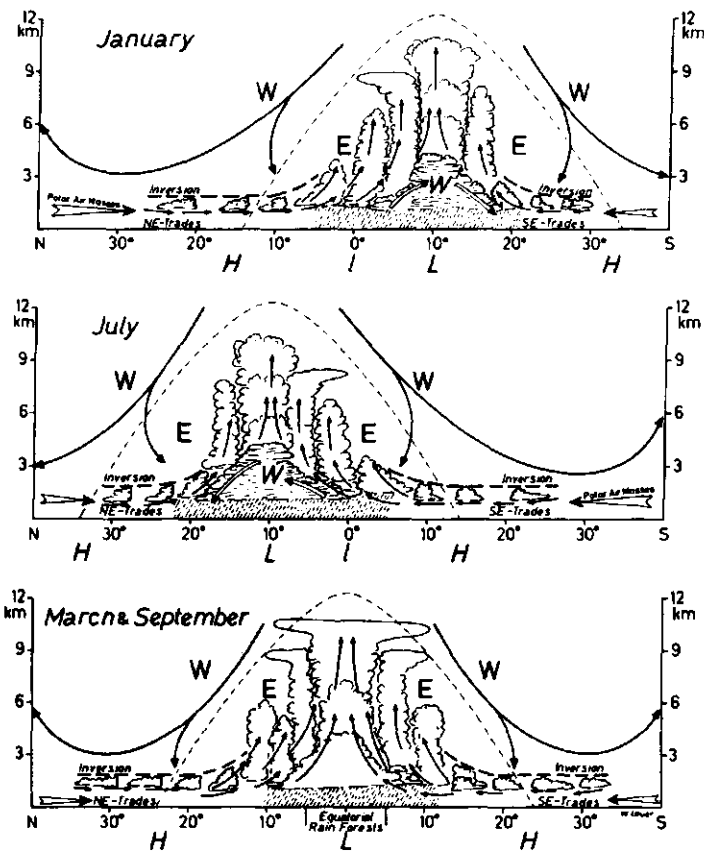


Fig. 2.1 Synoptic structure of the Intertropical Convergence Zone; W = West wind, E = East wind, H = high pressure, L = low pressure (Lauer 1989).

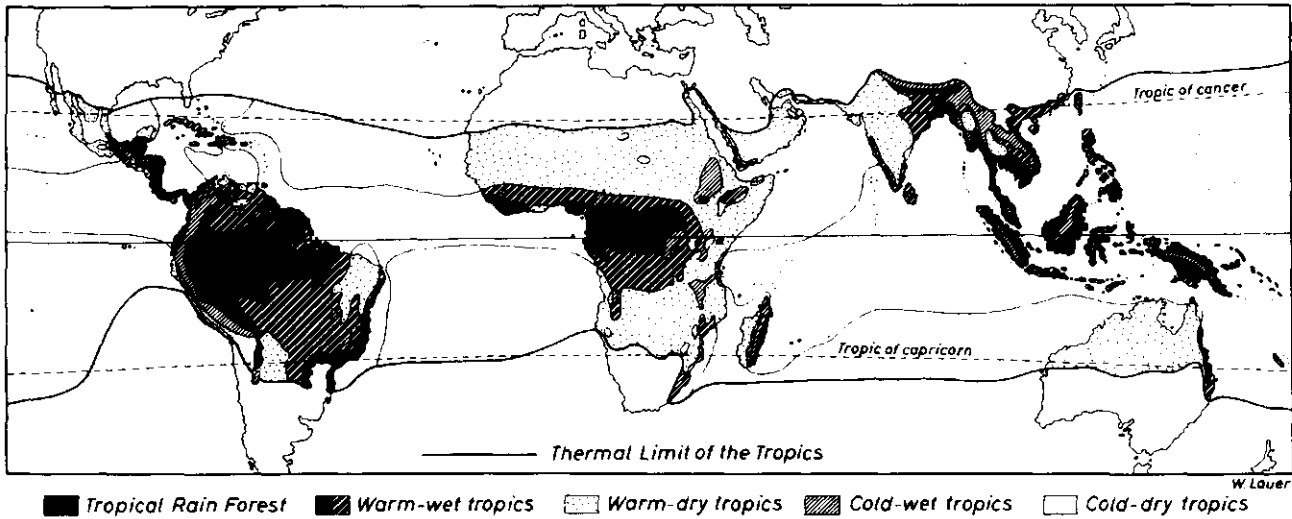


Fig. 2.2 Hygrothermal zonation of the tropics (Lauer 1989).

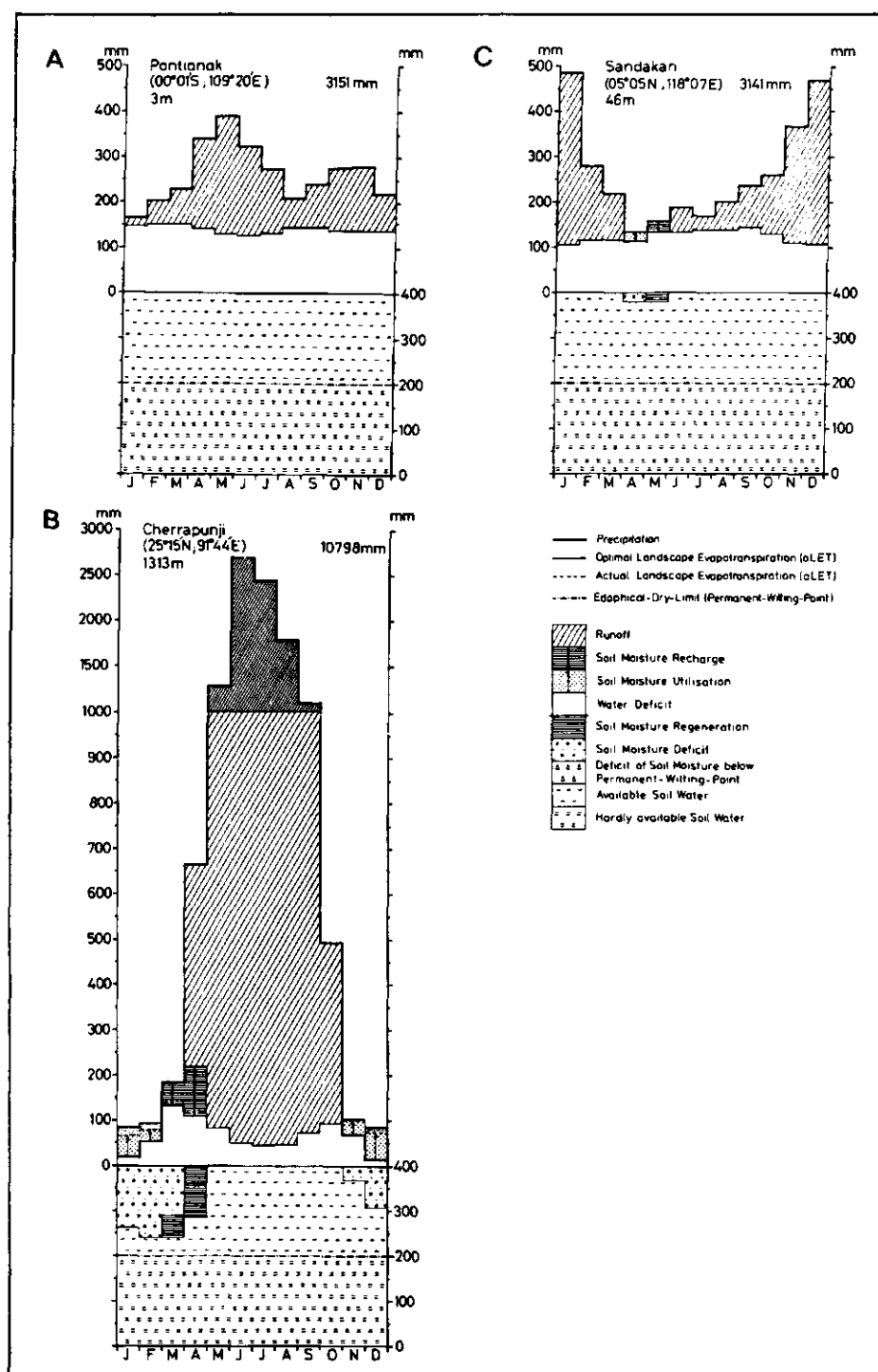


Fig. 2.3 Water budget diagrams for some tropical rainforest types (Lauer 1989).

- a. Pontianak, Kalimantan: equatorial type;
- b. Cherrapunji: tropical type;
- c. Sandakan, Malaysia: marginal tropical type.

The **equatorial type** is located along the equator where in the long run, all months show a positive water balance (a surplus of precipitation over water loss through evaporation and transpiration). Arid type periods with a negative water balance rarely last more than one or two months. Examples are the Amazon basin, Congo and the Sunda Islands. The Pontianak Station (00°01'S; 109°20'E, Figure 2.3) on the island of Borneo is an example of a location with the rainfall distribution of the Indo-Malayan evergreen rainforest. In this climate, Whitmore (1984) described the evergreen tropical lowland rainforest occurring in Kalimantan as the most luxuriant plant community with a great richness in species and a clearly marked stratification with giant trees that reach heights of up to 50 m. This type of rainforest can be found at elevations of up to 1200 m above sea level. Figure 2.4. gives an example of the distribution of forest types in East Kalimantan as published by Van Bremen et al. (1990).

The tropical lowland evergreen forest of Southeast Asia is known for the family dominance of the Dipterocarpaceae in the western block. The main genera are Anisoptera, Dipterocarpus, Dryobalanops, Parashorea and Shorea (Sal). The family develops its greatest richness in terms of abundance of species in Sarawak and Brunei, in the northwest of Borneo. Here the formation is known as mixed-Dipterocarp. On Borneo vast areas of this forest type have been logged and shifting cultivation is practised. Cassava, upland rice, banana and pepper are produced for domestic use and for the market. Huge areas of wasteland are covered by "Alang-alang" (*Imperata cylindrica*), especially in areas where short cycled shifting cultivation is practised (Van Bremen et al. 1990).

The **tropical type** of climate occurs at a certain distance from the equator where the two annual rainfall maxima converge and merge into a twin or single peak maximum. The dry period becomes longer. If there is a strong monsoonal influence, the short dry period disappears and is replaced by a rainfall maximum. This climatic type shows a marked seasonality which leads to a vegetation that is characterized by monsoon forests. A humid or evergreen forest type prevails if the dry period does not last longer than three to four months and a semi-humid or semi-evergreen forest type, if it lasts for more than four months. These forest types occur on the west coasts of the Indo-Malayan archipelago, the southern Himalyan mountains, the African gulf of Guinea, in Liberia and on the Panamanian and Colombian west coasts. For the Asian tropics, the Cherrapunji station (25°15'N; 91°44'E) represents a location with a monsoon type climate with evergreen and semi-evergreen rainforests (see Figure 2.3).

The **marginal tropical type** receives its water from rainfall during the summer location of the Intertropical Convergence Zone. Very often, the rainfall received is complemented by rainfall from tropical cyclones. This type of climate occurs mainly along the tropical east coasts towards the tropics of Cancer and Capricorn. A forest type with a marginal tropical water budget occurs in Southeast Asia on almost all east coasts of the island archipelago. The station of Sandakan on Borneo (05°05'N; 118°07'E) (Figure 2.3) is an example of a location with this type of climate. A negative water balance may occur for two

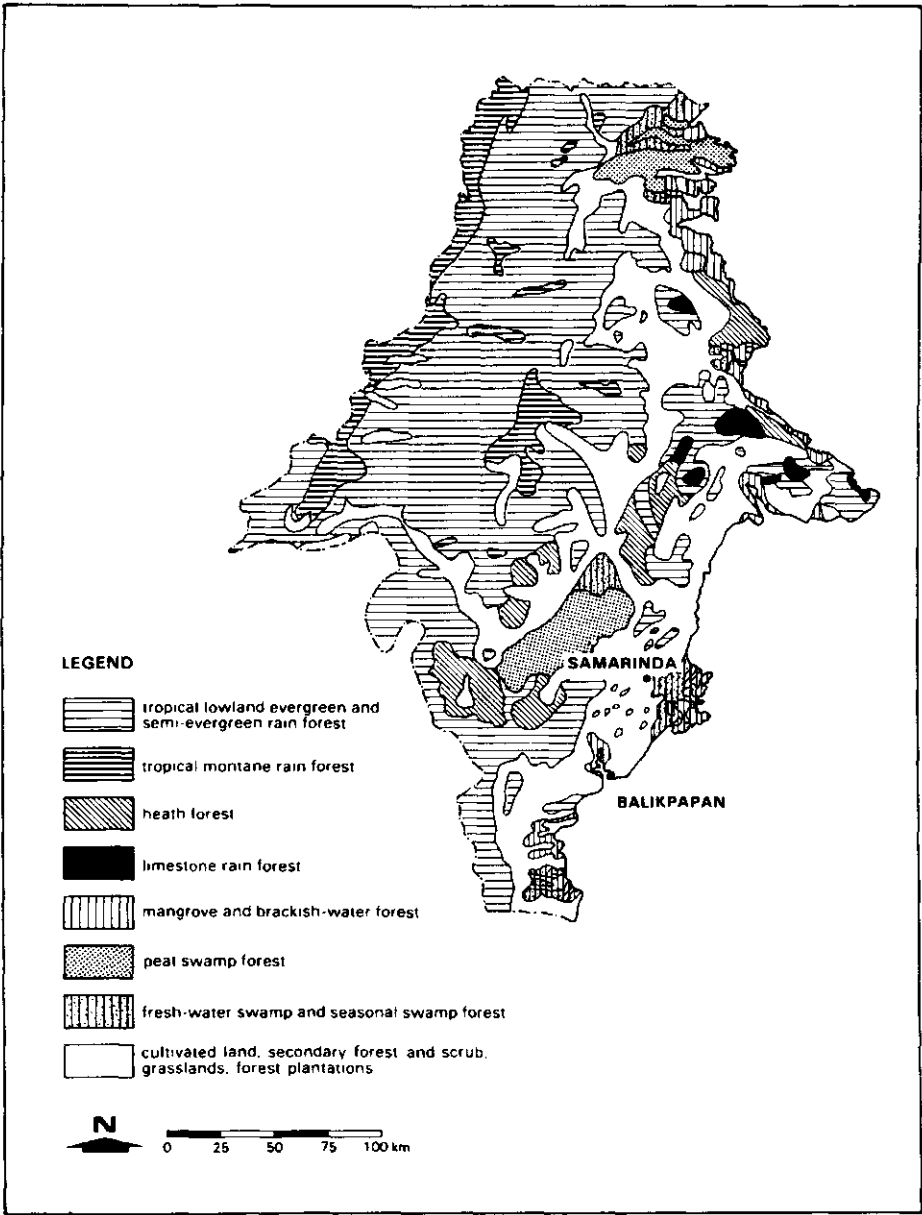


Fig. 2.4 Vegetation types of East Kalimantan (Van Bremen et al. (1990) after Whitmore).

or three months during the "summer" period. The regions with this climatic type carry the semi-evergreen rainforest which is of somewhat lesser importance for this study. It is a closed rainforest in which the trees sometimes reach large sizes. It includes both evergreen and, in the top of the canopy, deciduous species. Up to one third of the bigger trees may be deciduous, but not all are necessarily leafless at the same time. These monsoon-like forests contain the commercially valuable species *Tectona grandis* (Teak). In a region where there is sufficient rainfall throughout the year to support evergreen forest, semi-evergreen forest may still occur because the soil has a limited water holding capacity.

Oxisols (Ferralsols) are deep, generally well drained red or yellowish soils with excellent granular structure and little contrast between horizons. The soils are acid (pH 4.5 - 5.5) and low in available nutrients and have an AI saturation of around 80%.

Ultisols (Acrisols, dystic Nitosols) are also old tropical outbased clay soils and are similar to Oxisols in their morphology, but they have a marked increase of clay content with depth (Buringh 1979). Ultisols are usually deep, well drained red or yellowish soils, somewhat richer in weatherable minerals than Oxisols but still acid and poorly fertile. As in Oxisols, the main limitations for plant growth of this soil type are chemical: high acidity, aluminium toxicity, deficiency of phosphorus, potassium, calcium, magnesium, sulfur and zinc and low cation exchange capacity, leading to a high potential for leaching.

The Inceptisols are young soils, but are sufficiently mature to have clear A, B and C horizons. The Inceptisols are subdivided in three main suborders: the poorly drained Aquepts (Gleysols), the volcanic Andepts (Andosols), and the well drained Tropepts (Cambisols). With the exception of acid sulphate soils, most of the gleysols are of moderate to high fertility. Many of them are in use for growing lowland rice. Andosols are generally fertile, with excellent physical properties. The well drained non-volcanic Cambisols can be divided into two groups: the acid Cambisols, often with characteristics similar to the Oxisols and Ultisols, and the non-acid Cambisols, which have a high base saturation and are very fertile.

The order of Entisols is divided into Fluvisols, Arenosols and Lithosols.

The Fluvisols which are not subject to periodic flooding are among the best soils of the tropics. Most of these soils are under intensive lowland rice production. Deep sandy Arenosols (including the Regosols) are often very acid and very infertile. They are very susceptible to erosion and forest clearing is not recommended. Lithosols are shallow soils over bedrock, usually found on steep slopes. They can be very fertile, but their shallowness is a serious limitation.

The Alfisols consist of well drained relatively fertile soils. The Rhodic Alfisols or Eutric Nitosols according to the FAO (1989) are very similar to Oxisols and Ultisols in terms of colour and structure, but their main difference lies in the high base saturation in the Rhodic Alfisols, which are fertile soils. The Plinthic Alfisols or Plinthic Luvisols according to the FAO have sandy, gravelly surface layers underlain by gravelly materials or plinthite. They have poor physical and chemical properties.

Histosols are the organic soils usually known as peats or bogs. These soils have serious limitations because of the difficulties in drainage, root anchorage and deficiency in micronutrients. The Podzol soils developed in sandy materials, away from the floodplains. Here the native forest vegetation is often very different from the tall rainforests found on Oxisols and Ultisols. Podzols are extremely infertile and very susceptible to erosion.

2.1.3. The Dipterocarpaceae

The reproductive ecology of Dipterocarps makes it possible to exploit the natural regeneration of these species after selective logging. An important characteristic of the family of Dipterocarpaceae is its irregular but abundant seeding (Nicholson 1979, Ashton 1989) and the very short period of seed viability but a relatively long life of some of the seedlings. Under undisturbed conditions these seedlings will hardly grow but they will show a rapid and marked response to increased light. Young seedlings however do not profit from exposure in completely open conditions (Ashton 1989). During their establishment phase even the most tolerant species grow best in semi-shaded conditions. There are indications that water stress plays an important role in the survival of seedlings and planted Dipterocarps (personal communication to C.G. van Eijk Bos, IBN-DLO, September 1992).

Once establishment and early growth is assured, the seedlings will respond to full overhead light. Many observations show that the best growth of Dipterocarps occurs when there is a rapid return to forest conditions with complete soil cover, but with the Dipterocarp in a dominant position in the young canopy (Nicholson 1979). Successful regeneration of the Dipterocarp stand can usually only be achieved when the Dipterocarps are already present in the forest in the middle layer before the logging takes place, and when sufficient trees remain after logging and timber extraction. A forester wishing to use the natural processes needs to ensure that at the time of selective felling there is a medium layer of Dipterocarp poles, which is not destroyed during extraction and which is protected from complete exposure in such a way that the microclimate favours intermediate pioneers. If the forest is logged too moderately or too heavily, the forest climate conditions will favour tree species other than the Dipterocarpaceae (Nicholson 1979). New trees grown from the Dipterocarp poles may reach commercial size in about 50 years.

2.2. Carbon dynamics in recovering tropical lowland Dipterocarp rainforest

2.2.1. Literature data

To set the model input values, data were gathered on the following parameters of tropical evergreen and semi-evergreen forests:

- stem, foliage, branch, root and undergrowth biomass (dry weight);
 - Net Primary Production (dry weight) in tropical evergreen and semi-evergreen forests;
 - allocation of the NPP to the different biomass compartments in mature forest;
 - basic wood density;
 - dry weight of dead wood, forest floor and the stable humus in the soil under mature forest ;
 - annual litter fall in mature forest;
 - biomass decrease through logging and regrowth data afterwards;
-

Results of biomass measurements vary considerably for the virgin tropical evergreen forests. Detailed data reflecting the diversity of this forest type are presented in Table 2.1.

Table 2.1 *Stem and total biomass dry weight and Net Primary Production (NPP) from several studies for tropical forests in Southeast Asia according to various authors in Cannell (1982) and Golley (1983).*
#: these figures in parentheses present stem volume ($m^3 ha^{-1}$), instead of stem biomass.

forest type	country	site	stem biomass d.w. ($Mg ha^{-1}$)	total biomass d.w. ($Mg ha^{-1}$)	NPP d.w. ($Mg ha^{-1} yr^{-1}$)	reference
evergr eq.	*	wet	*	440	*	Olsen, in Cannell 1982
				330-550		
lowl. wet f.	Riau, Sumatr.	alluvial	143	*	*	Dilmy 1971
"	"	"	164	*	*	"
"	"	"	183	*	*	"
rainforest	Sumatra	podzolic	128	*	*	"
rainforest	Kalimantan	podzolic	239	*	*	"
"	"	alluvial	214	*	*	"
"	"	"	170	*	*	"
montane	West Java	Andosol	549	*	*	"
lowl wet for.	New Guin.	*	(380) #	*	*	Pajmans, in Golley
1983						
"	"	*	(437)	*	*	"
"	"	*	(477)	*	*	"
"	"	*	(992)	*	*	"
lowl. wet f	Malaysia	*	*	880	*	Brünig, in Golley 1983
lowl. wet f.	Malaysia	*	*	377	*	Wong, in Golley 1983
"	"	*	(490-700)	478	*	"
"	"	*	*	421	*	Kira, in Cannell 1982
"	"	*	*	431	*	"
"	*	*	*	475	*	"
"	Malaysia	*	*	366	37-50	Whitmore 1978
"	"	sandy clay	287	365	*	Bullock, in: DeAngelis et al. 1981
"	Malaysia	*	*	266	*	Chan 1982
"	Malaysia	*	*	466	*	"
"	Malaysia	drained	*	493	*	Kira & Ogawa 1971
tr. rainf.	average	average	*	440	20	Whittaker & Likens 1973
tr. seasonal	average	average	*	355	15	"
tr. humid	average	average	*	420	23	Ajtay et al. 1977
tr. seasonal	average	average	*	250	16	"
rain forest	Thailand	*	*	*	28.6	Murphy 1975
montane rf.	Java	*	*	*	24.3	Wanner 1970
lowland rf.	Sarawak	*	*	*	32.1	"
evergr seas.	Kampuchea	Latosol	225	415	*	Hozumi, in Cannell 1982
"	"	"	197	347	*	"
tr. rainf.	Malaysia	sandy clay	522	657	*	Kato, in Cannell 1982
"	"	"	367	466	26.9	Kira, in Cannell 1982
"	"	"	346	432	26.6	"
low stocking	"	*	*	178	*	Chan 1982
"	"	*	*	289	*	"
lowl. mature	Kalimantan	Ultisol	532	649	*	Yamakura et al. 1986
lowl. build.	Kalimantan	Ultisol	118	141	*	"
lowl gap	Kalimantan	Ultisol	21	27	*	"
dipt forest	Sarawak	podzolic	*	650	*	Anderson et al. 1983
moist trop.	SE Asia	average	*	225	*	Brown et al. 1991
lowl rf	tropics	average	*	344	*	Brown & Lugo 1986
lowl m. f.	tropics	average	*	369	*	"
moist zone	SE Asia	average	*	225	*	Brown et al. 1991
hill forest	Malaysia	average	*	296-391	*	Brown et al. 1989
hill for.	Malaysia	average	*	172-220	*	Brown et al. 1989

Although some very large amounts of dry matter for the total biomass appear in Table 2.1, Brown (1984) suggests that such large amounts of biomass probably occur much less frequently than values close to the average amounts of total biomass (350 Mg ha^{-1}) which they found for mature tropical forests in Asia. Later (Brown et al. 1991), state that the average biomass of tropical moist forests of South and Southeast Asia should be estimated at 225 Mg ha^{-1} dry weight. This last estimate was based on inventories representing $22 \times 10^6 \text{ ha}$ of tropical forest, inclusive logged forest. Other general average data from Whittaker & Likens (1973) suggest a stock of dry matter of 450 Mg ha^{-1} in the total plant biomass of the evergreen tropical rain forest. An amount of 350 Mg ha^{-1} dry matter is suggested for tropical semi-evergreen forest.

Basal area measurements obtained by C.G. van Eijk Bos (unpublished data) in the ITCI concession area in East Kalimantan, suggest an average biomass of 350 Mg ha^{-1} dry matter, with figures ranging from 170 to 540 Mg ha^{-1} . These biomass figures were obtained by multiplying the basal area ($\text{m}^2 \text{ ha}^{-1}$) by a factor of 10. According to Brown et al. (1991) this procedure can be applied for tropical forest in Malaysia and the Philippines.

Whittaker & Likens (1973) suggest that the NPP of evergreen tropical rainforest is $20 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ and that of tropical semi-evergreen is $15 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. Data presented by Murphy (1975) from various authors suggest a Net Primary Productivity of tropical rainforests ranging from 16.8 to $32.1 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ matter.

In some biomass measurements of mature tropical rainforest, the biomass compartments branches, roots, foliage and undergrowth are distinguished separately. These are presented in Table 2.2.

Table 2.2 *Biomass (dry weight) of biomass compartments distinguished in some tropical forests.*

forest type	stem biomass (d.w.) (Mg ha^{-1})	branch biomass (d.w.) (Mg ha^{-1})	foliage biomass (d.w.) (Mg ha^{-1})	root biomass (d.w.) (Mg ha^{-1})	undergrowth biomass (d.w.) (Mg ha^{-1})	reference
mature	520.5	101.6	6.1	*	21.0 (dbh<10 cm)	Yamakura et al. 1986
building	99.6	16.4	2.5	*	22.7 "	"
gap	0	0	0	*	26.4 "	"
tr. lowl.	360.0	*	7.7	32.0	*	Ogawa, in Cannell 1982
tr. lowl.	286.0	*	8.2	30.0	*	"
seasonal	225.4	107.5	6.5	69.2	6.5 (dbh<4.5 cm)	Hozumi, in Cannell 1982
seasonal	197.1	88.1	6.4	49.9	6.5 "	"
heath	106.3	34.0	6.8	18.0	*	"
rainfor.	287.1	59.4	4.8	29.6	13.4 (understorey)	Bullock, in DeAngelis et al. 1981
rainf.	522.2	125.4	7.8	*	1.2 (ground veg.)	Kato, in Cannell 1982
rainf.	367.5	90.1	8.0	*	0.2 "	"
rainf.	346.0	77.9	7.8	*	*	"

Bullock in DeAngelis et al. (1981) mentions that of the Net Primary Production of $15.38 \text{ Mg ha}^{-1}\text{yr}^{-1}$, in a tropical rainforest in Malaysia, 28% was stored in the stem and 18%, 3% and 50% were stored respectively in the branches, fruits and foliage. The allocation to the roots was not measured. For the allocation to stem, branches, fruits, foliage and roots in mature tropical rainforest Kato et al. in Cannell (1982) mention figures of 35%, 19%, 0%, 29% and 17% respectively and 30%, 17%, 5%, 28% and 20% in another study (see also Appendix E).

The litter input in tropical rainforests ranges from 13.7 to $25.8 \text{ Mg ha}^{-1}\text{yr}^{-1}$ (Reiners 1973, Coleman et al. 1989), although Bray & Gorham (1964) mention much lower values for the annual litter input in the Dipterocarp forest in Malaya ranging from 5.5 to $7.3 \text{ Mg ha}^{-1}\text{yr}^{-1}$. In secondary forest in Malaysia the annual litter input was found to range from 8.3 to $14.4 \text{ Mg ha}^{-1}\text{yr}^{-1}$. Bullock in DeAngelis et al. (1981) mentions a litterfall of $17.3 \text{ Mg ha}^{-1}\text{yr}^{-1}$ and a dry weight of the forest floor of 12.6 Mg ha^{-1} . He found 13.9 Mg ha^{-1} standing dead wood.

Van Bremen et al. (1990) mention figures for East Kalimantan of $72 - 96 \text{ Mg C ha}^{-1}$ in the stable humus in Alisols under primary lowland forest. Under logged forest on Alisols lower values were found, ranging from $58 - 104 \text{ Mg C ha}^{-1}$. Other more general data from Millemann & Boden (1986) suggest 97 and 66 Mg C ha^{-1} in the stable humus under tropical wet and moist forest respectively in Asia. Raich (1983) mentions that the dry weight of the stable humus in an Inceptisol decreased in secondary forest to 148 Mg ha^{-1} from 161 Mg ha^{-1} under virgin forest. Dry matter in the forest floor decreased from 37 to 14 Mg ha^{-1} (see also Jordan 1989).

According to Dixon et al. (1991) the basic wood density (dry weight per green volume) of the wood in the tropical lowland forests is 610 kg m^{-3} for all Dipterocarp genera. Cannell (1984) mentions a figure of 590 kg m^{-3} for *Shorea* and *Tectona* species and Chan (1982) mentions an average figure of 570 kg m^{-3} for Dipterocarp forest.

Gómez-Pompa & Burley (1991) distinguish four silvicultural systems in natural tropical forests.

- 1: The natural regeneration or selective cutting system. This system exists of selecting only a few trees at the time of removal, allowing natural regeneration to fill in the gaps created and maintaining standing volumes of all species.
 - 2: The clearing system eg. Malayan Uniform System. This involves the extraction of some or all commercially valuable trees and the immediate elimination of unwanted individuals through cutting or poisoning. The best known system of this group, the Malayan Uniform System, has been successful in the Dipterocarp forests of Southeast Asia.
 - 3: The replacement system. This system involves an often large-scale clear cut of the entire forest, which is then replaced by tree plantations of *Eucalyptus*, *Tectona* or *Pinus* spp. Shifting cultivation is also a kind of replacement system.
 - 4: The restoration system. This last system is the least known, but the most needed. It includes the management of heavily disturbed, unproductive
-

forests and wasteland. The system includes a variety of techniques for planting desirable species in the logged forest or the wasteland which are covered by grasses and shrubs.

Although the timber extracted in the clearing system is usually only 15% (ranging from 0 to 32%) of the standing volume, up to 65% of the original stand may be damaged through the logging operations (Nicholson 1979, C.G. van Eijk Bos, unpublished data). On average, approximately 45% of the standing volume of the virgin stand is influenced in some way (either removed or damaged).

Basal area increment measurements after a selective logging (C.G. van Eijk Bos, unpublished data), indicate that 15 years after the virgin forest had been logged, reducing the basal area by 45%, the secondary forest had reached on average 88% of the initial basal area of the primary forest. Miller (1981) also states that when a selective logging has taken place, the ingrowth of the stand shows a significant increase. At a logging severity of 20%, the mean diameter growth six years after logging, is 1.6 cm yr^{-1} , compared with only 0.7 cm yr^{-1} in the virgin forest for trees of the same diameter class. Miller (1981) also shows data of a net growth rate of $-16.3 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, 2 years after 76% of the trees in a stand had been logged. Regrowth in the longterm, after several cycles is rather uncertain, and soil productivity can probably only be maintained in the most careful systems.

2.2.2. Model input

In this study six different silvicultural systems were used when modelling the carbon sequestration in the tropical zone in Southeast Asia.

- 1: Regrowing, heavily logged evergreen tropical lowland Dipterocarp rainforest in three site classes with I_m values over the regrowing period of 11.7, 14.1 and $18.7 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. The regrowing forest is heavily logged every 70 years, as a result of which the standing biomass decreases by 80%. The modelling starts with the logged-over situation.
- 2: Regrowing, selectively logged evergreen tropical lowland Dipterocarp rainforest in three site classes with I_m values over the regrowing period of 12.4, 15.8 and $18.1 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. The regrowing forest is selectively logged every 70 years, as a result of which the standing biomass decreases by 50%. The modelling starts with the same heavily logged situation as in system 1.
- 3: Regrowing, heavily logged semi-evergreen tropical lowland rainforest in one site class with an I_m over the regrowing period of $7.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. The regrowing forest is heavily logged every 70 years, as a result of which the standing biomass decreases by 80%. The modelling starts with the logged-over situation.
- 4: Regrowing, selectively logged semi-evergreen tropical lowland rainforest in one site class with an I_m over the regrowing period of $10.5 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. The regrowing forest is selectively logged every 70 years, as a result of which the standing biomass decreases by 50%. The modelling starts with the same heavily logged situation as in system 3.

- 5: Afforestation of tropical wastelands in one site class starting with a pioneer afforestation consisting of *Albizia* spp., which after 10 years is underplanted with *Dipterocarps* (*Shorea* spp.). Next a selective cut is applied every 70 years, through which the standing volume decreases by 50%. I_m is $9.3 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
- 6: Recovering heavily logged evergreen tropical lowland *Dipterocarp* rainforest on a moderate site, on which the regrowth is hampered by the vigorous growth of lianas. The modelling starts with logged-over rain forest, and I_m is $8.4 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. A cutting cycle of 140 years is applied, and the standing biomass decreases by 60% at logging.

Silvicultural system 1:

The initial situation is a severely damaged lowland evergreen rainforest. There is still enough cover to hamper the pioneer species and the lianas. The modelling was done for three site classes in the evergreen rainforest, all located on Alisols, but differing in nutrient availability.

The initial amounts of dry matter in the virgin rainforest cannot be traced back from the model output, but the regrowth is based on the assumption that the forest can reach 80% of its original biomass. The amounts of dry biomass in the virgin tropical lowland evergreen rainforest for the sites of good, moderate and limited fertility are 625, 475 and 400 Mg ha^{-1} respectively, of which approximately 70% is stored in the stems. The rest is stored in branches, foliage, roots and undergrowth. The initial values for stable humus, dead wood and litter are given in Table 2.3. Basic wood density was set at 560 kg m^{-3} (see also Appendix C). Humification and decomposition constants and residence times of dead wood and stable humus are given in Appendix H.

Table 2.3 Initial values (Mg ha^{-1} dry matter) of the virgin tropical forest for stable humus, dead wood and litter used as basis for input. Based on data from Bray & Gorham (1964), Ajtay et al. (1977), Post et al. (1982), Buringh (1984), Reiniers (1973), Brown & Lugo (1986) and Millemann & Boden (1986).

	evergreen			semi-evergreen	waste lands
	good	moderate	limited	moderate	
stable humus	150	140	140	155	90
dead wood	95	72	52	45	0
litter	19	15	12	11	0

The heavy logging is assumed to result in a biomass that is only 20% of that of the virgin forest. Only 20% of the destroyed volume is harvested for timber; the rest is left in the forest (see Appendix I6 for use of the wood). It is assumed that sufficient middle class Dipterocarp trees which were already present before the selective logging survive the logging operations and can be used in the next rotation. This ensures that after approximately 70 years, another logging can be carried out through which the biomass decreases again with 80%. Half of the wood from this logging-over is also left in the forest, while the other half is used as sawn timber and as packing wood (see Appendix I6). If there are not enough middle class Dipterocarps left, enrichment line planting will have to be carried out.

Since much of the debris is left in situ after logging, it is assumed that the soil fertility does not decrease and therefore the same regrowth can be assumed in each rotation. The volume increment at the end of a rotation is therefore the same as in the virgin forest, with an increased growth in the period of 25 to 50 years after the logging (see Appendix D1 for volume increment). Regrowth of commercial species is improved through two subsequent thinnings, 20 and 40 years after the selective logging. The allocation fractions of NPP to the other biomass compartments is given in Appendix E.

Silvicultural system 2.

The initial situation is also a heavily logged tropical lowland rainforest, but this time enough Dipterocarp pole trees are left or an enrichment line planting is carried out resulting in a growth which is concentrated on the commercially interesting species. At the end of a rotation a careful logging operation is carried out through which the biomass decreases by only 50%. In this system it is fairly certain that the soil fertility can be maintained, so that the forest quickly regrows to about 80% of the biomass in the virgin tropical forest. It is assumed that this regrowth can be achieved each rotation. Cleaning and thinning operations are carried out 5 and 20 years after the selective cut. Because the thinnings are carried out carefully and are aimed at producing high quality wood, it is assumed that a larger part of the wood from the selective cut is used as sawn timber (see appendix I6).

Silvicultural system 3 & 4:

The same silvicultural systems are assumed as in systems 1 and 2, but here the initial forest type is the lowland semi-evergreen rainforest on moderate sites with a lower amount of initial biomass. The virgin forest biomass is assumed to be 300 Mg ha^{-1} dry matter, but the modelling starts with only 20% of this amount. It is assumed that the soil fertility does not decrease.

Silvicultural system 5:

The fifth starting point is the vast extent of wasteland (see Figure 2.4) which no longer carries any forest vegetation. The vegetation usually consists of grasses (Alang-alang) and some scattered trees and scrubs. This land-use type has developed from logged-over rainforest which was burned down by shifting cultivators who then used the land for agriculture for some years. The model includes afforestation with *Albizia falcataria* which will be underplanted with *Shorea* spp. after 10 years. A careful and selective logging system is carried out every 70 years. Since regrowth on the impoverished wasteland

soils is very uncertain, only one site class was modelled. It is assumed that the soil fertility does not decrease any further, so the same regrowth can be assumed in each rotation.

The model starts with a short rotation (10 years) of *Albizia falcataria*; these trees should provide the shelter necessary to establish an undergrowth of *Shorea* spp. (Long & Johnson 1981). *Albizia* is known for its high production potential and its light foliage makes it an excellent cover for agroforestry crops and for enrichment line planting with *Dipterocarps* (Long & Johnson 1981).

Although very high increments are recorded for *Albizia* on Java (Pandey 1983), with mean increments of up to $56 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ at an age of 10 years, one has to take into account that the Ultisols of Kalimantan are very infertile and have probably lost some of their already low fertility through shifting cultivation. Long & Johnson (1981) mention a standing volume of $375 \text{ m}^3 \text{ ha}^{-1}$ for a plantation of *Albizia falcataria* on an Ultisol on Kalimantan at an age of 15 years. The current volume increment in the *Albizia* of 10 years is set at $16 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (see Appendix D1). A mean annual volume increment in the *Shorea* stand of $7.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ was used. In this study the amount of stable humus was set at 90 Mg ha^{-1} dry matter.

At the time of planting the *Shorea* seedlings, the *Albizia* stand is thinned to 50% (see Appendix 17 for use of the wood). Ten and 20 years after the establishment of the *Shorea* stand, the rest of the *Albizia* is removed (they may have died already). When the *Shorea* trees are 70 years old a selective logging is carried out in the *Shorea* forest, at which 60% of the volume is either harvested or damaged; 50% of this is used as sawn timber. Natural regeneration of *Shorea* seeds should then be present, to provide a new generation under the shelter of *Shorea* trees.

Silvicultural system 6:

The last silvicultural system is a recovering heavily logged lowland evergreen tropical rainforest on a moderately fertile site, where regrowth is hampered by the vigorous growth of lianas. This system has been added for comparison and models a rainforest which has had 80% of its trees cut down, as a result of which pioneer species and lianas have been stimulated. This type of situation occurs when logging has been too drastic and no cleaning operations have been carried out. The regrowth of the climax tree species is severely hampered by the lianas climbing over the tree crowns. The modelling starts with the heavily logged rain forest and the I_m over the regrowing period is $8.4 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. A cutting cycle of 140 years is assumed because the regrowth of the commercially valuable species will be very slow. Another selective logging can then be applied, as a result of which the standing volume decreases by 60%. It is reasonable to believe that the fertility of the soil decreases, although the same regrowth is modelled for the second rotation.

2.2.3. Results and discussion

The results of the modelling are visualized in Figures 2.6 to 2.10, and for the various criteria presented in Table 2.4. Since the results could be presented

both for the initial situation of the virgin tropical forest and of the logged situation, Figure 2.6 gives a comparison of these two possibilities for only one rotation.

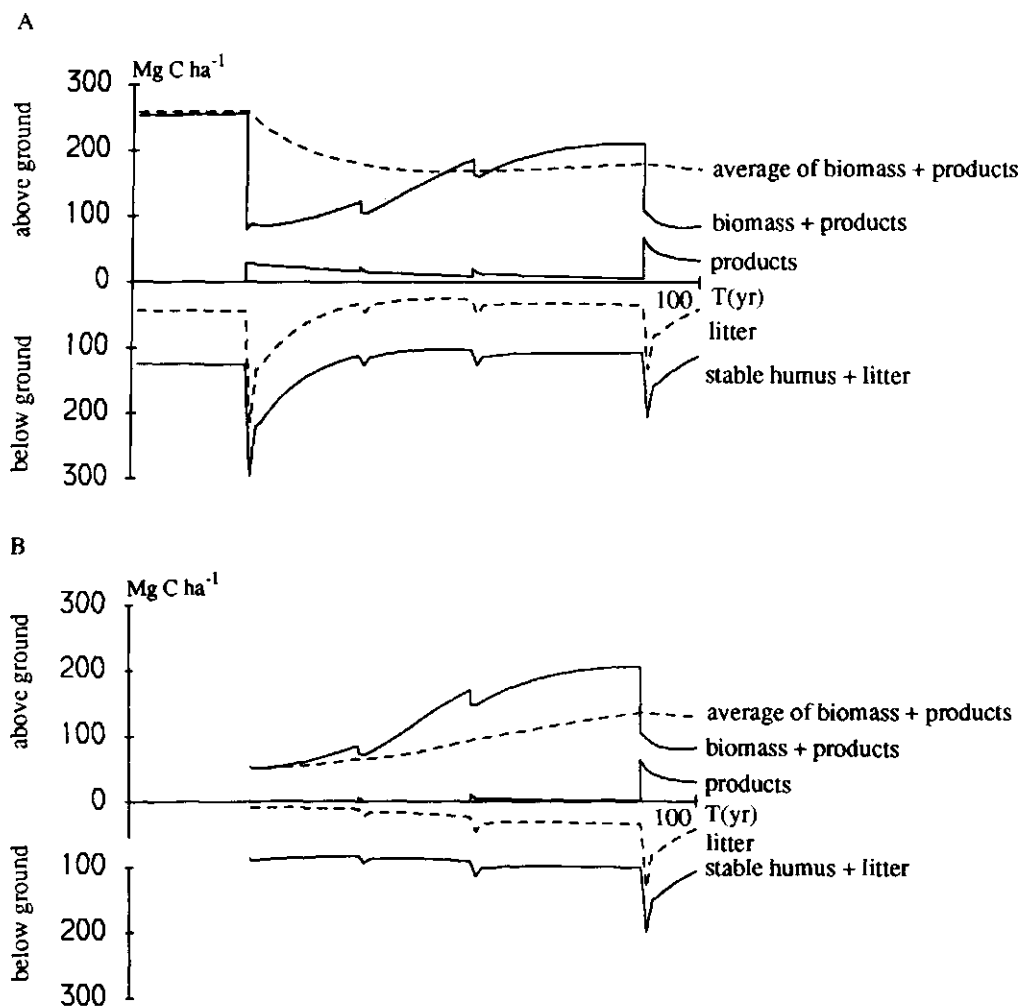


Fig. 2.6 Carbon stocks in biomass, forest products and soil organic matter in recovering heavily logged lowland evergreen Dipterocarp rain forest on moderate sites. The figure shows the results starting from the virgin forest (A) and starting from the logged-over situation (B) and visualizes the differences. (Mg C ha⁻¹). Starting with the virgin forest is closer to what really happens when virgin forest has been logged in some way, but starting from the logged situation is more representative of the results of management practices in already logged rainforests.

From Figure 2.6 it is clear that the results fairly quickly tend to approach one another, regardless whether the modelling is started with the virgin rainforest or the logged situation. When the modelling is started in the virgin forest, the amounts of carbon in the products and litter (from logging slash) are higher in the short term, but they quickly decline. Graphical display of the results is

therefore based on the results of the runs starting with the logged situation, for this is also the situation in practice. The results presented in the Table are always based on the modelling variant which starts with the logged situation.

Table 2.4 *Comparison of carbon stocks and fluxes of the six silvicultural systems in tropical forests.*

- 1) Total stock of carbon at the end of the rotation in biomass and products (Mg C ha^{-1});
- 2) Total stock of carbon at the end of the rotation in the soil organic matter i.e. litter, dead wood and stable humus (Mg C ha^{-1});
- 3) Total stock of carbon at the end of the rotation in biomass, forest products and in dead organic material on or in the soil (Mg C ha^{-1});
- 4) Long-term average stock of carbon in the biomass and the forest products (Mg C ha^{-1});
- 5) Long-term average stock of carbon in the forest products (Mg C ha^{-1});
- 6) Long-term average stock of carbon in the soil organic matter (Mg C ha^{-1});
- 7) Long-term average stock of carbon in the total system of biomass, products and soil organic matter (Mg C ha^{-1});
- 8) Net accumulated amount of carbon over the first 100 years after afforestation (Mg C ha^{-1});
- 9) Average net annual carbon flux at the end of the first rotation ($\text{Mg C ha}^{-1}\text{yr}^{-1}$).

	1	2	3	4	5	6	7	8	9
heavily logged evergr. $I_m = 18.7 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	261	114	375	194	19	108	301	120	3.06
heavily logged evergr. $I_m = 14.1 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	206	100	306	144	16	92	236	70	2.40
heavily logged evergr. $I_m = 11.7 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	175	96	271	122	13	88	210	59	2.04
selectively logged evergr $I_m = 18.1 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	277	123	400	247	23	117	364	197	3.42
selectively logged evergr $I_m = 15.8 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	229	108	337	207	19	102	309	167	2.85
selectively logged evergr. $I_m = 12.4 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	192	103	295	177	15	99	276	147	2.41
heavily logg. semi-evergr. $I_m = 7.0 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	113	88	201	76	8	76	151	10	1.07
select. logg. semi-evergr. $I_m = 10.5 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	163	105	268	151	13	98	249	126	2.03
afforest. of wasteland $I_m = 9.3 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	133	71	204	121	12	67	188	117	1.69
heavily logged evergr. hampered by lianas, $I_m = 8.4 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	151	99	250	125	5	92	217	115	0.79

The main conclusion for the silvicultural systems in the tropical rainforest is that in the variant with the careful logging and enrichment line planting system, the long-term average amount of carbon in the biomass and products is substantially higher than in the heavy logging system. See the upper dashed line in Figure 2.7A and 2.8A. This conclusion is valid for both the evergreen and the semi-evergreen rainforest. Compared to the virgin rainforest, the selective logging system is able to keep much more carbon in the biomass and the products than the heavy logging system. For a moderately fertile site in the evergreen rainforest, this amount is 207 Mg C ha^{-1} , but is only 144 Mg C ha^{-1} in the heavily logged forest. In the worst variant with vigorous growth

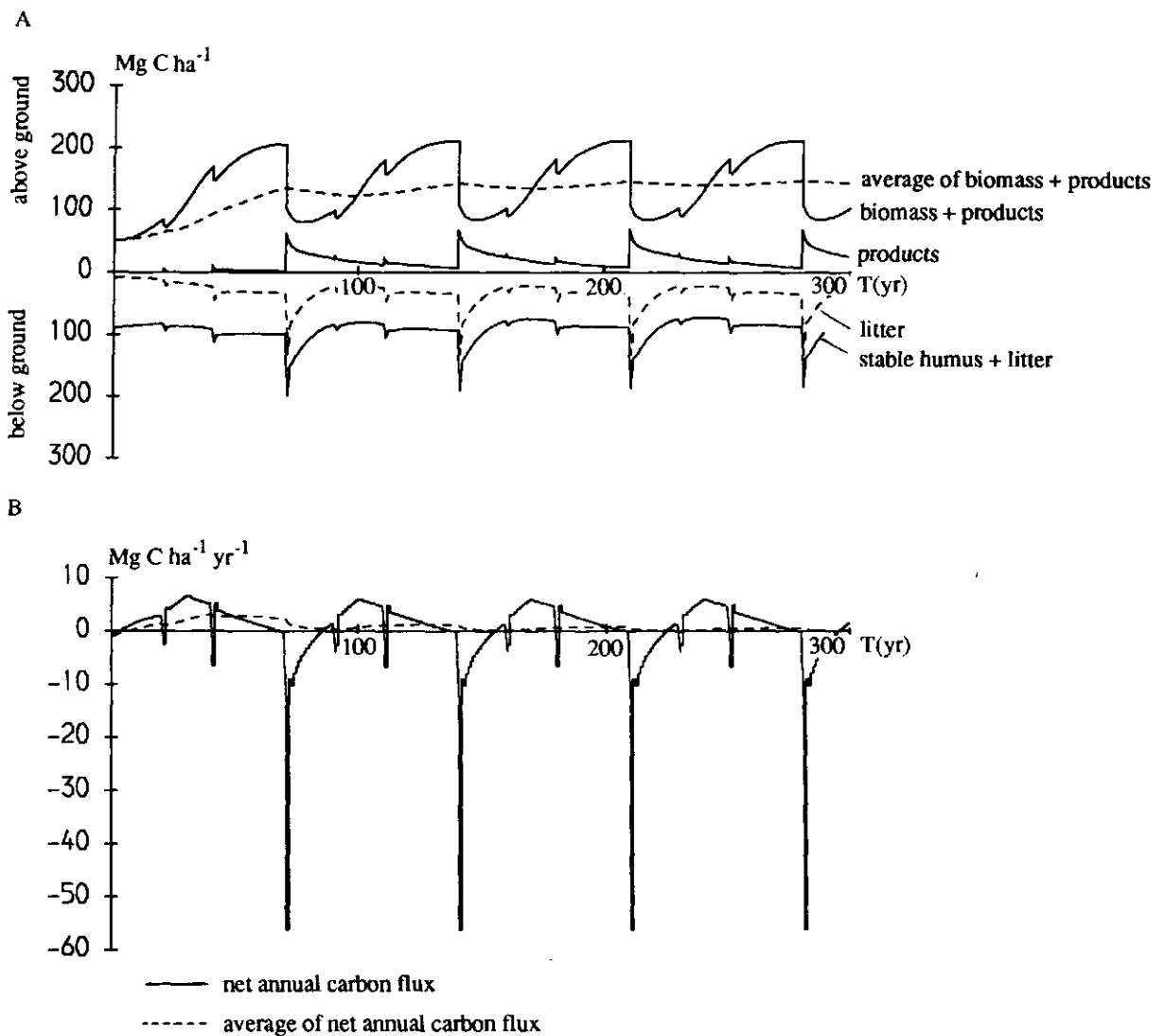


Fig. 2.7 A: Carbon stocks in biomass, forest products and soil organic matter in recovering heavily logged lowland evergreen Dipterocarp rainforest on moderate sites. $I_m = 14.1 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. (Mg C ha^{-1})
B: Carbon fluxes both annually and as a running mean ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$).

of lianas, this long-term average is only 125 Mg C ha⁻¹. This still seems to be a good result, but this is caused by the fact that the rotation length in forests which are hampered by lianas is set at 140 years, because it takes much longer for the commercial species to reach valuable sizes. Through applying the selective cutting and enrichment line planting system, an extra amount of approximately 80 Mg C ha⁻¹ can be stored.

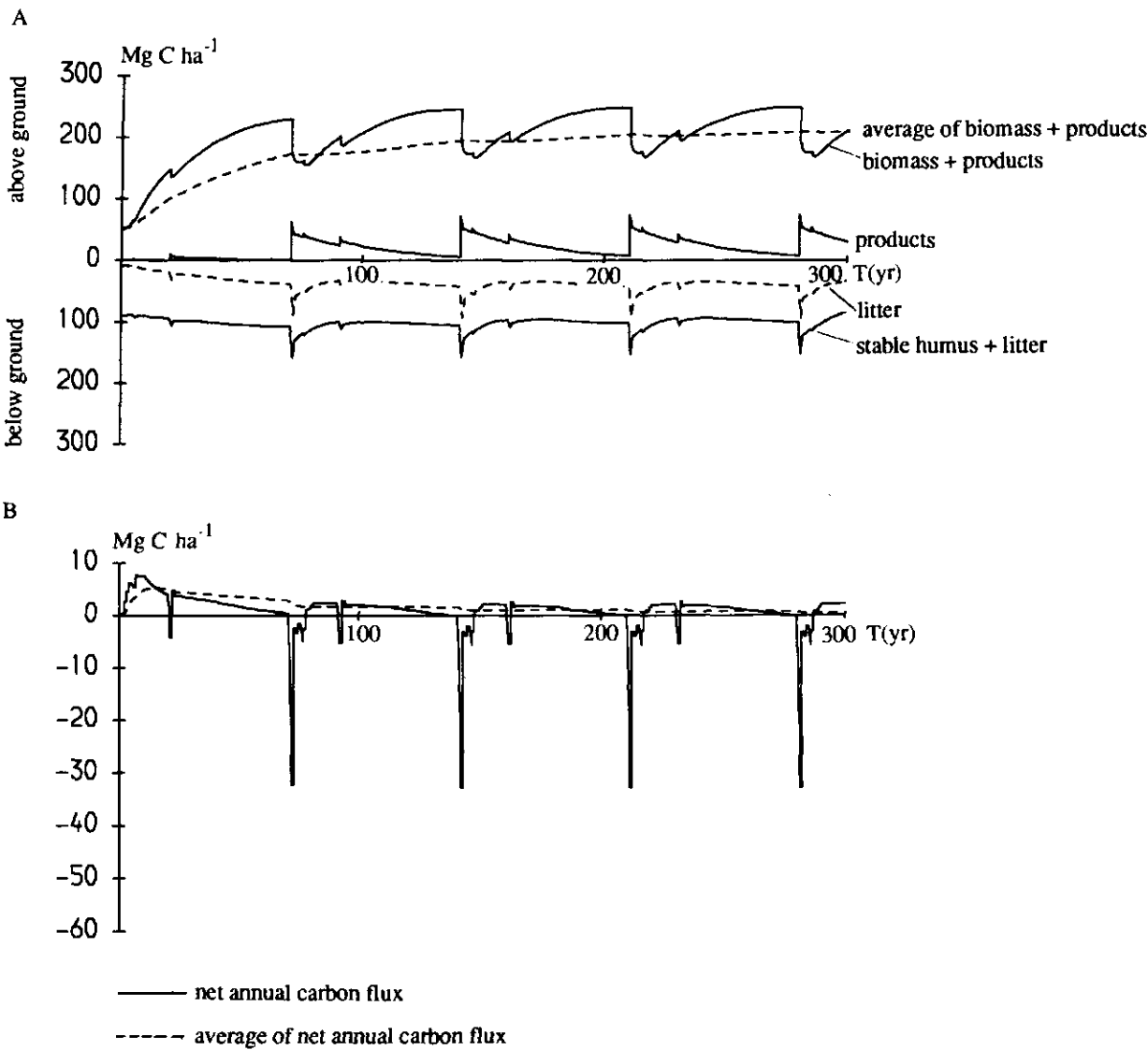


Fig. 2.8 A: Carbon stocks in biomass, forest products and soil organic matter in recovering selectively logged lowland evergreen Dipterocarp rainforest with enrichment line planting on moderately fertile sites. $I_m = 15.8 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. (Mg C ha⁻¹)
B: Carbon fluxes both annually and as a running mean (Mg C ha⁻¹ yr⁻¹).

The results as presented are based on the assumption that the soil productivity can be maintained. If this is not possible, then the long-term average in

biomass and products will continue to fall and will approach a much lower equilibrium than the one presented.

Because only a small part of the harvested wood is used as timber, the storage of carbon in the products is limited, but it is somewhat higher in the selective system because this system invests more in producing high quality wood and applies a more careful thinning regime. Because of the reduced input of dead wood and litter to the soil in the secondary forest, the amount of carbon in soil organic matter (i.e. stable humus, dead wood and litter) has decreased but is stabilized at a lower level than in the virgin tropical forest (only visualized in Figure 2.6A). The main decrease is in the amount of dead wood and litter; as a result, the compartment of soil organic matter decreases, by approximately $20 \text{ Mg C ha}^{-1}\text{yr}^{-1}$. The amount of stable humus decreases only slightly. Raich (1983) also found a decrease of carbon stocks in soil organic matter, litter and small roots of $20.6 \text{ Mg C ha}^{-1}$ in secondary forest compared with virgin forest.

The net annual carbon flux over the first rotation is the largest in the selective logging system ($2.85 \text{ Mg C ha}^{-1}\text{yr}^{-1}$ on a moderately fertile site), resulting from the strong reduction of biomass in the selectively logging system and the high growth rates concentrated on the commercially valuable species which can reach large sizes. The annual net storage rate is comparable in the heavy logging system ($2.40 \text{ Mg C ha}^{-1}\text{yr}^{-1}$) because here the growth is just as fast, but more divided over all sorts of species.

The silvicultural system with afforestation of wasteland, shows a reasonable net annual accumulation over the first rotation and reasonable long-term averages in the biomass and products. At the end of the Albizia rotation already 33 Mg C ha^{-1} is stored in the biomass. Because growth is limited on the impoverished site, the amount of carbon stored on average in the biomass and products tends to only 121 Mg C ha^{-1} . This results in a net annual accumulation of $1.69 \text{ Mg C ha}^{-1}\text{yr}^{-1}$ over the first rotation. The amount in the soil organic matter increases slowly mainly through accumulation in litter and dead wood (see lower dashed line in Figure 2.9A).

The initial amounts of carbon in the biomass of the virgin tropical forest have been chosen rather high compared with the average of 175 Mg C ha^{-1} given by Brown et al. (1991). These values were used because the forest type considered here is the most abundant of all tropical forests and biomass values can start in the upper range of the values found in the literature. If the carbon storage of vast areas of forest is considered, it is probably best to use the results of the lowland evergreen tropical rainforest on sites of limited fertility.

The main critical parameter value is the volume increment in the regrowing forest. This parameter had to be based on a small number of measurements which indicated that rapid regrowth was possible if the forest had not been damaged too much and the sites were not impoverished. This also agrees with the results given by Houghton et al. (1984) who state that on mature fallow, 15 years after logging the primary forest down to approximately 10% of its original biomass, the forest had still regenerated almost 40% of the original biomass.

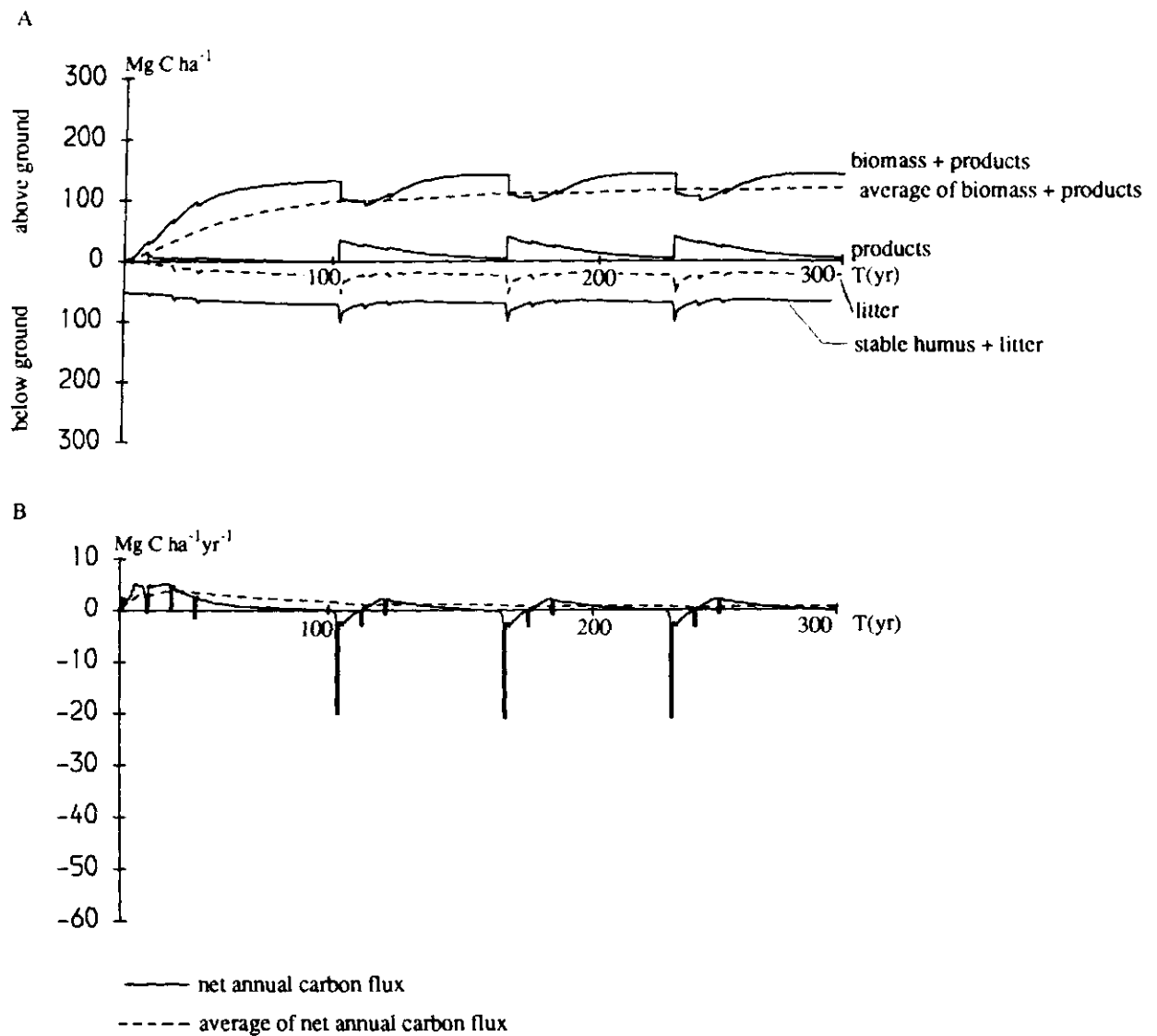


Fig. 2.9 A: Carbon stocks in biomass, forest products and soil organic matter in afforestations of wasteland with *Albizia* as a pioneer on moderately fertile sites with enrichment line planting after 10 years. $I_m = 9.3 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. (Mg C ha⁻¹)
 B: Carbon fluxes both annually and as a running mean (Mg C ha⁻¹ yr⁻¹).

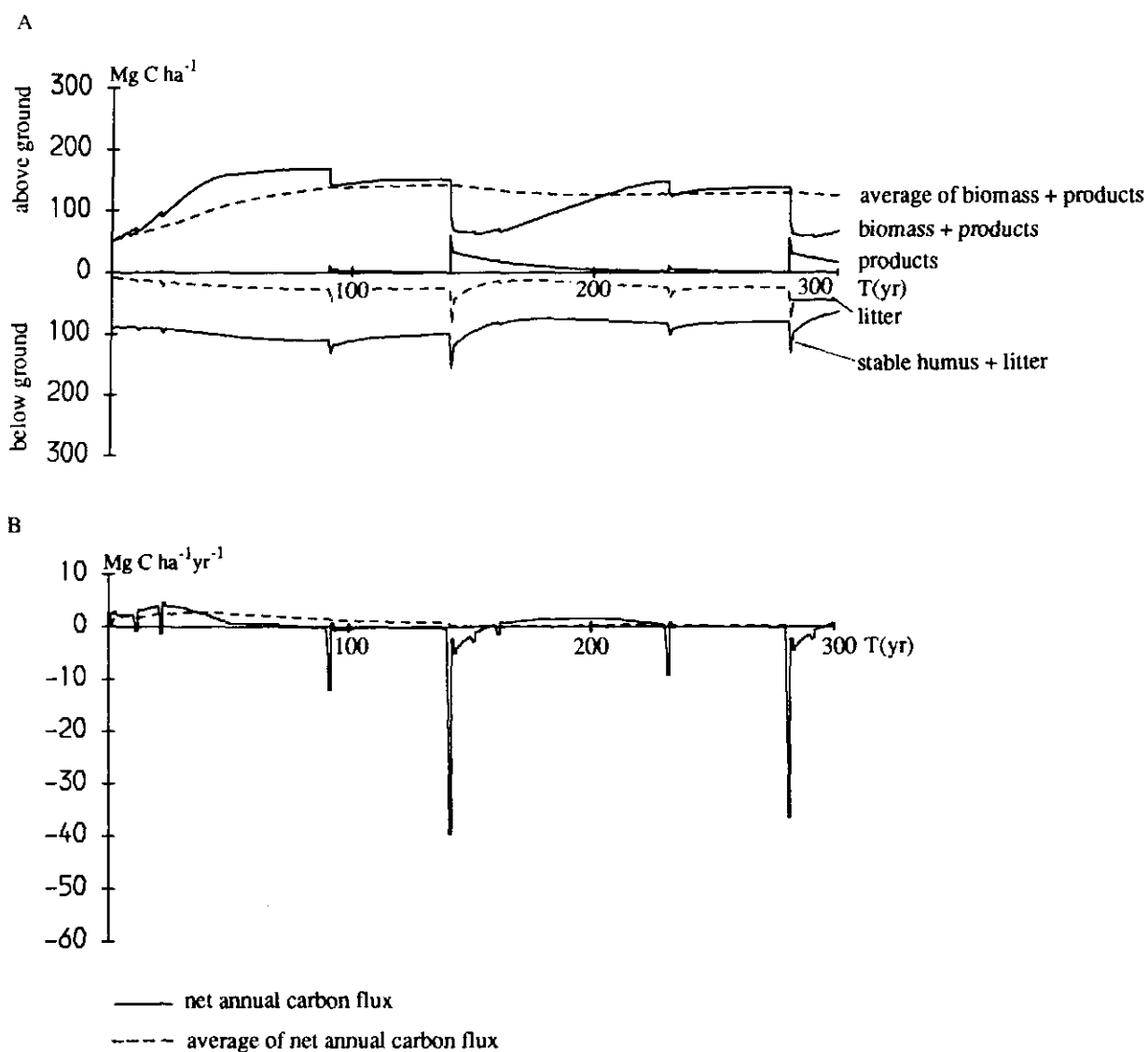


Fig. 2.10 A: Carbon stocks in biomass, forest products and soil organic matter in heavily logged lowland evergreen rainforest on moderately fertile sites, where regrowth is hampered by lianas, starting with logged-over rainforest. $I_m = 8.4 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$; (Mg C ha⁻¹);
 B: Carbon fluxes both annually and as a running mean (Mg C ha⁻¹ yr⁻¹)

Statistics on the growth figures on wasteland are rather uncertain, and therefore values for sites of limited fertility were used to avoid overestimating growth. An increment half of that given for the worst site class of *Albizia* on Java was used (Pandey 1983). This results in a standing volume of the *Albizia* stand of $91 \text{ m}^3 \text{ ha}^{-1}$. Long & Johnson (1981) mention a total standing volume of $375 \text{ m}^3 \text{ ha}^{-1}$ for *Albizia* in Kalimantan, at an age of 15 years on an unimproved site.

Other rather critical parameters like humification and decomposition factors, were set in such a way that they agreed with the other forest types (see Appendix H) and so that the stocks of, for example, stable humus and litter etc. agree with data in literature.

It can be concluded that the long-term average amount of carbon in biomass and products of regrowing tropical rainforest can be increased considerably by logging carefully and selectively and by carrying out an enrichment line planting and sufficient cleanings and thinnings. This selective logging system stores approximately 80 Mg C ha^{-1} extra in biomass and products of lowland evergreen rainforest on moderately fertile sites. By applying this system the long-term average tends to be much higher. The lowland evergreen rainforest on sites of limited fertility with a long-term average of 177 Mg C ha^{-1} in biomass and products in the selective logging system is representative for large areas. When wasteland is afforested, 121 Mg C ha^{-1} is stored on average in the biomass and products, with an annual rate of $1.69 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ during the first rotation.

3. MONTANE CONIFEROUS FOREST AT ITS OPTIMUM IN EUROPE.

3.1. Introduction to the forest type

Norway spruce (*Picea abies* (L.) Karst.) is the main coniferous tree species determining the montane forests in Central Europe. The discussion here will be limited to this species. It is a tree species with a very wide natural distribution ranging from Central and Southeast Europe to Northeast Europe and Siberia (Schmidt-Vogt et al. 1977, see Figure 3.1), but is also present in North America and Eurasia. The wide distribution in today's European forests, the high yields and the wealth of practical experience with this species among forest managers, makes this a suitable species for sequestering carbon in forests in Central Europe, particularly because extensive Norway spruce stands in Central Europe have been severely damaged by air pollution. There are large areas on which spruce ecosystems can be restored, provided that the pollution impact is drastically reduced.

After giving an overview of the sites, climate, forest types, growth and silviculture, this chapter will describe the model input parameters in more detail. Finally, the carbon sequestering potential, and the annual storage and final total stocks of spruce forests in Central Europe will be outlined.

3.1.1. Sites, climate and growth

In general Norway spruce can be established within the borders of its natural distribution, the subalpine region, although the sites with the highest yields are usually found outside its natural borders, the montane region. The vertical distribution of *Picea abies* starts at sea level in Norway and ends at approximately 2200 m above sea in the Central Alps. Its optimum lies in Central Europe at an altitude of 500 to 1100 m above sea level. Its natural vertical distribution in Central Europe starts at approximately 400 m and ends at 2000 m (Schmidt-Vogt 1991). The optimum of its distribution, considered in this study, includes the West German hills, Switzerland, Bayern, Oberschwaben, Schwäbische alps, Black Forest, Neckarland, Carpathian and Bohemian hills (see Figure 3.1). In these regions, spruce can attain higher yields than those presented in the yield table of Wiedeman, in Schober (1975) which goes up to a mean volume increment of $12.2 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (see the section on "Literature data").

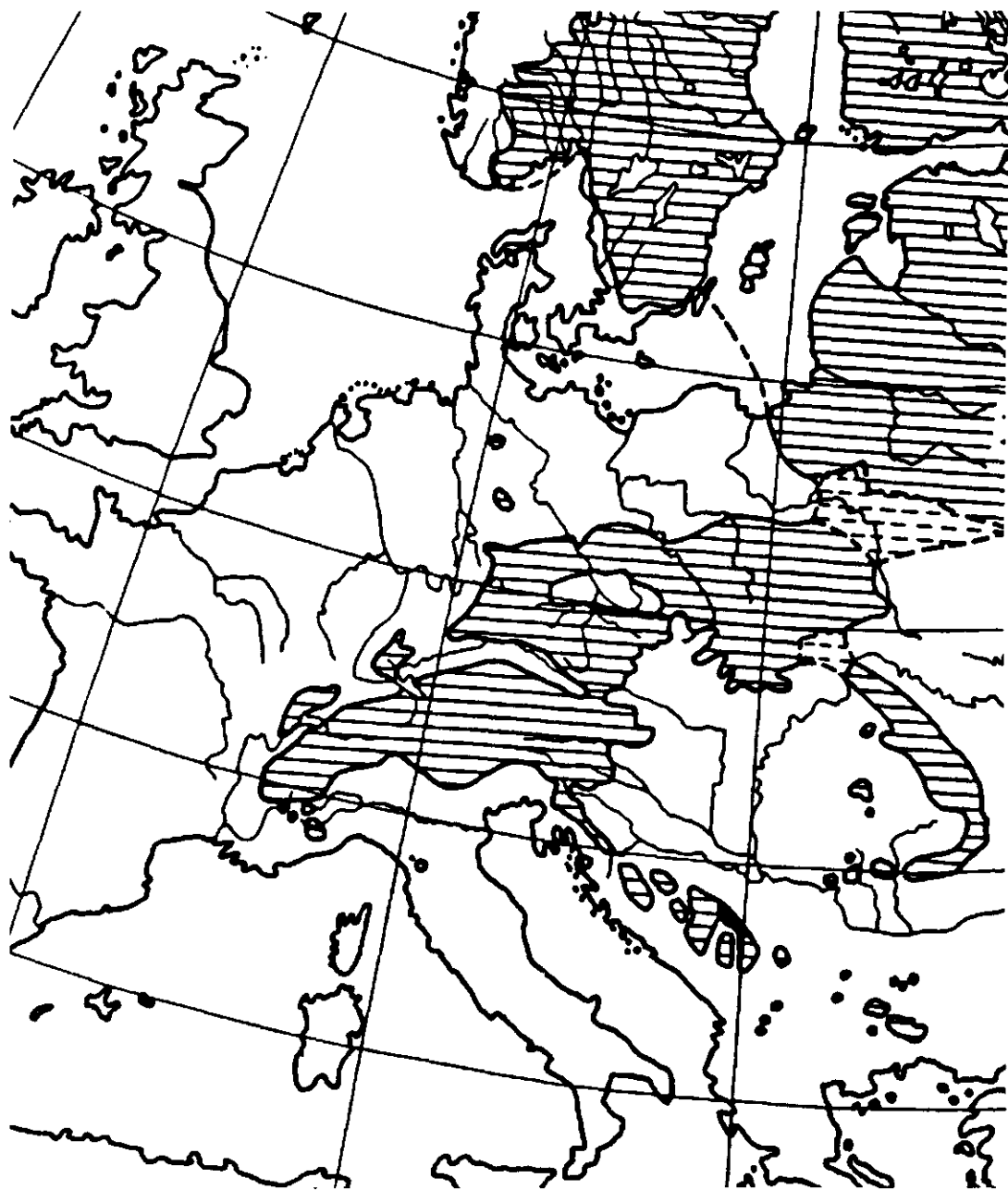


Fig. 3.1 Natural distribution of Norway spruce (*Picea abies* (L.) Karst.) in Central and Southeast Europe (after Schmidt-Vogt et al. 1977).

At its optimum, the species is limited in its vertical distribution at an altitude of about 1500 m above sea level. Limits are mainly imposed by a combination of lack of warm temperatures, the occurrence of frost, drought and wind, and through soil quality and water availability. Water is often the limiting factor, especially in somewhat warmer regions. During the growing season, 300 mm of rainfall can be seen as the lower limit (Schmidt-Vogt 1991). The forest type can be seen as the climax vegetation of the subalpine region of Central Europe (altitude 1300 - 1800 m) and as an intermediate forest type in the montane regions (altitude 900 -1300 m), where beech and fir are the climax tree species.

3.1.2. Silviculture

Norway spruce is very often established in pure stands in rotations of approximately 120 years. Modifications are made to achieve certain goals. If a combined yield and protection forest is desired, 60% of the stand may consist of spruce with 40% larch. Larch is usually established first, after which the spruce is planted under its cover. The quality of the site determines whether the spruce is able to catch up with larch in height. In this forest type the quick culminating increment of larch is compensated by the late culminating growth of spruce, which results in relatively high total volume productions (Zöhrer, in Schmidt-Vogt 1986). If wood of a high quality is desired and one wants to achieve a natural stand, 80% spruce is usually mixed with 10% beech and 10% fir (*Abies* spp.). On good sites beech is able to maintain its growth of pure stands. In general can be stated that mixtures with shade-tolerant and light demanding species usually perform very well and fulfil several functions simultaneously, while the total volume production does not necessarily need to decrease (Schmidt-Vogt 1986). Another important point is that the stand can resist storm damage and snow pressure better than pure stands of spruce (Wenk et al. 1990). In the subalpine regions mixtures are usually not possible.

Rotations are usually changed through clear-felling and renewed planting of spruce, although "Schirmschlag", "Femelschlag", "Saumschlag" and felling of small groups to change the pure stands into mixed stands are becoming more and more popular. The conventional way is to establish the new stand with approximately 6000 plants per hectare, although natural regeneration, if possible, is recommended for the subalpine regions to preserve the gene resources. In the subalpine regions the natural forests have adapted to the extreme climates, and therefore the seeds from local seed sources are best for planting at a certain site.

In general, heavy thinnings are recommended in the young stands and regular but light thinning in the older stands. Thinning can be carried out every 5 years, depending on the site and the growth of the stand. Pruning and selective Z-Baum (future tree) thinning is necessary, especially when wood of a high quality is desired. Depending on the risks at the site, 150 to 250 future trees are selected (Schmidt Vogt 1986/1991). Much of the wood of the final cut can then be used as sawn timber. This is done in many spruce stands in Germany, and hence Norway spruce is second to Douglas-fir in financial yields (Ripken & Spellmann, in Schmidt-Vogt 1991).

3.1.3. Soils

As the yield of Norway spruce is predominantly determined by the quality of the soil, this is a good indicator of the attainable production. The soil type may also contain information about the altitude and the moisture availability. The relevant soil types of Central Europe are discussed below. Since many regional soil maps and classifications are based on the German soil classification with German names, these will be used later in this chapter. The following soil types are relevant (Rehfuess 1981):

- Parabraunerde in Loess
- Ranker and Braunerde from carbonate-free, siliceous rock;
- Rendzina from carbonate-rich rock;
- Ranker and Podzol from silicate and base-poor, quartz-rich rock;
- Stauwasserböden (gley soils).

Parabraunerde (grey-brown podzolic soils or pseudogley) are distinguished from the Braunerde by their clay illuviation. They may develop in Loess, in Tertiary sediments, in carbonate-rich alluvium or on calcium-rich sandstones. Despite the clay illuviation from the topsoil into the deeper layers, the drainage is rather good. Spruce can root deep and attain high yields on deep developed, base-rich loamy Parabraunerde.

Ranker and Braunerde are the most widespread soil types of montane and subalpine Central European regions. They can develop on basalt, calcium-silicate rich gneiss and granite, phyllite and from silicate-rich sandstone and moraines. The main regions where they are found are: the Central Massif (F), northern Oberpfalz (G), Vosges mountains (F), Black Forest (G), Spessart (G), Fichtel mountains (G), Harz (G), Sudete (G), Carpathian (Cz), Central Alps (A & S), Northeastern Bayern (G) and the Ore mountains (Cz). Both soil types develop from weathering of parent material in situ from which a loamy substrate is formed. At the initial stage the Rankers are formed; the Braunerde may develop from these in a later stage of the soil formation. Rankers are usually found on exposed hill tops and steep slopes. At these sites, any further soil formation is usually interrupted because of the rapid erosion of the soil material. Growth of spruce is limited on these sites.

The Braunerde (brown forest soils) are divided into three soil types: the eutrophic (base-rich) Braunerde, the base-poor Braunerde and the podzol Braunerde. This division is mainly determined by the parent material. The natural vegetation of the base-rich Braunerde consists of rich deciduous forests with maple, ash, lime and beech. Spruce can give high yields on this soil type, but the wood is often infected by the fungus *Fomes annosus*. The base-poor Braunerde are often known for their loam-sandy texture. In the montane heights mixed forests of beech, spruce and fir with some maple and ash are the natural vegetation. The podzol Braunerde are usually found on quartz-rich sandy sediments or acid gneiss and phyllites. A species poor deciduous and coniferous forest type is the natural vegetation.

The Rendzina soil is a shallow soil type that has originated from weathering of limestone. Rendzinas usually show a rather thin humic, clayey A horizon on top of the original carbonate rock. They are found in the Jura, Schwäbische

Alps (G) and French Alps and in the Neckar region (G). In the sub-montane region, the mull-rendzinas can carry a natural vegetation of beech, ash, maple and lime. At subalpine altitudes, spruce can form the natural vegetation. As the weathering of the substrate continues, a Terra Fusca may develop. This soil type has a rather deep clayey soil profile. The natural vegetation consists of a mixture of beech, fir and spruce sspecially at altitudes of the upper montane region. Spruce can give high yields on deep Terra Fusca, but is often damaged by the fungus Fomes annoses.

The rankers and podzols on silicate-poor, base-poor and quartz-rich rock can develop from gneiss and granites in the central German mountain regions and from base- and clay-poor sandstones in the Harz (G) and the stained sandstones in the Vosges mountains (G), Black Forest (G), Oden forest (G), Spessart (G), Vorrhön and the Bayern and Schwaben "Keuper" mountains. Asa result of a combination of a low nutrient supply and a limited water-storing capacity of podzols, the growth on these sites is often limited. Figure 3.2. shows the location in the landscape where the different soil types are found.

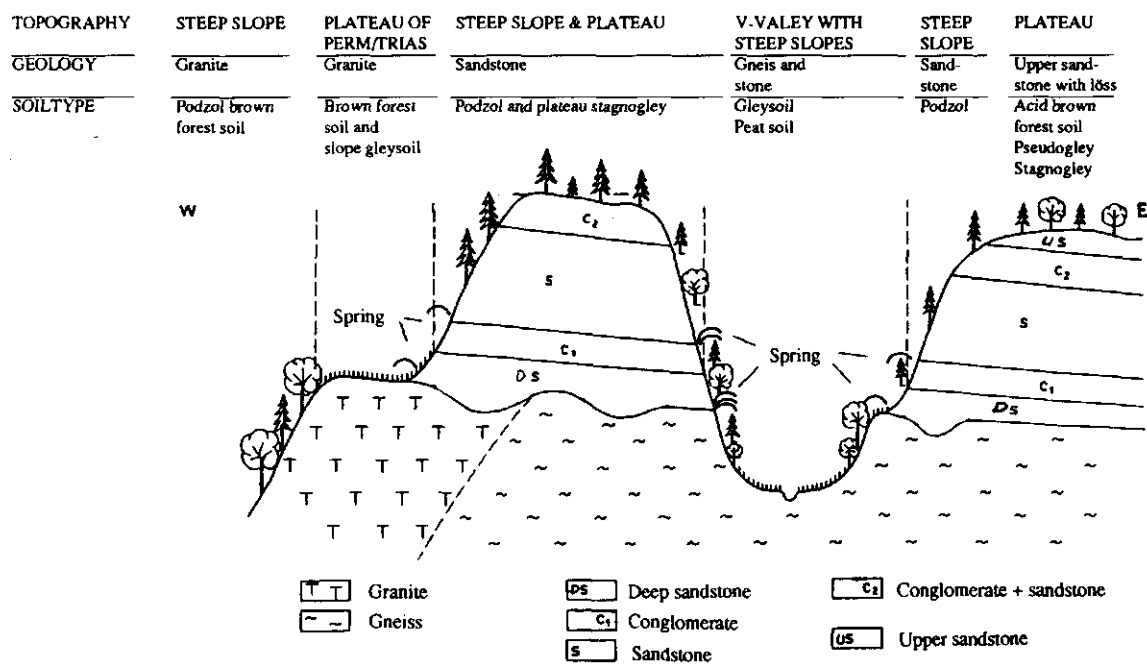


Fig. 3.2 Example of the distribution of soil types in a Central European hilly landscape (Northern Black Forest) (adapted after Rehfuess 1981).

Gley soils can occur in a wide variety of landscapes, parent material and climates and soils. Very often they develop in clay soils or soils with clay illuviation. Either the drainage water stagnates on a dense soil horizon within a limited distance from the soil surface (Pseudogley) or the rain water accumulates in depressions in the landscape (Stagnogley). Generally only poplar, alder and white fir are capable of relatively deep rooting in these soil types. Spruce usually develops a very shallow root system, which makes it suscep-

tible to drought and wind throw. For example, in the Black Forest region the forest on this kind of soil usually consists of low-yielding spruce, pine and fir stands in which the spruce is often damaged by storm.

3.2. Carbon dynamics in Norway Spruce forests on three sites in montane Europe.

3.2.1. Literature data

The main yield table for Norway spruce in Central Europe, is the one from Wiedemann given in Schober (1975). In rotations of 120 years, mean volume increments range from 4 to 12.2 m³ha⁻¹yr⁻¹ (i.e. relative site classes V - I). Mitscherlich (1963), however, recorded a more limited growth for the Bohemian hills. In their yield table for spruce in the Czech republic, Halaj & Rehák (1979) present a mean volume increment (MAI) of 10.1 m³ha⁻¹yr⁻¹ for the best site and a MAI of only 2.1 m³ha⁻¹yr⁻¹ for the worst sites at an age of 120 years. But higher total volume productions are presented also. A total volume production on rich loams of up to 1700 m³ha⁻¹ in a rotation of 120 years is possible (Horndasch, in Schmidt-Vogt 1986; Mitscherlich 1963).

Horndasch, in Schmidt-Vogt (1986), established the relation between absolute site class and soil type (see Table 3.1, the local soil type name is given). But it must be remembered that the region in which the soil type is found can upgrade or degrade the relative site class.

Table 3.1 *Relation between soil type and relative site class given by Horndasch for Schwaben (Horndasch, in Schmidt-Vogt 1986).*

soil type	relative site class	standing volume at age 100 (m ³ ha ⁻¹)	mean annual vol. increm. at 100 years (m ³ ha ⁻¹ yr ⁻¹)
Parabraunerde (Loess)	0	1100	17.0
Loamy deep Braunerde	0	950	14.5
Base-poor Braunerde	I	750	12.2
Podzol Braunerde	II	600	9.6
Pseudogley	II	600	9.6
Podzol, loamy sand	II	600	9.6
Gley soil	III	480	7.5
Ranker	IV	360	5.6

Biomass measurements were gathered so that the allocation of the Net Primary Production to the biomass compartments could be determined (see also Appendix E).

Annual litter fall values were derived from Kimmins et al. (1985). He mentions figures of 2.9, 4.5, 3.8, 3.4, 3.6, 3.1 and 3.4 Mg ha⁻¹yr⁻¹ dry matter for Norway spruce forests in Germany aged respectively 34, 46, 70, 87, 90, 115 and 125 years.

The amount of carbon in the stable humus in German forest soils is given by Rehfuss (1981). For brown forest soils this amount ranges from 90 to 110 Mg C ha⁻¹. Post et al. (1982) and Millemann & Boden (1986) present figures of approximately 120 Mg C ha⁻¹ for the amount of carbon in the stable humus under cool temperate moist forest.

According to Cannell (1984) the specific gravity of the spruce wood is 470 kg m⁻³. Cerny (1990) mentions an average for Bohemia of 423 kg m⁻³. Dixon et al. (1991) mention an average figure of 410 kg m⁻³ for spruce spp.

Much of the wood from long rotations with Norway spruce is used for sawn timber (Schmidt-Vogt 1986). Thinning wood is mainly used for pulp and board wood.

3.2.2. Model input

The carbon dynamics in Norway spruce stands in Central Europe was modelled for three sites with good, moderate and limited growth of Norway spruce. The mean increment of spruce at an age of 120 years on these sites was set at 14.2, 9.3 and 5.8 m³ ha⁻¹yr⁻¹, mainly based on the yield table of Wiedemann in Schober (1975), although better and worse sites do occur (Halaj & Rehák 1979, Mitscherlich 1963). This range of sites covers most of the sites in Central Europe. For current volume increments in relation to stand age, see Appendix D2.

The carbon allocation of Spruce was assessed from biomass measurements and NPP measurements of several authors presented in Table 3.2. (see Appendix E). The allocation of harvested wood to the products is given in Appendix I1. The modelling was done for three rotations each of 120 years. Thinnings start at an age of 25 or 35 years (depending on the site) and are regular and light.

The basic wood density of the spruce wood was set at 410 kg m⁻³ (Appendix C). The litter residence time for the good, moderate and limited sites were set at 2, 3 and 3.5 years respectively and the humification factor was set at 3%, 2% and 2% (see Appendix H). The initial amount of dry matter in the stable humus was set at 190, 175 and 140 Mg ha⁻¹ for the good, moderate and limited sites respectively.

Table 3.2 *Biomass and Net Primary Production measurements of Norway spruce in temperate regions in Europe according to various authors.*

stand age	55	260	34	76	87	115	55	80	57	78	106
Country	Belg.	Finl.	Ger.	Ger.	Ger.	Ger.	Swe.	Ger.	Cz.	Cz.	Cz.
reference	1	2	3	4	3	3	5	6	7	7	7
<hr/>											
biomass dry weight: (Mg ha ⁻¹)											
stem	170.0	67.3	105.1	268.0	198.4	195.8	262.0	268.0	240.0	277.5	247.2
branch	16.6	17.1	18.7	38.3	28.2	24.6	28.0	28.3	22.7	33.9	32.8
foliage	16.1	6.6	18.9	15.9	17.9	12.7	18.0	15.9	18.9	20.8	18.9
root	31.0	37.5	34.6	*	71.7	74.9	58.0	*	75.1	64.5	91.6
<hr/>											
total	233.7	128.5	177.3	322.2	316.2	308.0	366.0	312.2	356.7	396.7	390.5
<hr/>											
dead organic material (Mg ha ⁻¹)											
forest floor	*	*	52.0	*	49.0	111.0	18.5	*	*	*	*
dead wood	7.8	4.2	0.3	*	*	*	*	10.0	*	*	*
undergrowth	*	0.13	*	*	*	0.0	0.01	*	*	*	*
<hr/>											
NPP (Mg ha ⁻¹ yr ⁻¹)											
stem	6.9	0.1	4.9	5.9	5.4	4.0	9.4	*	*	*	*
branch	4.0	*	0.6	3.2	0.6	0.3	1.7	*	*	*	*
foliage	2.3	1.5	2.9	6.3	3.4	3.1	3.3	*	*	*	*
root	1.8	*	1.6	*	*	0.9	2.6	*	*	*	*
<hr/>											
total	15.0	*	10.0	15.5	9.4	8.4	17.0	15.5			
<hr/>											
References:	1:	Kestemont, in Cannell (1982);			5:	Nihlgard (1972);					
	2:	Havas in Cannell (1982);			6:	Baumgartner (1975);					
	3:	Ellenberg et al. (1986);			7:	Cerny (1990).					
	4:	Droste zu Hulshöff (1970);									

3.2.3. Results and discussion

The results of modelling the carbon sequestering potential of Norway spruce in montane Europe during 300 years are displayed in Figure 3.3. and summarized in Table 3.3. With Appendix J, it's possible to determine site class of a certain spruce stand, and thus the carbon storing capacity.

Since a vital part of the modelling of carbon storage in spruce forest ecosystems is based on well established and reliable yield tables, the results can be seen as reliable. Although a wide range of sites is covered by the site classes chosen, it must be remembered that the results may be less than given for site class 5 especially in the subalpine regions. Because carbon storage through afforestation is mainly achieved in the living biomass and products and not so much in the litter, the long-term average amount of carbon stored in the biomass and products is the most important criterion.

Table 3.3 Comparison of carbon stocks and fluxes for Norway spruce on three site classes.

	<ol style="list-style-type: none"> 1) Total stock of carbon at the end of the rotation in biomass and products (Mg C ha⁻¹); 2) Total stock of carbon at the end of the rotation in the soil organic matter ie. litter, dead wood and stable humus (Mg C ha⁻¹); 3) Total stock of carbon at the end of the rotation in biomass, forest products and in dead organic material on or in the soil (Mg C ha⁻¹); 4) Long-term average stock of carbon in the biomass and the forest products (Mg C ha⁻¹); 5) Long-term average stock of carbon in the forest products (Mg C ha⁻¹); 6) Long-term average stock of carbon in the soil organic matter (Mg C ha⁻¹); 7) Long-term average stock of carbon in the total system of biomass, products and soil organic matter (Mg C ha⁻¹); 8) Net accumulated amount of carbon over the first 100 years after afforestation (Mg C ha⁻¹); 9) Average net annual carbon flux at the end of the first rotation (Mg C ha⁻¹yr⁻¹). 								
	1	2	3	4	5	6	7	8	9
good site class (I _m = 14.2 m ³ ha ⁻¹ yr ⁻¹)	272	125	397	191	48	126	317	274	2.37
moderate site class (I _m = 9.3 m ³ ha ⁻¹ yr ⁻¹)	225	121	346	137	35	117	254	228	2.02
limited site class (I _m = 5.8 m ³ ha ⁻¹ yr ⁻¹)	156	102	258	84	22	95	179	168	1.46

The spruce forest ecosystem shows very good results, because of generally good growth in long rotations. This forest type can therefore build up large amounts of standing biomass. For the good, moderate and limited sites, figures of respectively 191, 137 and 84 Mg C ha⁻¹ were found for the average amount of carbon in the biomass and products. It is clear from Figure 3.3. that this forest type does not show good results in the short term, i.e. 10 years. Over the first rotation a net annual carbon flux of 2.02 Mg C ha⁻¹yr⁻¹ was found for the moderate site. This is considerable, given the long rotations.

The results from this study can be compared with the results given by Dewar & Cannell (1992) and by Dixon et al. (1991) for carbon storage in spruce forests. Dixon et al. mention an annual net carbon flux in spruce forests in southern Germany of 2 Mg C ha⁻¹yr⁻¹ at a mean increment of 6 m³ha⁻¹yr⁻¹ in a rotation of 85 years. The relatively short rotation period is probably responsible for the quite high annual carbon storage at the above mentioned mean increment. They state that in 50 years after reforestation, a total of 86 Mg C ha⁻¹ is stored in the biomass. This is in accordance with the figures found in this study for limited sites.

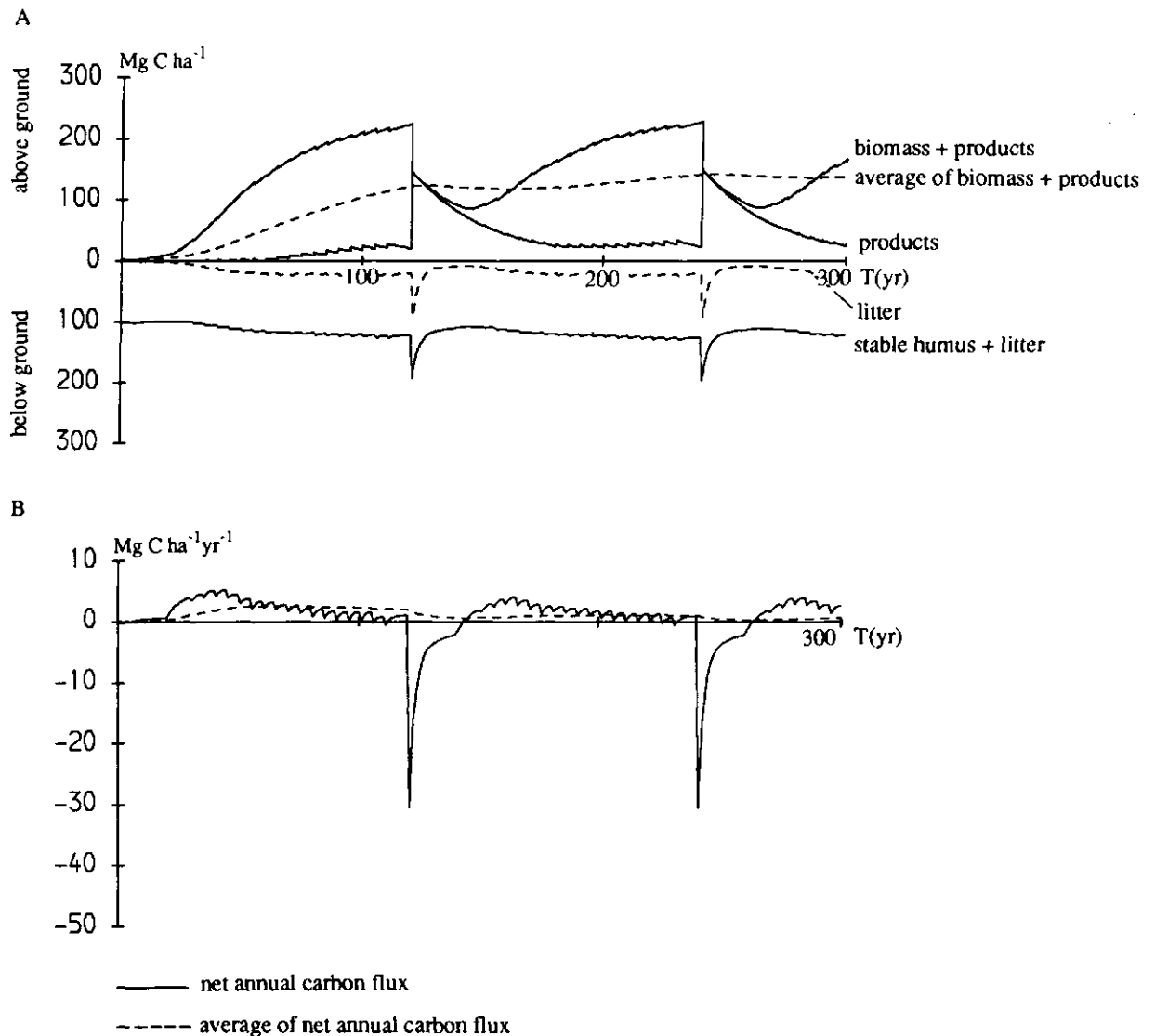


Fig. 3.3 A: Carbon stocks in biomass, forest products, and soil organic matter for Norway spruce on moderate sites with an I_m of $9.3 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (Mg C ha^{-1}).
 B: Carbon fluxes both annually and as a running mean ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$).

For spruce in a rotation of 47 years and a mean increment of $14 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ Dewar & Cannell mention an equilibrium storage in the trees of 74 Mg C ha^{-1} and a very high storage rate of $4.1 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ during the first rotation. This very high rate can only be achieved by the very intensive silvicultural system which they assume.

The amounts of carbon stored in the products are considerable compared with the living biomass. This is caused by the large part of the wood from the final cut which is allocated to sawn timber. This is reliable, for this silvicultural system is rather intensive. During the simulation period, carbon in the stable

humus remained almost constant, because the fluctuations in the compartment of stable humus, litter and dead wood in Figure 3.3A. are mainly caused by the litter and dead wood part (belowground dashed line).

In conclusion it can be stated that spruce forest ecosystems are good carbon storers, for they can build up large average amounts of carbon in the living biomass and forest products. On a moderately fertile site 137 Mg C ha^{-1} is stored on average. The net annual carbon flux at the end of the first rotation is $2 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$.

4. MIXED DECIDUOUS TEMPERATE FORESTS IN EUROPE.

4.1. Introduction to the forest type

Temperate deciduous forests occur over the world in regions with a pronounced seasonal change of temperature, a cold winter with snow and a mild, wet summer. Trees are tall, broadleaved and deciduous. The regions where deciduous forests occur are: eastern United States from 30 to 45° north, western and Central Europe extending in a narrow strip to just the east of the Urals, a small region in the Near East, eastern Asia with the northern boundary at about 50° N latitude, and the smallest zone in Chile at about 37-55° south (Röhrig & Ulrich 1991). Temperate deciduous forests show big regional differences depending on climate, altitude, soil conditions and floristic history.

In this study, the deciduous forests of the plains, foothills and the submontane zone of subatlantic and Central Europe are taken as a typical example (see Figure 4.1). The carbon sequestering potential of the oak-beech forests on rich soils will be outlined after the forest types, soils, climate and silviculture have been described in more detail.

4.1.1. Sites, climate and forest types

The temperate climate of Europe is characterized by a more maritime climate than the temperate regions in America and Asia. The western coast of Europe is subjected to the influence of the warm Gulf Stream, while the coasts of North America and Asia are under influence of cold currents from the north. This explains why the deciduous forests of Europe extend 10 degrees of latitude further north than in east Asia and America. Since the topography of Europe is marked by large mountain barriers running from west to east, moist oceanic air masses are able to penetrate deep into the continent. This may partly explain the dominant position of beech in the European temperate forests. Due to the air humidity, beech can still compete with oak on even the poor sites in the plains (Jahn 1991). Only on those sites which are too wet, dry or poor for beech, did natural mixed oak forests exist.

The altitudinal zonation of the European deciduous forests can be described as follows (according to the vegetation zones for Herzynian mountains in Jahn 1991, see also Figure 4.1). The plains and the foothill zone of mixed oak woodlands are today mainly used for agriculture. Sites subject to cold air and waterlogging are relatively frequent in the plains. The woodlands in the plains contain a large number of deciduous species like *Carpinus betulus*, *Quercus robur*, *Q. petraea* and *Tilia cordata* while the foothill zone (150-300 m a.s.) is mainly dominated by mixed oak forests. The submontane zone (300-450 m a.s.) is an extensive transitional zone in Central Europe consisting of *Fagus sylvatica* forests with *Quercus petraea*, gradually changing into the montane zone dominated by beech.

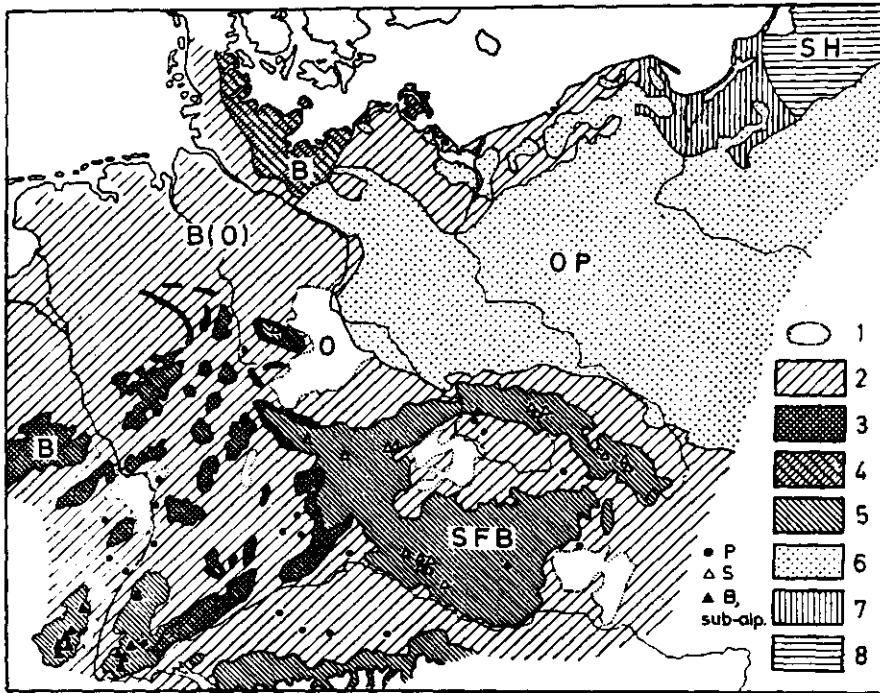


Fig. 4.1 General distribution of the natural vegetation in Central Europe at about the time of Christ, based on pollen analyses (Ellenberg, 1988).

- 1) Dry areas with an annual precipitation of less than 500 mm; mixed oak woods with some beech.
- 2) Low-lying areas with mixed beech woods, in parts with a strong admixture of oak; on the North Sea coast many alder; black circles = pine locally dominant.
- 3) Low mountains with beech, generally lacking conifers.
- 4) Moraine area with beech, few pines.
- 5) Mountain beech woods with fir and (or) spruce (white triangles); black triangles = subalpine beech woods.
- 6) Sandy soil areas where pines dominate, in places with oaks and other broadleaved trees.
- 7) Area of mixed broadleaved woodland with many hornbeam.
- 8) As 7 with the addition of spruce.

Of the forest communities of the temperate deciduous forests of Europe, the most important here are: the mesotrophic beech woods, the acidophilous beech woods and the cool temperate oak woods (see also Figure 4.1) (Jahn 1991).

The mesotrophic beech woods occur on base-rich igneous substrates, richer gneiss and sandstones and on some Quaternary soils such as boulder clay, loamy sands and loess. Their main distribution is in the submontane and the montane zone of the moderately high mountains, but they also occur in the plains (lowland beech woods). The soils are classified as deep, rich Parabraunerde and Braunerde. Organic matter decomposes quickly. Sometimes, associate trees such as *Q. petraea* and *Q. robur* occur in the beech forests, but only on sites where the growth of beech is limited. The vigorously growing and closed beech canopy usually preclude a significant shrub layer.

The acidophilous beech woods are the most widespread forest type of the

Central European hill and mountain area. They are found in the extensive moderately high mountains, on soils derived from weathering of argillaceous shists, granites, poorer gneiss and red sandstone. In the Pleistocene plains they occur on poorer boulder loam, sandy loams and poor loess. The soil types are base-poor brown forest soil, podzolic and moderately developed podzols. Further west (due to the air humidity) these beech woods are competitive even on poorer or wetter soils, like true podzols or waterlogged soils. Organic matter decomposes more slowly than in the mesotrophic beech woods. In this forest type, beech forms closed, productive and frequently pure stands. In the lowland beech woods, *Q. robur* (on wet sites) and *Q. petraea* (on drier sites) are associates. In the montane zone, associates like *Abies alba* occur. Because of the closed stands, no shrub layer develops. During medieval times the lowland beech woods of this forest type were rapidly converted to agricultural lands. Later afforestations mainly used oak on sites of the acidophilous beech woods. Beech was often planted under a shield of old oak, with the goal of producing oak with a high timber value. But very often the much younger beech surpassed the oak and totally outcompeted it.

The cool temperate oak woods are almost never pure oak forests. They occur where beech is limited by climatic or soil. Clay-rich or sandy soils, soils that are dry in summer or waterlogged, or soils with periodically high water tables weaken beech. On nutrient-rich sites, the hornbeam oak woods occur, while on the poor sites, the birch oak woodlands occur, with an increasing proportion of Scots pine towards the more continental Eastern Europe.

4.1.2. Silviculture.

As indicated in section 4.1.1, stands of individually mixed oak and beech trees are not very natural in Europe. Either the sites are too rich and beech becomes dominant, or the sites are too poor or wet for beech. Thus, establishing evenaged mixed stands of oak and beech is somewhat hazardous under these conditions. Very often, the goal of an individually mixed mature stand is not achieved because of the vigorous growth of beech. Wiedemann (1942 & 1951) states that oak may keep up with the growth of beech on warm sites (south slopes) with deep calcium-rich Loess soils. The higher or richer the site, the worse the result of establishing a mixed stand will be. In the plains, on poor or wet soils, oak may compete better with beech.

The thinnings, which are mainly intended to favour the oak, will have to favour the oak trees, even more on better sites or higher altitudes. After stand establishment, the strong juvenile growth of the oaks results in an advantage in height of the oaks, but if no thinnings in favour of the oaks are carried out, at an age of approximately 70 years, beech will take over the dominant position. Thinnings to stop this development therefore usually remove the most vigorous beeches from the stand (Wiedemann 1951). Total volume increment is rather uncertain and depends on the thinning regime. The total average annual increment may be somewhat less, but the increment is concentrated more on future oaks. It is therefore expected that at the end of a rotation the stands which have been subjected to intensive thinnings aimed at the future oaks, result in 30% extra yield (Wiedemann 1951).

4.2. Carbon dynamics in mixed oak/beech forests

4.2.1. Literature data

Growth figures for mixed oak/beech stands are scarce. Although the results for volume increment in a mixed oak/beech stand given by Wiedemann (1942) for site class I in Kramer et al. (1988) do not have a general validity, they are still seen as the most accurate available. In general these increments are somewhat reduced compared to the increments of a pure beech stand, but they show the same growth characteristic, with the current increment culminating rather late. Available biomass and Net Primary Production measurements are presented in Table 4.1.

Table 4.1 Biomass and Net Primary Production measurements (dry weight) in oak and beech stands in Europe (Röhrig & Ulrich 1991, after DeAngelis et al. 1981).

stand age	144	130	117	120	90	66	59	80	122	140
Country	Belg	Belg	Belg	Belg	Belg	Belg	Ger	Ger	Ger	Neth
Tree species [#]	Fs	Fs	Qp	Qr	Qr	Qr	Fs	Fs	Fs	Qp
reference	1	1	2	2	2	3	4	4	4	5
<hr/>										
biomass dry weight (Mg ha ⁻¹)										
stem	318.5	213.6	180.2	210.0	93.2	130.5	108.1	129.6	238.4	236.5
branch	50.8	122.4	58.3	88.2	37.0	36.9	41.5	25.9	32.5	28.5
foliage	3.0	2.9	3.5	4.0	3.2	3.6	3.2	3.3	3.1	3.3
root	74.0	68.0	53.0	51.2	31.1	41.8	24.0	22.1	30.0	41.8
<hr/>										
total	446.3	406.9	295.0	353.4	164.5	212.8	176.8	180.9	304.0	310.1
dead organic matter (Mg ha ⁻¹)										
forest floor	*	*	*	*	*	*	29.0	39.0	29.7	*
dead wood	1.8	*	*	*	*	2.9	*	*	0.7	*
undergrowth	*	*	18.1	29.3	26.7	*	*	*	1.3	9.0
<hr/>										
NPP (Mg ha ⁻¹ yr ⁻¹)										
stem	4.1	7.1	2.5	2.2	1.3	3.6	7.7	5.9	6.5	3.6
branch	3.1	*	5.4	5.1	3.4	4.6	1.0	0.5	0.8	1.9
foliage	3.0	2.9	3.5	4.0	3.2	3.6	3.3	3.4	3.2	4.4
root	1.4	1.8	1.7	0.8	1.0	1.7	1.3	0.6	0.7	2.2
<hr/>										
total	11.6	11.8	13.1	12.1	8.9	13.5	13.3	10.4	11.2	12.1
annual litter fall	*	*	*	5.6	*	*	*	4.0	5.4	3.7

#: Fs = *Fagus sylvatica* = beech
Qp = *Quercus petraea* = sessile oak
Qr = *Quercus robur* = pedunculate oak

References: 1: Duvigneaud & Kestemont 1977;
2: Duvigneaud et al., in Cannell 1982 (all stands with coppiced understorey);
3: Duvigneaud 1971;
4: Ellenberg et al. 1986;
5: Van der Drift, in Röhrig & Ulrich 1991.

Jahn (1991) concluded that the total aboveground dry biomass of mature mixed deciduous stands (over 100 years) lies within the range of 150 to 400 Mg ha^{-1} and that the net primary production of mature stable temperate forests can be estimated at 12 to 15 Mg ha^{-1} .

Kimmins et al. (1985) presents annual litter fall measurements of 3.5, 4.2, 4.6, 5.0 and 4.5 $\text{Mg ha}^{-1}\text{yr}^{-1}$ dry matter in an age series of beech stands in Germany with average ages of 30, 50, 70, 90 and 100 years. Lemee and Bichaut, in Kimmins et al. (1985) present annual weight losses of oak litter in Fontainebleau (F) of 0.31 - 0.46 of the dry weight. The amount of stable humus was derived from Rehfuess (1981) and was assumed to be the same as the figures used for spruce in Central Europe for the same soil types considered.

According to Cannell (1984) the basic wood density is 650 kg m^{-3} for beech wood and 600 kg m^{-3} for oak wood. Later, Dewar & Cannell (1992) use figures of 550 and 560 kg m^{-3} . Dixon et al. (1991) mention figures of 560 and 660 kg m^{-3} respectively.

4.2.2. Model input.

The yield table of Wiedemann (1942) was used for site class I ($I_m = 8.1$ at an age of 150 years, on south slopes in the submontane zone with loamy brown forest soils). The increments on the other two sites (the foothill zone with sandy loams and poor loess, and the plains with podzolic soils), were established by combining Wiedemann's yield table with the yield table for pure beech stands from Schober (1975). The rotation length was set at 150 years. For the good, moderate and limited sites this resulted in mean annual increments at an age of 150 years of 8.1, 5.4 and $3.3 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, respectively. For current volume increment during stand development, see Appendix D2. The allocation of NPP to the biomass compartments other than stems is given in Appendix E.

Thinnings are carried out regularly and are light. In general, vigorous beeches are removed (usually 10% of the standing volume). Much of the thinning wood is used as fuel wood, while at greater ages the wood is used for sawn timber (see Appendices G and I5).

The basic density of the wood was set at 635 kg m^{-3} . The initial values for stable humus were set at 190, 175 and 150 Mg ha^{-1} . The decomposition parameters are given in Appendix H. Although the sites are comparable to those of the montane spruce ecosystems, here the humification factor has been chosen to be higher and the residence time of litter shorter because the litter in oak/beech forests is of a much better quality than the spruce needle litter. Hence decomposition and humification proceed faster.

4.2.3. Results and discussion

The results of the modelling of carbon dynamics in mixed oak/beech stands in Europe are displayed in Figure 4.2 and summarized in Table 4.2. With Appendix J, it is possible to determine the site class as used here for a particular oak/beech stand.

Table 4.2 *Comparison of carbon stocks and fluxes for oak/beech mixed stands on three site classes.*

- 1) Total stock of carbon at the end of the rotation in biomass and products (Mg C ha^{-1});
- 2) Total stock of carbon at the end of the rotation in the soil organic matter i.e. litter, dead wood and stable humus (Mg C ha^{-1});
- 3) Total stock of carbon at the end of the rotation in biomass, forest products and soil organic matter (Mg C ha^{-1});
- 4) Long-term average stock of carbon in the biomass and the forest products (Mg C ha^{-1});
- 5) Long-term average stock of carbon in the forest products (Mg C ha^{-1});
- 6) Long-term average stock of carbon in the soil organic matter (Mg C ha^{-1});
- 7) Long-term average stock of carbon in the total system of biomass, products and soil organic matter (Mg C ha^{-1});
- 8) Net accumulated amount of carbon over the first 100 years after afforestation (Mg C ha^{-1});
- 9) Average net annual carbon flux at the end of the first rotation ($\text{Mg C ha}^{-1}\text{yr}^{-1}$).

	1	2	3	4	5	6	7	8	9
good site class $I_m = 8.1 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	258	123	381	150	29	122	273	177	1.79
moderate site class $I_m = 5.4 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	199	108	307	110	20	105	216	139	1.35
limited site class $I_m = 3.5 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	162	106	268	88	15	102	190	124	1.19

From the results it is clear that this forest type can store on average, large amounts of carbon in the biomass and that it still has a considerable storage rate over the first rotation. On a moderate site, 110 Mg C ha^{-1} are stored on average in the biomass and products with a net annual flux over the first rotation of $1.35 \text{ Mg C ha}^{-1}\text{yr}^{-1}$. The carbon stocks in the forest products are relatively small, compared to other stocks. The accumulation in the stable humus is negligible because it is assumed that the afforested sites are not degraded. This results in a stable amount of carbon in the total compartment of humus, litter and dead wood (see belowground solid line in Figure 4.2).

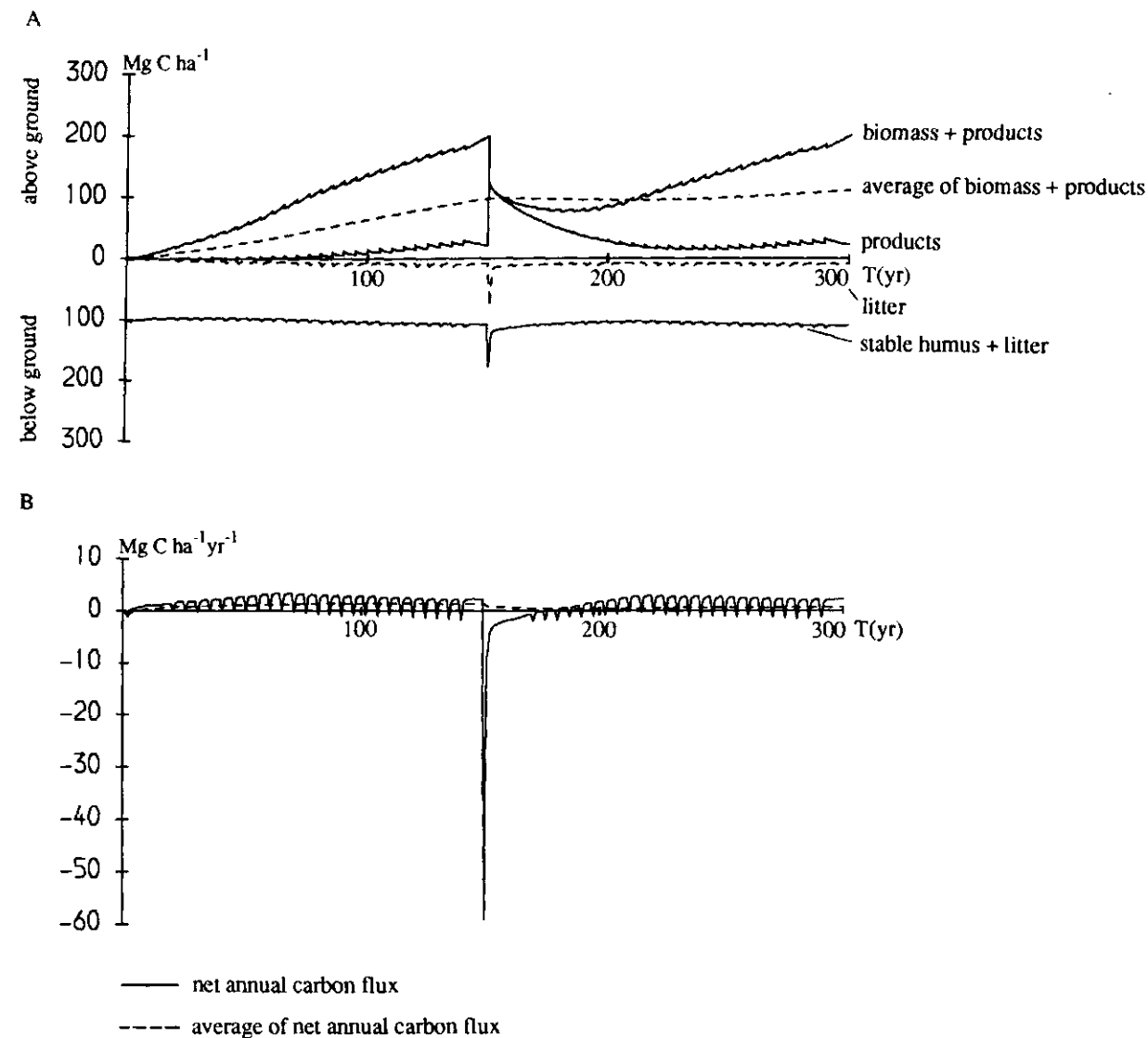


Fig. 4.2 A: Carbon stocks in biomass and forest products, and soil organic matter for mixed stands of oak and beech on moderate sites ($I_m = 5.4 \text{ Mg C ha}^{-1} \text{yr}^{-1}$ at $T = 150 \text{ yr}$) (Mg C ha^{-1}).
B: Carbon flux both on an annual basis and as a running mean ($\text{Mg C ha}^{-1} \text{yr}^{-1}$).

Although it is questionable whether the goal of a mixed mature stand of oak and beech is realistic from the silvicultural point of view, the results presented here provide a reliable picture of mixed deciduous stands. Silvicultural management of such mixed stands requires much experience and an intensive thinning regime. Beech may still be able to suppress oak, especially on the better sites in the submontane zone, but this will not alter the amount of carbon eventually sequestered. Since the volume increments are based on a yield table made for one region and site class, the increments are somewhat

arbitrary, although comparison with other data, such as the yield tables for pure stands (well established and representative of a wide range of soils and sites, Schober 1975), Net Primary Production and total biomass data (Jahn 1991, Cannell 1992) for temperate oak and beech forests does not essentially change the outcome.

For beech forests in the UK with a mean annual increment of $6 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ in a rotation of 92 years, Dewar & Cannell (1992) mention an equilibrium carbon storage of 60 Mg ha^{-1} and a rate of storage during the first rotation of $2.4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. These figures are higher than the results for the moderate site in this study when the criteria are compared on the same time scale. The difference is attributable to the different growth dynamics used in the model. The yield table used in this study has its maximum current increment rather late, at an age of 80 years. This yield table can still present the same maximum mean increment in the long-term, but with lower carbon stocks and fluxes compared to the period considered by Dewar & Cannell (1992). Another explanation for the high net annual carbon flux which Dewar & Cannell present is the fact that they start the modelling with no carbon in the soil compartment; this results in a high net storage rate in the stable humus compartment.

For the equilibrium carbon stock in soil and litter under beech stands in the UK with a mean annual increment of $6 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ in a rotation of 92 years, Dewar & Cannell (1992) mention a figure of 114 Mg C ha^{-1} . This matches very well with the results of this study, which for sites of good, moderate and limited fertility gave respectively 122, 105 and 102 Mg C ha^{-1} in the humus, litter and dead wood compartments combined.

Concluding it can be stated that mixed oak/beech stands in Europe store considerable amounts of carbon in the longterm in the living biomass and the products (110 Mg C ha^{-1} on a moderate site). Over the first rotation, the net carbon flux on a moderate site is $1.35 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$.

5. CONIFEROUS FORESTS IN NORTHWEST AMERICA.

5.1. Introduction to the forest type

The temperate coniferous rainforests of northwestern North America extend from the gulf of Alaska to Northern California, within 60-120 km of the Pacific Ocean. Mild moist maritime conditions characterize the region, producing forest dominated by massive evergreen conifers, including *Pseudotsuga menziesii* (Douglas-fir), *Tsuga heterophylla* (Western hemlock), *Thuja plicata* (Western red cedar), *Picea sitchensis* (sitka spruce) and *Sequoia sempervirens* (coast redwood) (Franklin 1989). These forests are known for the greatest biomass accumulations and some of the highest production levels of the world and an immense ecological and genetic wealth. Natural forests are to some extent being logged (Dudley 1992). After a brief overview of sites, climate and silviculture, the carbon sequestering potential of Douglas-fir stands in the Pacific Northwest of the US will be outlined as a typical example.

5.1.1. Site, climate and forest types

The Pacific Northwest is characterized by north-south running mountain ranges, like the Cascade Range which is the major climatic divide. A maritime climate characterizes the Pacific Northwest, west of the Cascade Range (see Figure 5.1). In coastal regions temperatures are mild with prolonged cloudy periods and narrow diurnal fluctuations (6-10 °C). Winters are mild with precipitation of 800-3000 mm, 75% of which occurs in the period October to March, mostly as rain. Summers are cool and can be relatively dry (Franklin 1989).

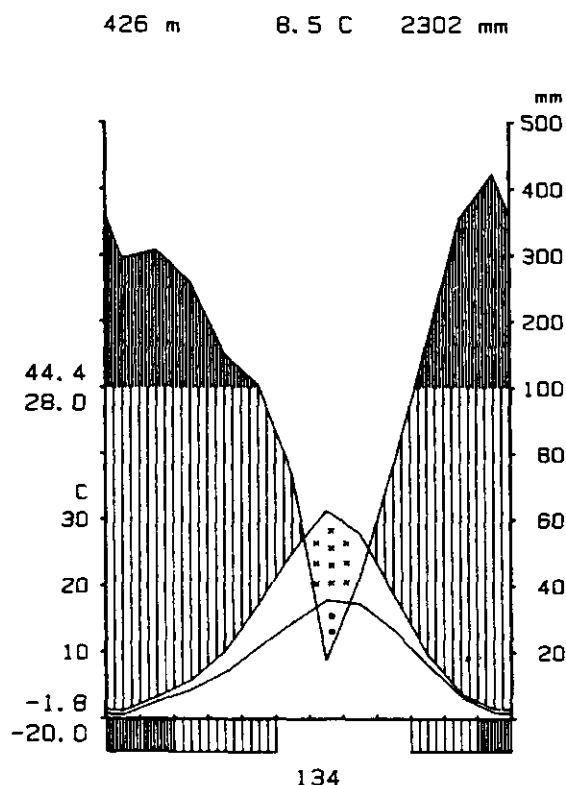


Fig. 5.1 Climatic diagram illustrating temperature and moisture regime for the H.J Andrews Experimental forest, Oregon in the *Tsuga heterophylla* zone in the western Oregon Cascade Range (Smith in Franklin 1989)

Geological conditions are highly varied, with sedimentary rock types typical of the Oregon Coast ranges and metamorphic rocks dominating much of the northern Cascade Range and Olympic mountains. Volcanic rocks are typical for the southern two-thirds of the Cascade Range. Glaciation has been an important process at higher elevations in the Cascade Range and Olympic Mountains, as well as in the ranges of British Columbia and Alaska. Forest soils are very varied, also reflecting the diverse parent materials and topography of the region. Haplumbrepts, Haplohumults, Haploorthods, Xerochrepts, Cryorthods and Vitrandepts are most characteristic (Franklin 1989). Deposition of parent material by alluvial, colluvial, glacial or aeolian action is an important soil forming process. It is typical for this region that the productivity of the forests mainly varies along the moisture gradient and that forest productivity is only to a lesser extent determined by the soil type. The soils are therefore not described in detail.

The forests of the Pacific Northwest can be divided into (Franklin 1989):

- *Pseudotsuga menziesii* - *Tsuga heterophylla* forests;
- *Picea sitchensis* - *Tsuga heterophylla* forests;
- *Sequoia sempervirens* forests;
- Klamath Mountains, mixed evergreen forests;
- Sierran type, mixed conifer forests.

The *Pseudotsuga menziesii* - *Tsuga heterophylla* forests are the most important for this study. This is the major forest complex of the Pacific Northwest, consisting of stands of *Pseudotsuga menziesii* and massive old-growth forests of mainly *Pseudotsuga*, *Tsuga heterophylla* and *Thuja plicata*. *Abies grandis* (grand fir), *Picea sitchensis* (sitka spruce) and *Pinus monticola* (Western white pine) occur sporadically. These forests occur from sea level to elevations of 700 - 1000 m in the Coast Ranges, Olympic Mountains and Cascade Range north of 43°N latitude. *Pseudotsuga menziesii* - *Tsuga heterophylla* forests

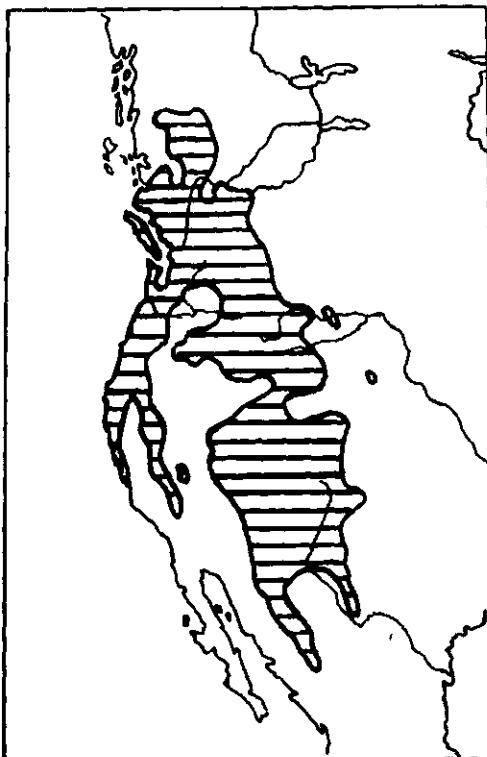


Fig. 5.2 Range of *Pseudotsuga menziesii* in the Northwest of the USA (Vidakovi 1991).

occupy a wide range of environments and are highly variable in composition and structure, depending on local conditions, especially the moisture regime. It is typical of this region that the productivity of this forest type mainly varies along the moisture gradient and that productivity is determined less by the soil type (Grier et al. 1986 & 1989). Less productive communities dominated by *Gaultheria* spp. or *Holodiscus* spp. characterize the hot dry end of the gradient. At the moist end of the gradient herbaceous understories dominated by *Polystichum* and *Oxalis* spp. are characteristic. Intermediate mesic sites have understories dominated by a variety of shrubs, subshrubs and herbs of which *Berberis* and *Rhododendron* spp. are common.

The early stages of succession are rather well known. After 5-7 years following logging and burning of an old growth forest, invading herbs begin to give way to shrubs like *Rubus*, *Berberis* and *Rhododendron*. The vegetational composition is heterogenous in the preforest stages of succession, reflecting variability in logging and fire disturbances. The diversity and biomass of the shrubs and herbs declines dramatically once the canopy of trees closes. *Tsuga heterophylla* and *Pseudotsuga menziesii* are the major climax species. *Pseudotsuga* dominates the young forests, often forming pure stands because of its relatively large and hardy seedlings and rapid growth rate. *Tsuga heterophylla* or *Thuja plicata* may establish themselves early in succession or later under the canopy of *Pseudotsuga*. Stand basal areas shift towards *Tsuga* and *Thuja* after 400 - 600 years (Franklin 1989). *Pseudotsuga* may persist as individuals for more than 1000 years.

5.1.2. Silviculture.

Douglas-fir can grow up to 100 m tall and up to 4 m in diameter. It can attain a great age, over 700 years. Growth can be rapid and the accumulated stem biomass can be very large in old growth stands. Two varieties of *Pseudotsuga menziesii* are distinguished (Vidakovi 1991). These are:

- var. *menziesii*, which is a typical coastal form and is also known as green Douglas-fir. It thrives in regions with mild ocean climate, with abundant precipitation and atmospheric humidity during the long vegetation period;
 - var. *glauca*, a mountain form which is also known as blue Douglas. This variety withstands cold and arid sites better than the green Douglas-fir.
- Sometimes an intermediate variety (f. *caesia*), which occurs east of the coastal and north of the blue Douglas, is distinguished.

Sites to be afforested with Douglas-fir should be moist and humid if rapid growth has to be achieved. The drier the site, the more limited the yield. The sites can be prepared in several ways. Most common is the practice of broadcast burning of the logging slash and planting of barerooted 2+0 planting stock (Cafferata 1986). Mechanical site preparation is less common and can consist of piling and burning, ripping skid trails, ripping to improve soil conditions and scarification (superficial ploughing). Natural regeneration may occur spontaneously on logged-over sites, but is not commonly used in a guided process in forestry. It is however recommended to use planting stock from local seed sources (Cafferata 1986). Planting densities are very low, with a minimum of only 500 trees per hectare (Curtis et al 1982) and when precom-

mercial and commercial thinnings are carried out, up to almost 3000 plants per hectare. Pruning is hardly ever carried out. Thinnings are usually carried out 4 to 5 times during the rotations of 100 years at basal areas of approximately $23 \text{ m}^2 \text{ ha}^{-1}$. Sometimes fertilization is applied in which $90 \text{ kg nitrogen ha}^{-1}$ is applied once or several times during the rotation

Although in Europe Douglas-fir is known for the absence of pests, it can be attacked severely in the Pacific Northwest of the US (Russell et al. 1986). Frost damage on stems and tops is a major problem in the lowlands, against which little can be done other than using local seed in afforestations. Douglas-fir may be damaged by flooding on extremely wet sites, or by drought on too gravelly extreme sites. Fungi like *Armillaria* root rot (*Armillaria ostoyae*) and laminated root rot (*Phellinus weirii*) can cause major decline of growth and vitality. It is usually advised to treat infected sites extensively or to plant root-rot-tolerant species like lodgepole pine, Western red cedar and Western hemlock. The Douglas-fir beetle (*Dendroctonus pseudotsugae*) may kill groups of trees when outbreaks are triggered by events like wind and fire.

5.2. Carbon dynamics in Douglas-fir forests

5.2.1. Literature data

Fujimori et al. (1976) recorded the greatest stem biomass for a *Pseudotsuga-Tsuga heterophylla* forest ever recorded. At the average age of 450 years the stand contained a volume of $3600 \text{ m}^3 \text{ ha}^{-1}$ at a basal area of $127 \text{ m}^2 \text{ ha}^{-1}$. The amount of dry matter stored in the stems alone amounted 1590 Mg ha^{-1} . This equals an amount of 795 Mg C ha^{-1} stored in the stems. An approximate average value is an amount of $800 \text{ Mg stem dry matter per ha}$ for an old-growth (450-500 yr) Douglas-fir Western hemlock forest. To set the range of the amount of biomass that can be reached, Table 5.1 was drawn up.

For 40-year-old Douglas-fir stands, Keyes & Grier (1981) state that total Net Primary Productivity differed only 13% between good (colluvial silt loam) and poor (gravelly loamy sand) sites, although big differences were found in aboveground biomass production (aboveground biomass production on the poor site was only 61% of that on the good site). They state that site quality i.e. site water balance and site nutrient status have a dramatic impact on the ratio of above- to belowground productivity and, to a lesser extent, total productivity.

Milleman & Boden (1986) present figures for the amount of stable humus under cool temperate wet forest and rainforest in North America of respectively 161 and 289 Mg C ha^{-1} . Post et al. (1982) mention an average value of 203 Mg C ha^{-1} .

According to Cannell (1984) the basic density of Douglas wood is 450 kg m^{-3} , which is confirmed by Dixon et al. (1991). Harmon et al. (1990) determined that approximately 40% of the harvested wood of an old growth forest was used for sawn timber, while the rest was used to produce paper, other short-lived products, or was lost during harvesting and conversion.

Table 5.1 *Dry weight biomass and Net Primary Productivity in Douglas-fir, Western hemlock and Western red cedar old growth forests and stands of Douglas-fir in the Pacific Northwest of the USA.*

stand age	450	450	40	40	30	42	49
reference	1,2	1,3	4	4	5	5	5
biomass dry weight (Mg ha ⁻¹)							
stem	891.6	733.9	221.5	424.0	145.9	206.2	201.2
branch	41.7	54.2	17.1	27.1	16.7	23.2	23.4
foliage	11.6	14.1	10.0	16.0	6.5	9.4	9.4
root	143.8	172.8	57.6	88.1	*	*	*
total	1088.7	975.0	306.2	555.2	169.1	238.8	234.0
dead organic material (Mg ha ⁻¹)							
forest floor	51.2	50.8	*	*	15.3	17.1	*
dead wood	215.0	*	*	*	14.0	*	*
undergrowth	6.7	5.6	*	*	10.9	3.4	3.4
NPP (Mg ha ⁻¹ yr ⁻¹)							
stem	2.5	2.5	5.1	9.9	5.0	3.7	3.3
branch	*	*	0.2	0.6	0.5	0.5	0.4
foliage	5.0	4.8	2.0	3.2	2.1	2.4	2.2
root	3.0	3.3	8.1	4.1	*	*	*
total	10.5	10.6	15.4	17.8	7.6	6.6	5.9
litter fall	6.1	3.0	*	*	4.5	3.1	*
References:	1:	Grier & Logan, in Cannell 1982;					
	2:	Sollins et al., in Kimmins et al. 1985;					
	3:	Abee, in Kimmins et al. 1985;					
	4:	Keyes & Grier 1981;					
	5:	Turner & Long, in Cannell 1982.					

5.2.2. Model input.

The modelling was mainly based on the yield tables of Curtis et al (1982) for planted Douglas-fir stands (1000 plants per hectare) with repeated (4 to 5) commercial thinnings on sites with indexes of 105, 125 and 145. These site indexes are determined by the average height (ft) of the largest trees at age 50 years. They can be translated into heights of 32, 38 and 44 m respectively. These are the tables 7B, 7C and 7D in Curtis et al. (1982) with a mean annual increment of respectively 11.5, 14.9 and 18.6 m³ha⁻¹yr⁻¹ at an age of 100 years.

Allocation of the Net Primary Production was set in combination with turnover times of foliage, branches and roots (see Appendices E and F). On all sites forest floor residence time was set at 2 years and humification factors at 6% (see Appendix H).

Basic wood density was set at 450 kg m³. Five thinnings are carried out on the good and moderate site, starting at ages of 27 and 31 years respectively. On the limited site, 4 thinnings are carried out. In each thinning, approximately 15-20% of the standing wood is harvested. Much of the thinning wood is used for pulp, while at higher ages, much is allocated to particle board and some sawn timber. 50% of the final harvest is allocated to sawn timber (see Appendix I).

Initial values for stable humus were set at 220 Mg ha⁻¹ (Post et al. 1982), in combination with residence times of stable humus of 250 to 300 years (see Appendix H).

5.2.3. Results and discussion

The results of the modelling of carbon dynamics in Douglas-fir stands in the Pacific Northwest of the US are visualized in Figure 5.3 and presented in Table 5.2. Appendix J allows the site class as used here for a particular Douglas-fir stand to be assessed, thereby allowing an estimation of carbon storage capacity.

It is clear from Figure 5.3 and Table 5.2, that Douglas-fir stands are very suited to store carbon. Through its high yields in long rotations, this forest type can store large amounts of carbon in the biomass and products on average (e.g. 196 Mg C ha⁻¹ on a moderate site), with high net annual carbon fluxes over the first rotation (eg. 3.43 Mg C ha⁻¹yr⁻¹ on a moderate site).

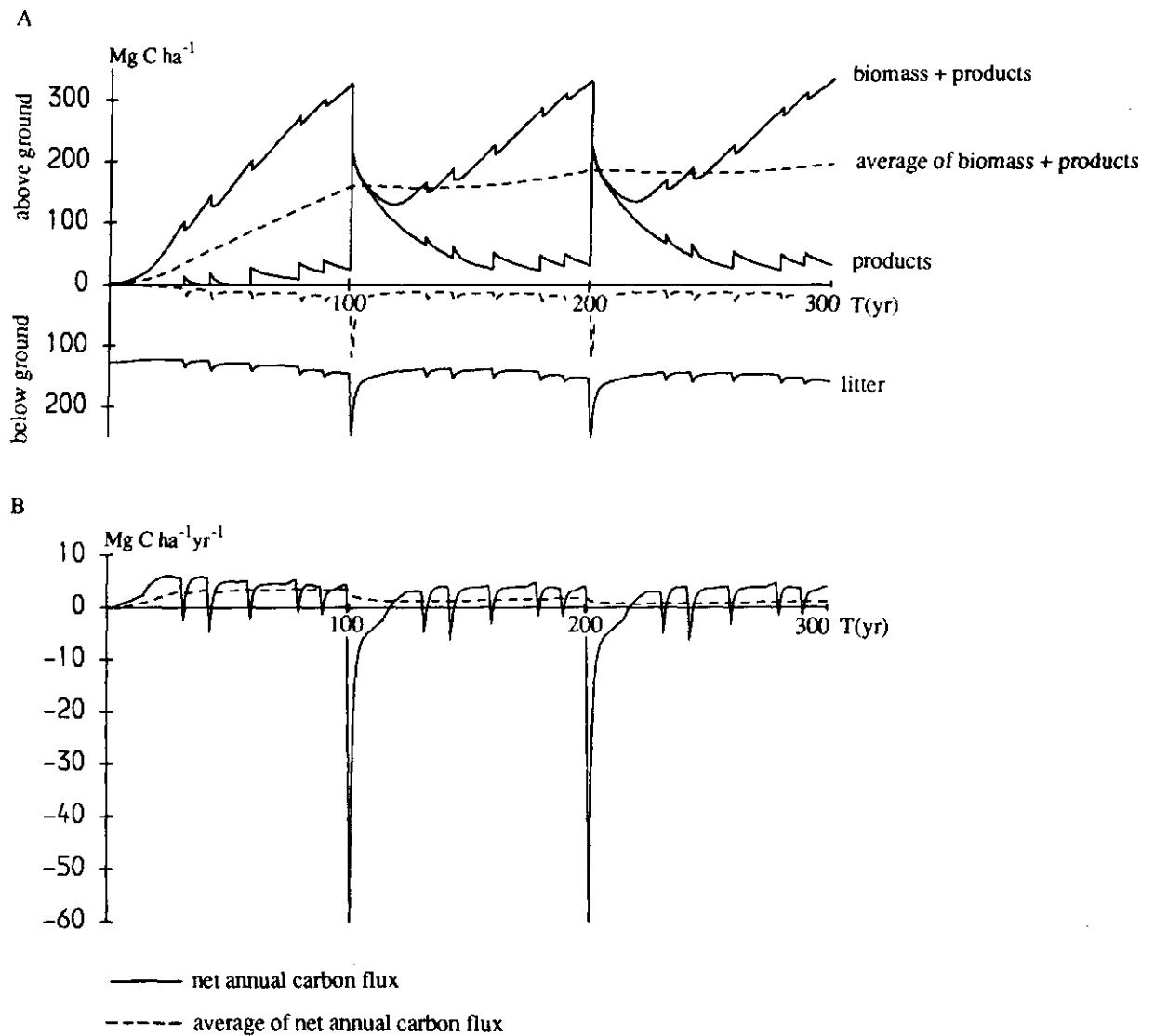


Fig. 5.3 A: Carbon stocks in biomass, forest products and the soil organic matter for Douglas fir on moderate sites ($I_m = 14.9 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ at $T = 100$) (Mg C ha^{-1}).
 B: Net carbon flux both on an annual base and as a running mean (dashed line) ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$).

Table 5.2 *Comparison of carbon stocks and fluxes for Douglas-fir stands on three sites in the Pacific Northwest of the US.*

- 1) Total stock of carbon at the end of the rotation in biomass and products (Mg C ha^{-1});
- 2) Total stock of carbon at the end of the rotation in the soil organic matter i.e. litter, dead wood and stable humus (Mg C ha^{-1});
- 3) Total stock of carbon at the end of the rotation in biomass, forest products and in dead organic matter on or in the soil (Mg C ha^{-1});
- 4) Long-term average stock of carbon in the biomass and the forest products (Mg C ha^{-1});
- 5) Long-term average stock of carbon in the forest products (Mg C ha^{-1});
- 6) Long-term average stock of carbon in the soil organic matter (Mg C ha^{-1});
- 7) Long-term average stock of carbon in the total system of biomass, products and soil organic matter (Mg C ha^{-1});
- 8) Net accumulated amount of carbon over the first 100 years after afforestation (Mg C ha^{-1});
- 9) Average net annual carbon flux at the end of the first rotation ($\text{Mg C ha}^{-1}\text{yr}^{-1}$).

	1	2	3	4	5	6	7	8	9
good site class $I_m = 18.6 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	401	145	546	248	54	150	398	417	4.17
moderate site class $I_m = 14.9 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	327	146	473	196	46	143	339	343	3.43
limited site class $I_m = 11.5 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	278	145	423	161	38	143	304	293	2.93

The results are supported by results of Harmon et al. (1990) and Dixon et al. (1991). Harmon et al. mention an amount of $192.1 \text{ Mg C ha}^{-1}$ in the living biomass of a 60-year-old Douglas-fir stand on the west side of the Oregon and Washington Cascade Range. This is in accordance with results of a site in between the moist and mesic ones in this study. However, they also state that when all the residues are left on the site, and when 45% of the harvested wood is converted to long term products, the amount of carbon in the total system after 3 rotations is still only 80% of what was once stored in the old growth forest.

Dixon et al. mention a figure of $4.47 \text{ Mg C ha}^{-1}\text{yr}^{-1}$ for the annual rate of carbon storage during the first rotation (100 yr) of Douglas-fir on wet cropland, but do not mention the mean increment. They also state that when a mean annual increment of $12 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$ can be achieved with extra N fertilization, the annual rate of carbon storage is $4.32 \text{ Mg C ha}^{-1}\text{yr}^{-1}$.

The value for the allocation percentage of the NPP to the stem for the 40-year-old stand was assumed to be 53% on the good site and 45% on the limited site. The first figure agrees well with the one given by Keyes & Grier (1981, see Table 5.1), the second is somewhat higher. This, in combination with turnover times of branches, foliage and roots of respectively 33, 3.3 and 10 years and the values for the residence time (2 yr) and humification factor of litter (6%), result in dry weights of the forest floor of up to 25 Mg ha^{-1} , which are in agreement with the data in Table 5.1.

It can be concluded that this forest type is very suited to sequester carbon. Because of the high mean annual increments and the long rotations, it sequesters carbon in large average amounts in the biomass and in products with high net annual carbon fluxes over the first rotation.

6. BOREAL CONIFEROUS FORESTS.

6.1. Introduction to the forest type

The northern coniferous biome, known as boreal forest or from the Russian, as Taiga, stretches from its northern limit in the treeless arctic tundra to its southern border, the gradual transition to a mixture with broadleaf deciduous forest. The boreal forest is circumpolar, occupying a belt in both North America and Eurasia (see Figure 6.1).

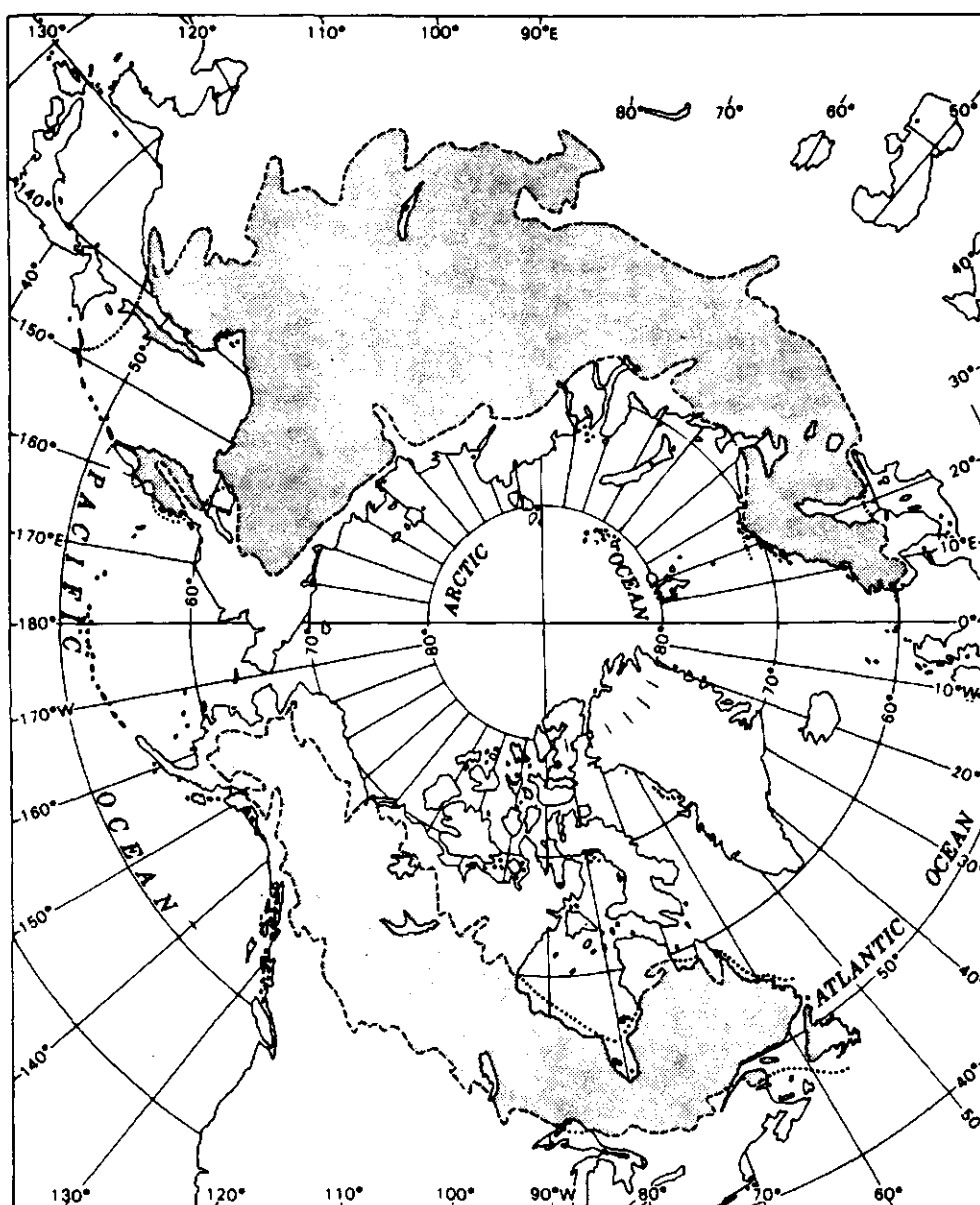


Fig. 6.1 The circumpolar range of the boreal forest (Larsen 1980, after Hare & Ritchie).

Generally the boreal forests of America and Eurasia are very similar. Both regions have many genera and even species in common (Larsen 1980) and the forests have the same physical structure. The canopy is single-layered and composed of coniferous evergreen trees. Large shrubs are usually widely scattered and sparse. The ground layer of vegetation is dominated by low shrubs and herbaceous plants, and is underlain by mosses and lichens. Mainly through this wide variety in mosses and lichens, it is stated that the boreal forest is richer in number of species than the tropical rainforests (Dudley 1992).

Not only the natural forests in the tropics, but also the boreal forests of Canada and Russia are being cut in a high speed. Thanks to natural and artificial regeneration carried out over vast areas it appears, however, that the area of boreal forest is not declining. But some authors contend that the regenerated or planted stands are not comparable to the climax vegetation and are ecologically poorer (Dudley 1992). As a result of the political instability in Russia, the state-owned timber companies have reduced their cutting in the boreal regions, but an increased interest is expected from foreign timber companies who expect to make a quick profit.

Because of the important role of the boreal forests in the global carbon cycle (Boana & Van Cleve 1992, Alban & Perala 1992), the carbon-storing capacity of reforestations of this forest type in the western Siberian region as an example, is outlined in this chapter.

6.1.1. Boreal climate and forest types

The boreal climate can briefly be described as a climate with long and cold winters and short, generally cool summers. Much of the precipitation falls as snow. For a large part of the year, the radiance balance is negative and for the rest of the time it is relatively low (Larsen 1980). Not surprisingly, climatic conditions vary greatly from the southern edge of the boreal forest to the northern limit. But there is also variation along the longitudinal gradients. The air mass pattern is most complex in the western areas of Eurasia, as they are affected by the wind and weather patterns of Europe. As the air masses move eastwards, they become more modified and continental, and are then called continental temperate in Russia.

In the northwestern Eurasian boreal region, the weather is highly variable, with passages of frontal depressions and as a result cool, wet summers. The region has a frost-free period of 90-120 days. The first snow occurs in the south by early October. The northeastern part of the Eurasian boreal region is characterized by a more continental climate. The western Siberian boreal region is characterized by very strong continentality, severe winters and deep snow. Still, the amounts of precipitation are sufficient for optimal forest growth. The snow cover usually lasts some 130 days in the far south of the region. The climate of the far east Siberian region is the most severe climate of the world. Winters are extremely cold and long and only the southern part of the region is free from frost in July. In summer, cold waves alternate with periods of relative heat.

The regions considered in this study are those with a relatively mild (for the

boreal region) climate and no permafrost. This is the region of the southern taiga-northern mixed forests border (Pastor & Mladenoff 1991) or as it is known in European Russia: the Boreonemoral zone (see Figure 6.2). The relatively mild climate and the less pronounced podzols result in closed mixed evergreen and deciduous tree species with a fair productivity of 3 to 8 Mg ha⁻¹ (Pastor & Mladenoff 1991, Rennie 1978). In the Eur-Russian Boreonemoral zone, the boreal-northern hardwood border is narrow and stretches from Finland across European Russia to where the boreal zone meets the Russian steppe.

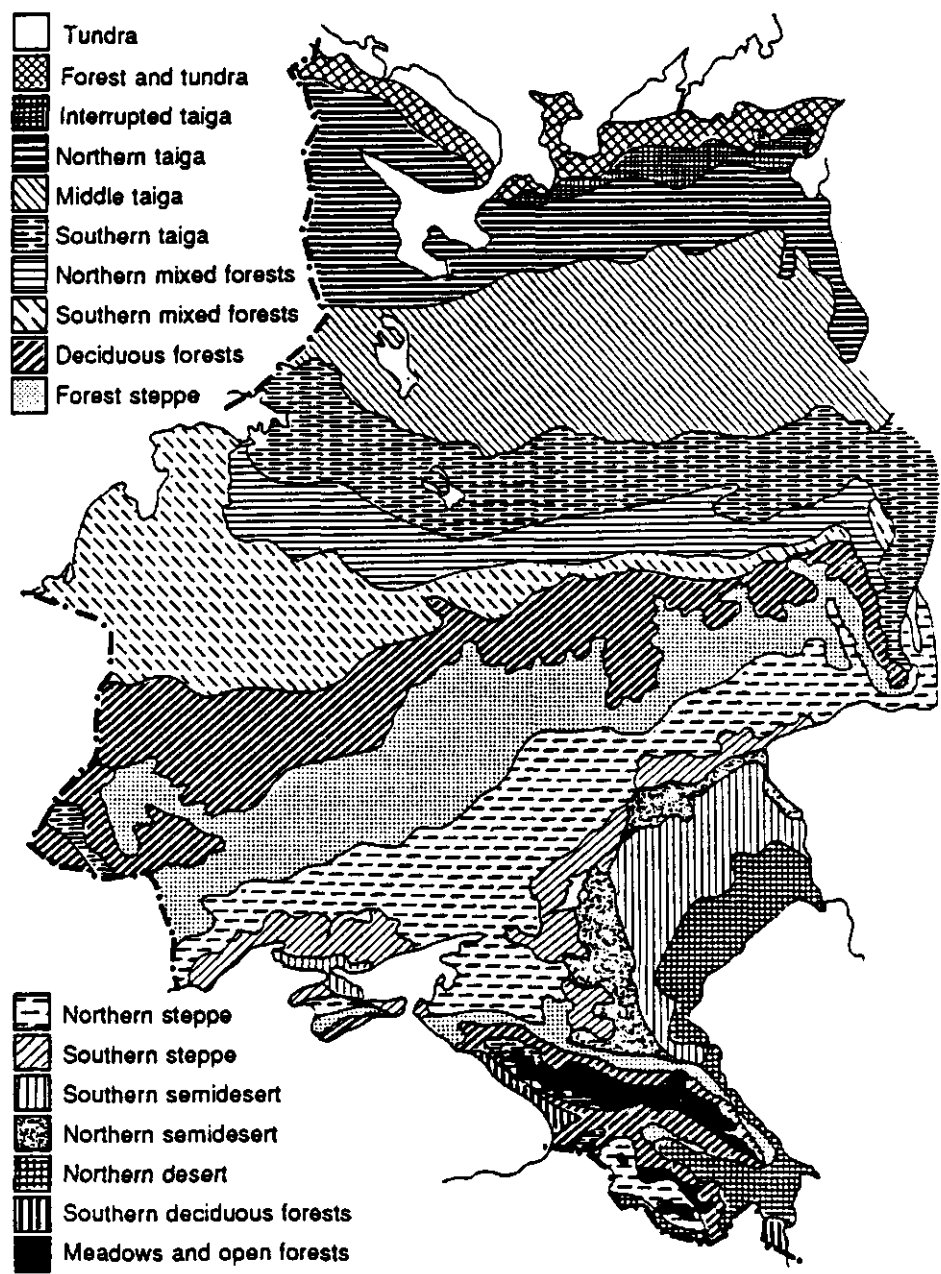


Fig. 6.2 Vegetation zones of the former European USSR (Nilsson et al. 1992 after Kurnaev 1973)

On the boreal side of the transition zone, *Pinus sylvestris*, *Picea abies*, *Populus tremula* and *Betula pubescens* dominate. Southwards they gradually mix with *Quercus robur*, *Carpinus betulus* and *Tilia cordata*.

Eastwards, the dominance of *Picea abies* is gradually overtaken by *Picea obovata*, which is believed to be a subspecies of *Picea abies* (i.e. *Picea abies* var. *obovata*), the Siberian spruce (Vidakovi 1991). The ranges of these two species overlap, which results in hybrids. In the Far East, *Picea obovata* is codominated by *Picea jezoensis* (syn. *P. ajanensis*). A transect drawing to characterize this transition type of boreal forest is given in Figure 6.3. Vast areas of boreal forest still exist and, so far, are hardly influenced by man, but the hardwood forests on the southern side have been cleared on a large scale and the land used for agriculture (Pastor & Mladenoff 1991).

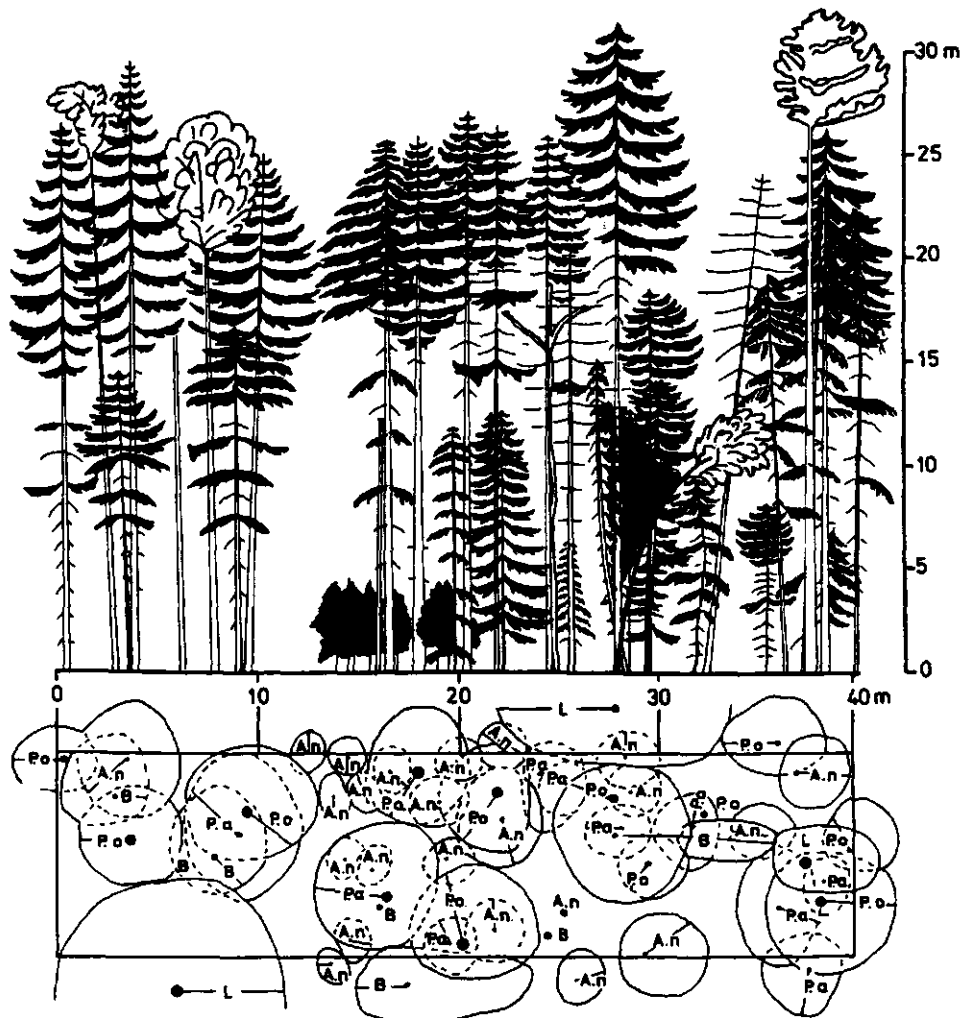


Fig. 6.3 Profile of a lowland natural forest with *P. obovata* and *P. ajanensis* in the valley of the river Amgun near the east coast of the former USSR (53°N, 139°E). Age of the spruces is 120-150 years (Schmidt-Vogt (1991) after Andreev).

P.o. = *Picea obovata* P.a. = *Picea ajanensis*
 A.n. = *Abies nephrolepis* L. = *Larix gmelinii*
 B. = *Betula* spp.

6.1.2. Soils

The soil type most widespread in the boreal region is the podzol (Gorshenin 1955). Podzolization occurs in climates characterized by high precipitation and low rates of evaporation. It is particularly intense on acid sandy glacial deposits and weathered sandstone material and leads to the formation of a bleached grey Ae, (eluviation) horizon and a reddish-brown B (illuviation) horizon. Raw litter and humus accumulate on top of the mineral soil because of decomposition is slow in the wet and cold conditions. Podzolization is influenced not only by climate and parent material, but also by the vegetation. Topography or stagnating layers may prohibit the draining of the rainfall; this leads to thick peat layers forming on top of the mineral soil, or as a transition type gleysols.

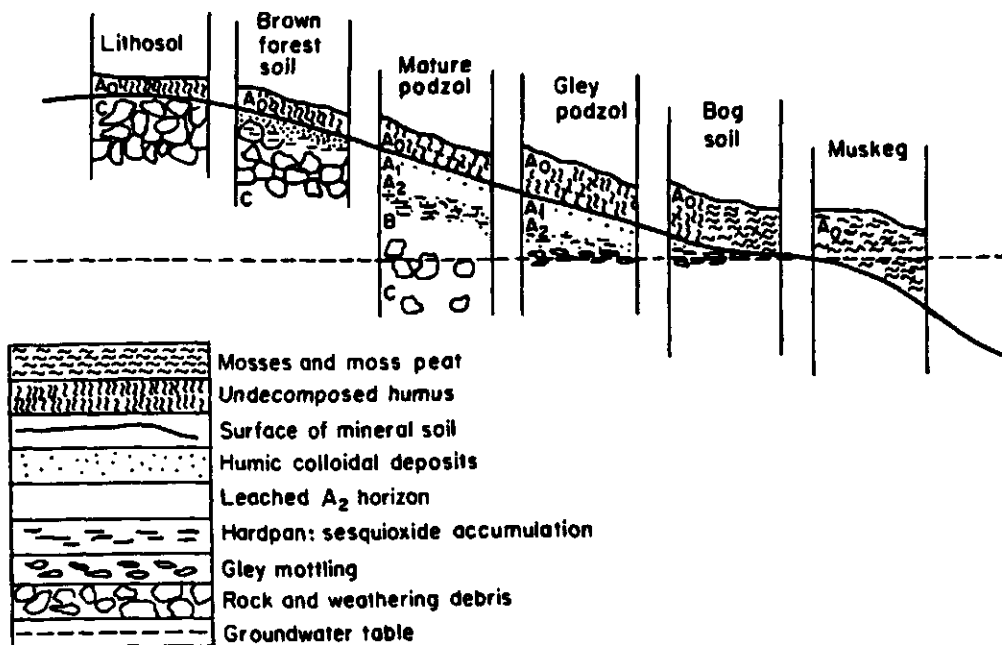


Fig. 6.4 Morphology of the basic boreal soils (Larsen 1980). On the left a Lithosol, dry and only slightly weathered. On the right the Histosol, locally known as Muskeg, composed entirely of organic material. The mature podzol, centre, has an upper horizon of organic material in various stages of decomposition. The light area, just below the upper horizon is the bleached mineral horizon (A₂), from which iron and aluminium oxides and clay minerals are leached. The darker area below the bleached horizon is the area of accumulation of oxides and clay.

In the southern boreal region, where podzolization processes are less intense, or where the parent material contains more clay or where the parent material is of calcareous origin, soils belong to the grey-wooded Luvisols, further south gradually changing to the Chernozems. The southern border of the Boreone-moral zone is characterized by this transitional soil type, the grey-wooded Luvisols (see Figure 6.4). Productivity on this soil type is considerably higher than on the podzols, and is favoured by the relatively good climate.

6.1.3. Silviculture

The main tree species which will be dealt with here are *Picea abies* and *Picea obovata*. These are the dominant species of the Boreonemoral zone. Original Russian literature on silviculture, biomass, growth and productivity was not consulted, but data on their counterparts in the boreal zone of Canada and the USA, i.e. *P. mariana* and *P. glauca* were used.

Picea abies grows naturally in areas with a continental climate and high amounts of precipitation. It is a dominant tree species of the European taiga (Nikolov & Helmisaari 1991). In the southern taiga it forms mixed coniferous-broadleaved forests with *Tilia cordata*, *Quercus robur* and *Ulmus* spp. In the Russian plains it is said to reach heights of 35 to 40 m. It is a shade-tolerant tree species, which prefers moist or wet soils, but not anaerobic soils. It is intolerant of drought. It requires acidic soils (pH 4-5) and good nutrition to grow well (Schmidt-Vogt et al. 1977).

Picea obovata is commonly found in continental areas, extending from the tundra zone in the north to the taiga in the south. It grows in the Siberian plains and in the Ural mountains both in pure and mixed stands. It is a typical dominant tree species of the boreal zone. In the southwestern part of its distribution it mixes with *Quercus robur*, *Tilia cordata* etc. It tolerates lower humidity and more continentality than any other shade-tolerant tree species and is found in steppe regions with an annual temperature amplitude of 40 °C. Its distribution, however, is determined more by soil type than by climate. *P. obovata* requires well drained to moist sandy loam soils and has poor growth on marshy soils of the central and southern taiga. It does grow on permafrost soils. Overall, the growth in the boreal forests is limited compared to for example temperate forests. Schmidt-Vogt (1986) cites Dyrenkov who found mean increments of 4.1 to 6.2 m³ha⁻¹yr⁻¹ for spruce in the former Soviet Union aged 80 years.

Silviculture in the boreal forests has to a great extent been limited to some form of exploitative forestry. After felling the natural stands, large amounts of debris remained; these were sometimes burnt to stimulate regeneration. The regenerating trees are, however, mainly pioneers, such as *Betula* spp. and *Populus* spp. Only after a long time of forest development are the pioneer trees succeeded by intermediate, and later climax trees such as Norway spruce, Siberian spruce and Siberian fir (Kuusela 1992). Thinnings in these natural regenerations are usually not carried out, as they are considered unprofitable. If the stage with pioneer trees is unwanted, small-scale felling followed by planting or natural regeneration of Norway spruce under a cover of old trees is advised. When the aim is to grow high-quality saw logs in the near future, planting and regular thinning have to be executed.

6.2. Carbon dynamics in spruce forests

6.2.1. Literature data

To set the model input values, literature data of the following parameters were needed:

- total biomass and biomass of the different compartments;
- volumetric growth and net primary production;
- allocation of the NPP to the biomass compartments ;
- basic wood density of the wood;
- amounts of dry matter in forest floor, dead wood and stable humus;
- humification and decomposition constants;
- annual litter fall.

Specific biomass and Net Primary Production allocation data on spruce forests in the Eurasian boreal forests were obtained from Cannell (1982), who cited Kazimirov & Morozova. The data are listed in Table 6.1.

Table 6.1 Biomass (dry weight) and productivity data from Cannell (1982) and DeAngelis et al. (1981) for boreal spruce forests in the Karelia region in the former Soviet Union.

stand age (yr)	22	37	45	54	43	38	45	68	82	98	109	126	138
<hr/>													
biomass dry weight (Mg ha ⁻¹)													
stem	13.9	42.3	56.3	73.0	58.5	65.3	29.0	106.0	116.0	158.0	165.0	183.9	176.0
branch	6.5	10.6	12.1	14.2	12.5	12.2	8.7	15.1	16.8	16.5	17.6	16.6	17.1
foliage	5.5	9.1	9.8	10.9	9.5	9.9	8.2	11.5	11.4	10.8	9.7	8.1	47.5
root	6.2	14.1	15.8	21.6	16.8	18.3	10.1	29.1	33.2	41.0	45.0	46.0	47.5
<hr/>													
total	32.1	76.1	94.0	119.7	97.3	105.7	56.0	151.7	329.1	226.3	237.3	254.6	288.1
dead organic material (Mg ha ⁻¹)													
dead wood	1.0	3.4	4.2	5.6	6.2	6.9	3.7	6.9	8.1	8.0	7.1	7.1	7.4
understorey	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
herb layer	1.3	1.5	1.6	2.1	1.0	0.8	1.8	2.2	3.2	3.1	3.6	4.0	4.6
forest floor	17.4	18.5	19.2	22.0	20.6	20.0	19.3	24.7	26.0	29.6	32.8	35.5	39.0
<hr/>													
NPP (Mg ha ⁻¹ yr ⁻¹)													
stem	1.6	2.7	3.0	3.2	3.6	4.0	2.3	3.2	2.9	2.4	1.9	1.3	1.0
branch	0.5	0.6	0.6	0.7	0.7	0.7	0.5	0.5	0.4	0.3	0.3	0.2	0.1
foliage	1.7	2.5	2.7	2.8	3.0	3.3	2.3	2.9	2.9	2.6	2.4	2.2	2.1
root	0.5	0.5	0.5	0.5	0.5	0.6	0.4	0.5	0.4	0.3	0.2	0.1	0.02
<hr/>													
total	4.3	6.3	6.8	7.2	7.8	8.6	5.5	7.1	6.6	5.6	4.8	3.8	3.2
litter fall	1.6	2.7	2.9	3.2	3.3	3.6	2.5	3.3	3.2	2.9	2.7	2.4	2.3

Popov in Schmidt-Vogt (1991) mentions a figure of $280 \text{ m}^3 \text{ ha}^{-1}$ for the standing volume of a 160-year-old spruce stand in the southern zone of central Siberia at an average stand height of 23 m. Some yield tables for unmanaged white spruce in Canada are available. In his yield table (spacing 2.0 m) Berry (1987) uses mean annual increments at an age of 60 years ranging from 4.1 to $8.7 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. The yield table of Love & Williams in Rauscher (1984) for white spruce in the Lake States, USA shows mean annual increments ranging from 6.0 to $8.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ at an age of 70 years. The yield table of Stiel in Rauscher (1984) shows mean annual increments ranging from 4.6 to $9.5 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ at an age of 50 years.

The amount of standing dead phytomass of the boreal forest is 0.5 Mg ha^{-1} dry matter according to Ajtay et al (1977). The litter fall is 6.0 and $5.5 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ dry matter for respectively the closed and open boreal forest and the average amount of litter is 35 Mg ha^{-1} . Bonan in Shugart et al. (1992) mentions figures of 47.1 to 105.3 Mg ha^{-1} for the amount of dry matter in the forest floor under white spruce forests on permafrost-free soils in Alaska ranging in age from 70 to 250 years. The residence time of the litter was found to be 19 years.

Ajtay et al. (1977) mention a figure of 259 Mg ha^{-1} dry matter for the amount of stable humus under boreal forest. Millemann & Boden (1986) give a value of 378 Mg ha^{-1} for this parameter under main taiga for all continents. This figure for Asia is 160 Mg ha^{-1} . Post et al (1982) mention a mean amount of stable humus of 200 Mg ha^{-1} dry matter under boreal moist forest and 226 Mg ha^{-1} under boreal wet forest although they use a median of 175 Mg ha^{-1} dry matter. Later Milleman & Boden (1986) distinguish figures of 267 and 259 Mg ha^{-1} dry matter in the stable humus under boreal moist and boreal wet forest respectively.

According to Dixon et al. (1991) the average basic wood density for spruce wood is 410 kg m^{-3} . Cannell (1984) mentions a figure of 470 kg m^{-3} for *Picea abies* and 380 kg m^{-3} for other *Picea* species.

6.2.2. Model input

The carbon dynamics of spruce afforestations in the Boreonemoral zone of the former Soviet Union were modelled for three site classes. The volumetric increments were set so that the mean increment at an age of 100 years was respectively 6.0, 4.6, and $3.2 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (see Appendix D2). Since all site classes are somewhat limited the maximum of the current annual increment is achieved at an age of 55 to 60 years. The volumetric increments are based on the Net Primary Production figures from Kazimirov & Morozova in Cannell (1982). This seemed more reliable than using the available yield tables for white spruce in Canada since the former are from local biomass measurements. The rotation length was set at 100 years, with thinnings at 30, 40, 45, 50, 55, 60, 65, 70, 75, 80 and 90 years. Thinnings are light. The allocation of the harvested wood to the wood products is given in Appendices I1. Much of the thinning wood is used as paper. Only 50% of the final cut is used for sawn timber with a residence time of 35 years.

Three rotations were modelled. On the best site, 40% of the Net Primary Production is allocated to the stem at an age of 40 years. On the limited site, this is 30%. The allocation parameter values are given in Appendix E.

The basic density of the wood was set at 410 kg m^{-3} . The residence times of wood products, dead wood, litter and stable humus are given in the Appendices G and H. The humification factor is given in Appendix H. The initial values for stable humus for the sites of good, moderate and limited fertility were set at respectively 230, 230 and 250 Mg ha^{-1} dry matter.

6.2.3. Results and discussion

The results of the modelling of carbon sequestration in spruce stands in the Boreonemoral zone of the former Soviet Union are displayed in Figure 6.5 and presented in Table 6.2.

More general average data for the boreal forests are given by Whittaker & Likens (1973), who mention a mean plant biomass (dry weight) for the boreal forests of 200 Mg ha^{-1} and a mean net primary production of $8 \text{ Mg ha}^{-1}\text{yr}^{-1}$. Lieth (1975) mentions a range of 2 to $15 \text{ Mg ha}^{-1}\text{yr}^{-1}$ for the Net Primary Production of the boreal forests and a mature biomass range (dry weight) of 200 to 520 Mg ha^{-1} . Ajtay et al. (1977) mention a figure of 60 - 400 Mg ha^{-1} dry matter for the biomass of boreal forests, where for the mean value they use 250 and 170 Mg ha^{-1} respectively for the closed and the open coniferous boreal forest. According to them the Net Primary Production ranges from 4 to $20 \text{ Mg ha}^{-1}\text{yr}^{-1}$, although for mean values they use 8.5 and $6.5 \text{ Mg ha}^{-1}\text{yr}^{-1}$ for closed and open coniferous boreal forest respectively.

More general average data for the boreal forests are given by Whittaker & Likens (1973), who mention a mean plant biomass (dry weight) for the boreal forests of 200 Mg ha^{-1} and a mean net primary production of $8 \text{ Mg ha}^{-1}\text{yr}^{-1}$. Lieth (1975) mentions a range of 2 to $15 \text{ Mg ha}^{-1}\text{yr}^{-1}$ for the Net Primary Production of the boreal forests and a mature biomass range (dry weight) of 200 to 520 Mg ha^{-1} . Ajtay et al. (1977) mention a figure of 60 - 400 Mg ha^{-1} dry matter for the biomass of boreal forests, where for the mean value they use 250 and 170 Mg ha^{-1} respectively for the closed and the open coniferous boreal forest. According to them the Net Primary Production ranges from 4 to $20 \text{ Mg ha}^{-1}\text{yr}^{-1}$, although for mean values they use 8.5 and $6.5 \text{ Mg ha}^{-1}\text{yr}^{-1}$ for closed and open coniferous boreal forest respectively.

Table 6.2 Comparison of carbon stocks and fluxes for spruce stands in the boreonemoral zone of the former Soviet Union on three site classes.

- 1) Total stock of carbon at the end of the rotation in biomass and products (Mg C ha⁻¹);
- 2) Total stock of carbon at the end of the rotation in the soil organic matter i.e. litter, dead wood and stable humus (Mg C ha⁻¹);
- 3) Total stock of carbon at the end of the rotation in biomass, forest products and in dead organic matter on or in the soil (Mg C ha⁻¹);
- 4) Long-term average stock of carbon in the biomass and the forest products (Mg C ha⁻¹);
- 5) Long-term average stock of carbon in the forest products (Mg C ha⁻¹);
- 6) Long-term average stock of carbon in the soil organic matter (Mg C ha⁻¹);
- 7) Long-term average stock of carbon in the total system of biomass, products and soil organic matter (Mg C ha⁻¹);
- 8) Net accumulated amount of carbon over the first 100 years after afforestation (Mg C ha⁻¹);
- 9) Average net annual carbon flux at the end of the first rotation (Mg C ha⁻¹yr⁻¹).

	1	2	3	4	5	6	7	8	9
good site class $I_m = 6.0 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	111	141	252	65	17	138	203	117	1.17
moderate site class $I_m = 4.6 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	95	143	238	53	13	139	192	103	1.03
limited site class $I_m = 3.2 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$	70	153	223	38	9	148	185	76	0.76

It is clear from the results that the carbon storing capacity in the living biomass of this forest type is rather limited compared to other temperate or tropical forests. This is mainly caused by the overall limited growth, even on the best sites available. Especially through the slow juvenile growth, this forest type is a very limited carbon storer in the short term. Only 53 Mg C ha⁻¹ are stored on average on the moderate site in the biomass and products. On the moderate site a net annual carbon flux over the first rotation of 1.03 Mg C ha⁻¹yr⁻¹ can be achieved. This forest type however, preserves the large amounts of stable humus of the boreal soils. Approximately 140 to 150 Mg C ha⁻¹ are stored in the litter and stable humus compartment.

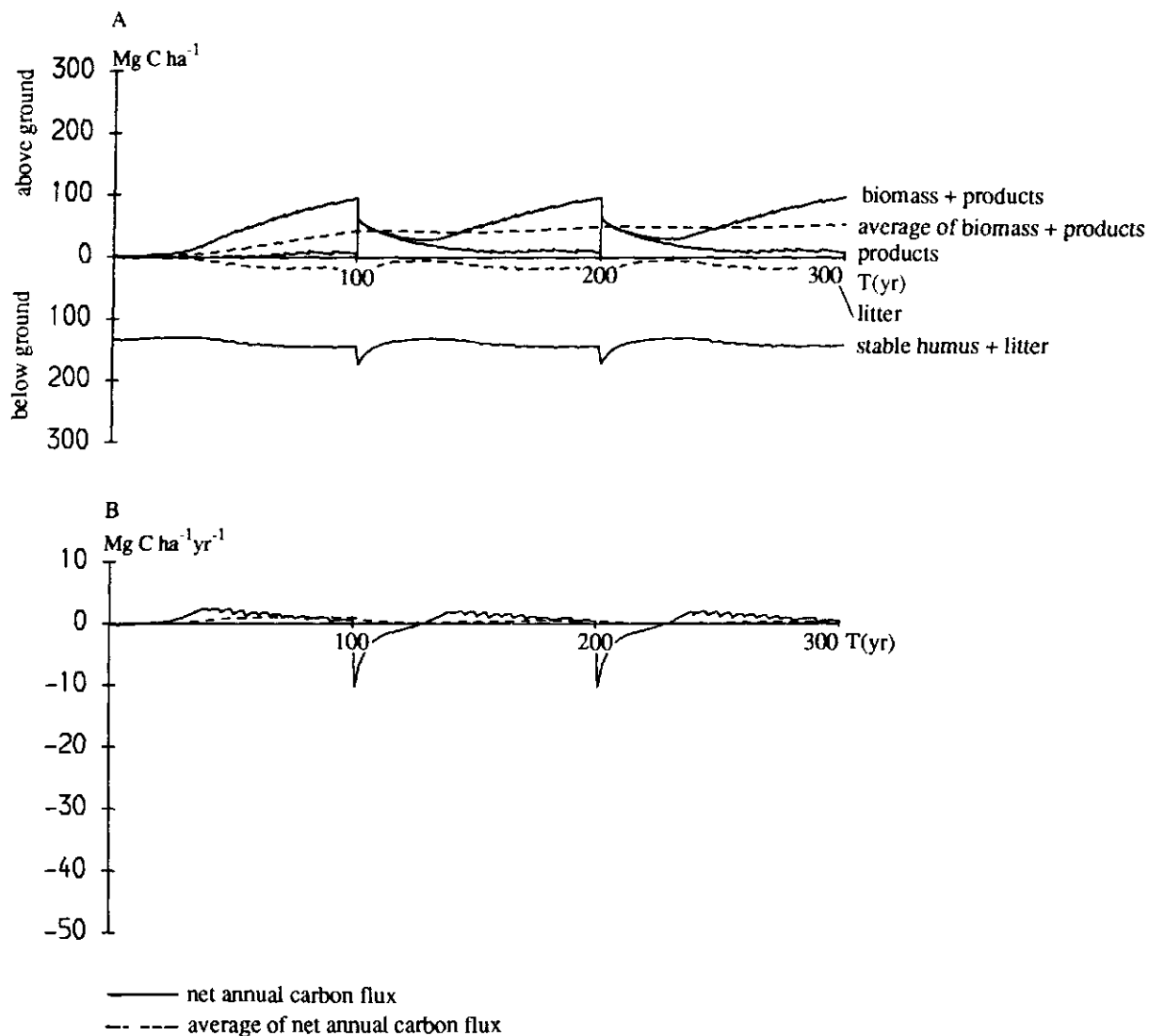


Fig. 6.5 A: Carbon stocks in biomass, products and the soil organic matter for spruce stands in the Boregmemoral zone of the former Soviet Union on moderate sites ($I_m = 4.6 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ at $T = 100$).
 B: Carbon fluxes both on an annual basis and as a running mean (dashed line).

Considering these figures, one has to realize that the chosen increments may seem low, but that they are at the upper range of what is recorded for the boreal forests of Siberia. At higher latitudes, growth will even be more limited than the lowest considered in this study. On the other hand, if sites of the northern hardwood forest zone at the southern edge of the boreal forest zone are considered (more favourable climate on brown forest soils), growth may be higher than the value chosen for the best site in this study. Volumetric increments were based on the Net Primary Productivity figures for spruce in

the Karelia region in the former Soviet Union taken from Cannell (1982). These figures are in accordance with the Canadian yield tables for white spruce at lower latitudes, which can achieve mean increments up to $9.5 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ at an age of 50 years.

The growth dynamics in the Canadian yield tables are however very different from the model input in this study. In this study the culmination point of the current increment lies at approximately 50 years, while the Canadian yield tables of Berry (1987) and Rauscher (1984) show a culmination point at approximately 25 years. Opting for the Soviet data has influenced the carbon dynamics mainly for the young stand and to a lesser degree in the long term.

The litter residence time (5 to 8 years) was kept in agreement with the other forest types (approximately twice as high as in the montane coniferous forest), which resulted in amounts of up to 30 Mg ha^{-1} for forest floor dry matter, which is in agreement with the data of Kazimirov & Morozova, in DeAngelis et al. (1981) (see Table 6.1). Using the literature value of 19 years (Bonan, in Shugart et al. 1992), would have resulted in much higher values of up to 80 Mg ha^{-1} forest floor dry matter and a net carbon fixation of $1.7 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ on the good site during the first rotation. The other constants like turnover time of biomass compartments, humification factor and residence time of stable humus were difficult to determine from literature, and were thus kept in agreement with the other forest types.

The results can be compared with results of Dixon et al. (1991) who mention an annual carbon flux of $1.37 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ for planted spruce stands on drained sites in the sub-boreal region of the former USSR in which a mean annual increment of $4.5 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ can be achieved in a rotation of 55 years. They also state that when site preparation is less intensive, mean annual growths in *Pinus* spp. of only $1.5 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ can be achieved, resulting in carbon storages of approximately $0.5 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$.

Grigal & Ohmann (1992) presented results of carbon stocks in the Lake States (Minnesota, Wisconsin and Michigan) upland forests. In 27 *Pinus resinosa* (red pine) plantations, they found a mean carbon stock in total biomass, forest floor and stable humus of 60, 10 respectively 80 Mg C ha^{-1} . Since this region can be seen as part of the northern hardwood zone, the carbon stock in the living biomass can indeed be somewhat higher than the one found in this study.

Concluding it can be stated that the carbon sequestration in this forest type is limited, with on average 53 Mg C ha^{-1} in the biomass and products on a moderate site. Here the net annual carbon flux over the first rotation is $1.03 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. The strength of this forest type as carbon storer lies not in the living biomass, but in the soil organic matter. This forest type preserves the largest amounts of stable humus and through the slow decomposition in the wet and cold climate, considerable amounts are stored in the forest floor.

7. INDUSTRIAL PLANTATIONS OF FAST GROWING BROAD-LEAVED TREES ON FORMER AGRICULTURAL LAND.

7.1. Introduction to the forest type.

Afforestation of agricultural land in Europe is being considered in various West European countries, because of the combined need to reduce agricultural overproduction and to meet public demand for more forest (Dimitri & Friedrich 1990). Depending on the tree species, sites and rotation length, these forests may serve several purposes simultaneously, such as wood production, protection of drinking-water reserves, recreation and carbon storage. Large-scale afforestations, on the other hand, can have a severe adverse impact on the socio-economics of once prosperous agricultural regions. For sound decision-making, all aspects should be taken into account (Bock et al. 1990).

Carbon storage through afforesting agricultural land can be achieved with many species, in varying rotation lengths. Since carbon storage in long rotations of mixed oak/beech and spruce was already considered in chapters 3 and 4, the afforestation of agricultural land dealt with in this chapter, involves Poplar hybrids (*Populus x euramericana*) in rotations of 45 and 20 years, and black locust (*Robinia pseudo-acacia*) in rotations of 50 years. Very short energy-rotations, of for example, 5 to 10 years with poplar or Eucalyptus are not considered in this study, because the longterm average carbon stock in these plantations is limited as the average biomass in the system is small (Dixon et al. 1991, Mohren en Klein Goldewijk 1990a). In each of the following sections the carbon dynamics will be outlined after a general introduction to silviculture.

7.2. Carbon dynamics in plantations of poplar hybrids.

7.2.1. Silviculture

The hybrid poplars were formed through hybridization between *Populus deltoides* (American black poplar) and *Populus nigra* (European black poplar). Many clones are now available, such as "Agathe F", "Dorskamp", "Heidemij", "Marilandica", and "Robusta". Not all clones are from this hybrid; clones like "Rap" and "Geneva" are from the hybrid *Populus x interamericana* (Van der Meiden 1976). They are reproduced by cuttings.

Poplars grow well on soils with sufficient moisture and nutrient supply. They yield best on heavy to light clays or soils with a considerable loam content. Production is limited when the groundwater level is too high or when there is a lack of water supply during the growing season. Poplars can resist strong winds quite well. Afforestations with poplars are recommended on marine clay soils, fluvial clay soils, recently drained marine clays and gley soils with a high pH. It is advised not to plant poplar on brown forest soils, gleyic acid podzols, peat soils, inland dune soils or other poor, dry sandy soils.

Afforestations can be carried out with one- or two-year-old rooted cuttings or unrooted cuttings. Depending on the goal, the spacings may be 4x4 m up to 10x10m in varying rotations. The narrower the spacing, the more thinnings will have to be executed, or the shorter the rotation will be. A 4x4 m spacing for example, will have to be thinned 2 or 3 times in a rotation of 45 years, or if no thinnings are executed the rotation length is limited to some 20 years. With wider spacings, the rotation length can be prolonged without the need to thin. A fairly common practice is a spacing of 4x5 m, with thinnings at 15 and 25 years, in a rotation length of 45 years. Thinnings are usually heavy and systematic, in each thinning, 50% of the standing trees are harvested.

The main pests with which poplars can be infected in Western Europe are canker (*Aplanobacter populi*), *Dothichiza* barkburn (*Cryptodiaporthe populea*), leaf rust (*Melampsora* spp.) and Marssonina leafstain disease (*Drepanopeziza* spp.) (Van der Meiden 1976). Each clone has a specific resistance to these diseases; most of them are to some extent vulnerable to leaf rust. Vulnerability to canker is usually low. For further details see the literature. Poplar wood is commonly used for paper, fibre board, packing wood and clogs.

7.2.2. Literature data

The main source of information on growth and standing volume of poplar plantations are the available yield tables. For the northwestern part of Europe, the yield table of Faber and Tiemens in Sevenster (1991), for *Populus x euramericana* cv. Robusta, and the table from Rätzel in Schober (1975), also for Robusta, are the most important. Sevenster (1991) gives 4 spacings, each on 7 relative site classes in thinned and unthinned form: a spacing of 6x6 m on good, moderate and limited sites results in mean annual volume increments at age 40 years of respectively 14.4, 11.0 and 5.7 m³ha⁻¹yr⁻¹. The $IcV_{(max)}$ values are respectively 33.5, 22.9 and 9.2 m³ha⁻¹yr⁻¹. This corresponds rather well with the yield tables of Schober (1975), who mentions mean annual volume increments of 15.0, 12.0 and 9.0 m³ha⁻¹yr⁻¹ respectively at an age of 40 years.

Biomass measurements for poplar were found for only a few young *populus x euramericana* plantations. These and available biomass measurements of more or less natural poplar forests are presented in Table 7.1.

Table 7.1 *Biomass measurements of natural poplar forests from various authors in Cannell (1982).*

stand age	66-89	66-89	6	7	8	9	11	52	41	34	40	51
country	Canada	Canada	USA	USA	USA	USA	USA	USA	USA	USA	USA	USA
site	top slope	bottom slope	*	*	*	*	silty	loamy	silty	*	*	sandy
biomass dry weight (Mg ha ⁻¹)												
stem	31.6	153.7	33.3	55.6	64.6	53.5	68.8	151.1	181.9	103.0	147.7	148.0
branch	5.7	19.1	3.4	7.2	10.8	10.6	4.9	18.0	20.9	16.0	17.0	23.3
foliage	1.4	2.9	2.5	3.6	3.6	2.0	1.3	2.4	3.7	5.2	3.8	2.4
root	*	*	*	*	*	*	*	*	*	*	38.0	20.2
total	38.7	175.7	39.2	66.4	79.0	66.1	75.0	171.5	206.5	124.2	206.5	193.9
dead wood	2.6	11.3	*	*	*	*	*	5.5	16.9	*	*	3.5
understorey	*	*	*	*	*	*	*	*	*	0.9	*	*
NPP (Mg ha ⁻¹ yr ⁻¹)												
stem	*	*	*	*	*	*	*	5.9	>4.4 [#]	3.9	*	4.6
branch	*	*	*	*	*	*	*	2.8	>0.8	2.2	*	3.3
foliage	*	*	*	*	*	*	1.3	2.4	3.8	3.8	*	2.4
root	*	*	*	*	*	*	*	*	*	*	*	1.2
total	*	*	*	*	*	*	*	11.1	>9.0	9.9	*	11.5

#: mean (not current) annual increment

Kimmins et al. (1985) reports annual litter fall values of 2.2 to 2.9 Mg ha⁻¹yr⁻¹ dry matter for a 50 years old *Populus tremuloides* forest in the USA and 4.9 Mg ha⁻¹yr⁻¹ dry matter for a 50-year-old *Populus tremuloides* forest in the USSR. According to them the forest floor dry matter is 20, 28.9 and 72.6 Mg ha⁻¹ respectively in Minnesota, New Mexico (USA) and Alberta (Can) under 50- to 60-year-old *Populus tremuloides* forests.

Johnson (1992) reports that when agricultural land was converted to forest in the UK, the stable humus doubled in 83 years. He also reports an approximate doubling of the soil C within 50 years when arable land was converted to grassland or forest in Puerto Rico. The soil C increased in this period to 90% of the amount under mature forest. Increase of the amount of stable humus after afforestation is generally expected, although relatively few data exist to support this. Strong increases are expected when former arable lands are converted to broadleaved forests with mull humus forms (Rehfuess 1981). Increases are especially strong when the stock of stable humus of arable land has declined because of annual intensive ploughing (Johnson 1992). Afforestations of grasslands are expected not to have such strong effects on the

stock of stable humus, because the stock under grassland is already relatively big. Afforestations with coniferous species usually result in raw humus accumulating in the forest floor (Rehfuess 1981).

The humification and decomposition factors and residence times are thus kept in agreement with the other forest types and climates. They are presented in the appendices. Millemann & Boden (1986) report a figure of $120 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ dry matter in the stable humus of agricultural soils in Mediterranean Europe. Kortleven (1962) mentions an average stock of stable humus of 80 Mg ha^{-1} dry matter in the top 20 cm of the agricultural soil.

According to Dixon et al. (1991) the basic density of the poplar wood is 340 kg m^{-3} . Laming (1978) reports a basic wood density of 330 kg m^{-3} .

7.2.3. Model input

The modelling was carried out for three production levels of poplar plantations in 7 successive rotations of 45 years. The yield tables of Faber & Tiemens in Sevenster (1991) for relative site classes I, IV and VII at a spacing of $6 \times 6 \text{ m}$ were used (see Appendix D3). The basic density of the wood was set at 340 kg m^{-3} .

On site class I, thinnings are carried out at an age of 17 and 27 years. In each thinning, 50% of the standing trees are harvested systematically. Much of the thinning wood is used for paper (see Appendix I2). On site class IV, only one thinning is carried out, because the growth is somewhat limited. The thinning at which 50% of the standing trees is harvested, is carried out at an age of 21 years. The thinning wood is used for paper and particle board. On site class VII no thinnings are carried out, for the growth is rather limited. Of the wood from the final cut, 30% is used for particle board, 30% for packing wood, 20% for paper, 10% for sawn timber and 10% is left at the site (see Appendix I2). To compare the carbon storage in rotations of 45 years with short rotation poplar plantations, model runs were also done for poplar on moderate sites in a rotation of 20 years, at a spacing of $4 \times 4 \text{ m}$ ($I_m = 19.2 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ at $T = 20 \text{ yr}$, see Appendix D3). No thinnings are carried out in this case. 40% of the wood from the final cut is used for particle board and 40% is used for paper, while 20% is left at the site (see Appendix I3).

Allocation to the biomass compartments was kept rather general to agree with the data in Table 7.1 (see Appendix E). Humification and resident time of litter and soil stable humus are given in the Appendix H and were kept in agreement with the other forest types and climates. Initial values for the amount of soil stable humus are set at 100, 90 and 90 Mg ha^{-1} for the good, moderate and more limited site.

7.2.4. Results and discussion

The results of the modelling of carbon sequestration in poplar plantations in Europe are displayed in Figures 7.1 and 7.2 and presented in Table 7.2.

Appendix J gives data to derive site class for a particular poplar stand for determination of carbon storage capacity.

Table 7.2 *Comparison of carbon stocks and fluxes for industrial plantations of poplar in Europe on three site classes.*

- 1) Total stock of carbon at the end of the rotation in biomass and products (Mg C ha^{-1});
- 2) Total stock of carbon at the end of the rotation in the soil organic matter i.e. litter, dead wood and stable humus (Mg C ha^{-1});
- 3) Total stock of carbon at the end of the rotation in biomass, forest products and in dead organic material on or in the soil (Mg C ha^{-1});
- 4) Long-term average stock of carbon in the biomass and the forest products (Mg C ha^{-1});
- 5) Long-term average stock of carbon in the forest products (Mg C ha^{-1});
- 6) Long-term average stock of carbon in the soil organic matter (Mg C ha^{-1});
- 7) Long-term average stock of carbon in the total system of biomass, products and soil organic matter (Mg C ha^{-1});
- 8) Net accumulated amount of carbon over the first 100 years after afforestation (Mg C ha^{-1});
- 9) Average net annual carbon flux at the end of the first rotation ($\text{Mg C ha}^{-1}\text{yr}^{-1}$).

	1	2	3	4	5	6	7	8	9
good site class ($I_m = 13.2 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$, rotation = 45 yr)	82	66	148	64	16	78	142	53	1.94
moderate site class ($I_m = 10.5 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$, rotation = 45 yr)	93	62	155	62	15	75	137	49	2.23
limited site class ($I_m = 5.5 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$, rotation = 45 yr)	68	57	125	40	8	61	101	23	1.57
moderate site class ($I_m = 19.2 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$, rotation = 20 yr)	104	59	163	60	25	84	144	139	5.41

From the results it appears that afforestation of former agricultural land with poplar is a considerable carbon storer in the short and medium term. The stock of carbon in the total system at the end of the simulation period is limited, however. The long-term average stocks of carbon in the living biomass and products for the sites of good, moderate and limited fertility are 64, 62 and 40 Mg C ha^{-1} respectively. These limited figures are rather close to each other, because site quality differences are levelled out by a decrease in thinning intensity, the more limited the site quality.

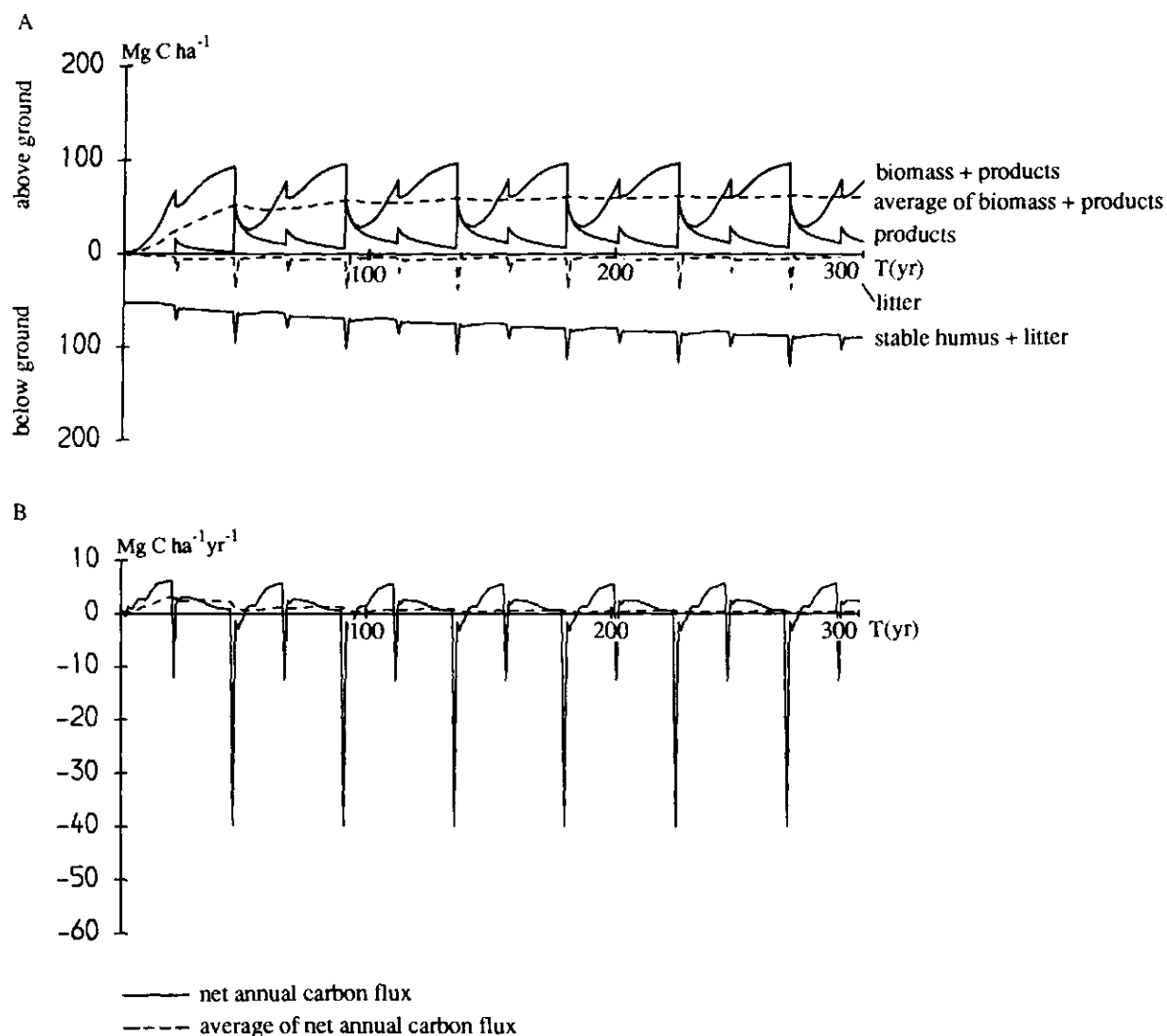


Fig. 7.1 A: Carbon stocks in biomass, forest products and soil organic matter for poplar plantations on moderate sites in a rotation of 45 years ($I_m = 10.4 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ at $T = 40 \text{ yr}$);
 B: Carbon fluxes both on an annual basis and as a running mean ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$).

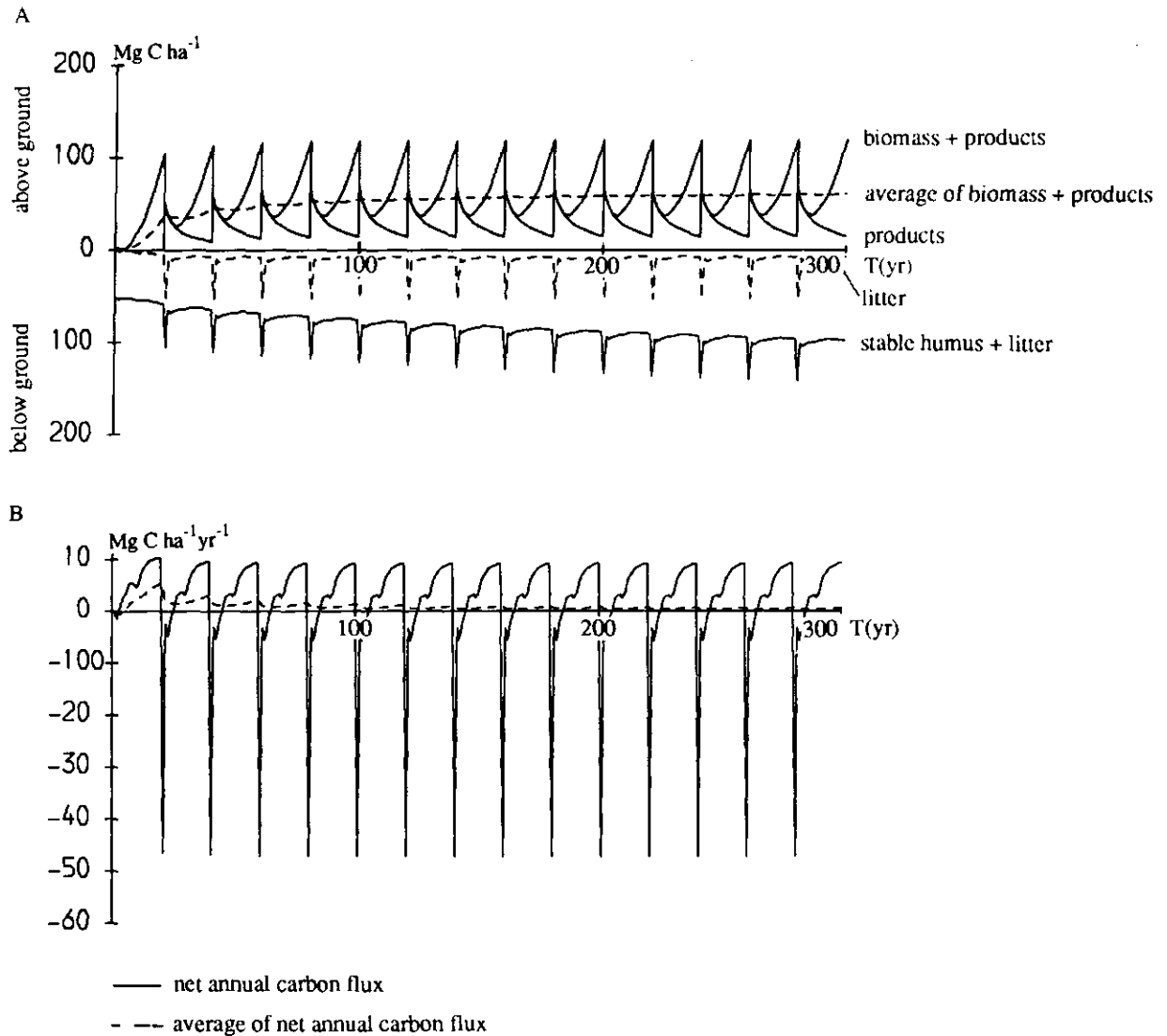


Fig. 7.2 A: Carbon stocks in biomass, forest products and soil organic matter for poplar plantations on moderate sites in a rotation of 20 years with a spacing of 4x4m ($I_m = 19.2 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ at $T = 20$);
 B: Carbon fluxes both on an annual basis and as a running mean ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$).

The net annual carbon storage on the good, moderate and limited site during the first rotation is 1.94, 2.23 and 1.57 $\text{Mg C ha}^{-1} \text{ yr}^{-1}$ respectively. Through the decrease in thinning intensity, approximately the same amounts of biomass can be reached regardless of the site class. In the long-term these net annual storage rates decline harply to a rate which is mainly determined by the accumulation in the soil stable humus.

By shortening the rotation, the long-term average stock of carbon stored in the living biomass and the products on a moderate site, is 60 Mg C ha^{-1} , but the

annual net flux ($5.41 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$) shows a strong increase. This strong increase is caused by the narrow spacings in short rotations, which result in high juvenile growth rates. These stands can thus accumulate approximately the same amount of biomass in a much shorter rotation. The amount stored 100 years after afforestation (column 8, Table 7.2) also shows a strong increase, but this is because in the short rotations this criterion coincides exactly with the end of a rotation, while this is not the case in the longer rotations.

The long-term gradual increase of the stock of carbon in the soil organic matter (Figure 7.1 and 7.2) is mainly caused by the ongoing accumulation in the stable humus of former agricultural soils. The stock of carbon in the dead wood, litter and stable humus compartment increases to a long term average of 84 Mg C ha^{-1} under the short rotation system. These increases are within the strong increases in stable humus, which are mentioned by Johnson (1992) who states that the soil C doubles 50 years after afforestations.

Dixon et al. (1991) report a net annual carbon storage of $2.75 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ for poplar in Germany with a mean annual increment of $13.5 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ in a rotation of 20 years. Mohren & Klein Goldewijk (1990a) report an annual net carbon storage rate during the first rotation of 1.88 and $1.46 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ for poplar with 1m values of respectively 13.5 and $8.5 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ in a rotation of 35 years.

The rather low annual carbon storage reported by Dixon is attributable to the fact that they used a lower mean annual increment (only 13.5 whereas in our short rotation this is $19.2 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$). The results from Mohren & Klein Goldewijk agree rather well in with the results from this study although slight differences occur because they use a slightly different yield table (i.e. thinning regime and spacing).

Some authors report very high net annual storage rates in short rotation poplar stands (Dewar & Cannell 1992 with $7.3 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$). These figures can only be achieved in very narrow spacings in short rotations which result in high juvenile growth rates and thus high net annual storage rates over very short periods, but also limited average stocks in the living biomass.

Since the results are only applicable to the northwestern part of Europe, it is useful to compare them with a Mediterranean industrial plantation. A good example is the Eucalyptus pulpwood coppice stands in Portugal in rotations of 12 years. Average data for Portugal such as a dry weight increment of $8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ in the stems, a rotation length of 12 years and 84% of the biomass in the stems (Pereira and Pereira 1988), result in a total dry weight of 114 Mg ha^{-1} at the end of a rotation. This means an approximate average amount of carbon in the living biomass of 28 Mg C ha^{-1} and a net annual carbon storage rate of $4.8 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ during the first rotation. Since the wood is used for pulp, there will hardly be any net storage after the first rotation. The results for this forest type lie within the same range as the results for poplar in a short rotation.

It can be concluded that poplar on former agricultural land is a limited carbon storer in the long-term, with a net annual flux of $2.23 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ during the first rotation for a plantation on a moderate site in a rotation of 45 years, and a limited average stock of carbon in the living biomass and products of 62 Mg C ha^{-1} . In the long-term there is still some annual accumulation, mainly in the stable humus. Shortening the rotation, results in higher net annual fluxes during the first rotation, but in the long-term differences with long rotations level out.

7.3. Carbon dynamics in plantations of black locust.

7.3.1. Silviculture

Black locust or common locust (*Robinia pseudoacacia*) has been attracting increasing interest recently, for use in afforestations of agricultural land (Stichting Robinia 1992). The species, which has its natural distribution in the temperate deciduous forests of the eastern United States, is thought to be able to produce high quality, durable wood in relatively short rotations. The wood may even replace tropical hardwoods. For centuries, the species has been managed in coppiced stands to produce fuel wood, poles and timber for tools throughout Europe (Jahn 1991).

Robinia grows on a wide variety of soils in a warm temperate, continental climate and maritime climates. The species is said to be very drought tolerant and can grow on extremely poor and dry sandy soils in which it establishes a deep root system (Boeljink et al. 1991). It shows its best growth on deep, well drained, rich loamy soils with a good water supply. Growth is limited on extremely dry or wet and heavy soils. At its optimum it shows a very vigorous growth, with a maximum at approximately 50 years. Its light demands are high, increasing with age. The species can be seen as a pioneer or late pioneer, which is limited on rich sites because of the vigour of climax tree species. Since its root nodules fix nitrogen, it is known as a site quality improver (Maas & Gubbels 1987). The leaf litter is of a very good quality, forming mull humus. Only in short rotations, when the bark, and the stemwood is removed from the site does black locust impoverish the site. No serious diseases or pests are known, although it is somewhat susceptible to spring frosts and older trees are susceptible to heart-wood rot.

Black locust is regenerated vegetatively by cuttings which are usually planted as 1- or 2-year-old shoots. Since many provenances reproduce very crooked stems, these are not suitable to produce sawn timber. If the goal is to produce high quality sawn timber, the choice of the provenance is very important. Generally it is advised to infect the site with *Robinia* forest soil because of the root nodules (Göhre 1952). A regular spacing is $1 \times 1 \text{ m}$. Light thinnings are carried out regularly, every 5 years. Rotation length depend on the goal which has to be achieved, but for fuel wood a rotation of 30 to 40 years is usual, while for the production of timber, rotations of up to 60 years are usual. Since heart-wood rot is a common problem in older trees, relatively long rotations are discouraged (Maas & Gubbels 1987). On poor soils heart-wood rot can already occur at an age of 50 to 60 years.

7.3.2. Literature data

The main source of information on the growth of black locust is the yield table from Erteld (1952) in Schober (1975) and Göhre (1952) which was made for the former German Democratic Republic. This yield table distinguishes three site classes with mean annual volume increments of 12.8, 9.5 and 6.5 $\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$ respectively at an age of 50 years. The standing volumes range from 135 to 301 m^3ha^{-1} at this age.

Keresztesi (1988) distinguishes 6 yield classes for black locust in Hungary, with rotation lengths of 20 years on the most limited site to 40 years on the best sites. The total gross timber yields vary from 85 on the worst site ($I_m = 4.3 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$ at $T = 20 \text{ yr}$) to 566 m^3ha^{-1} on the best site ($I_m = 14.2 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$ at $T = 40 \text{ yr}$). Only the growth on the best sites of Hungary is explicitly higher than the growth mentioned by Erteld (1952). Stands are usually established with 2500-3500 plants per ha. In Hungary thinnings are mainly carried out in the young phase, e.g. at ages 5, 9, 12, 18, and 25 years on site class I.

According to Göhre (1952) the basic wood density is 630 kg m^{-3} . Dixon et al. (1991) mention a basic density of 660 kg m^{-3} for *Robinia* species. No biomass measurements for pure black locust stands were found in the literature.

7.3.3. Model input

Model runs were done for black locust on three relative site classes in rotations of 50 years with regular thinnings. The three site classes of Erteld (1952) with mean annual volume increments at an age of 50 years of 12.1, 8.9 and 5.8 $\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$, were used (see Appendix D3). The basic density of the wood was set at 630 kg m^{-3} (see Appendix C).

Since no biomass measurements of the biomass compartments were available, allocation to the compartments was kept rather general, using averages for deciduous trees (see Appendices E and F). At an age of 50 years, 72% of the total living biomass was stored in the stemwood. The rest was stored in branches, roots, foliage and undergrowth. On the limited site, 66% of the total living biomass was stored in the stemwood. Here allocations to roots and branches were set somewhat higher.

Since the litter is of a good quality, the humification factor was kept rather high at 10% with a litter residence time of 1 year and a stable humus residence time of 250 years. These are thus in agreement with the other forest types and climates (see Appendix H). The initial value of the amount of stable humus at the time of afforestation was kept the same as for poplar plantations on former agricultural land which has lost stable humus. The parameter was set at 100, 90 and 90 Mg ha^{-1} dry matter respectively.

Thinnings start at an age of 10 years and are executed every 5 years up to an age of 45 years. Much of the thinning wood is used for fire wood. Of the wood from thinnings which are executed at an age of 30 years or later 40% is allocated to sawn timber. The average diameter on the good site is now 20 cm

and more (Erteld 1952). Of the wood from the final cut at an age of 50 years 60% is allocated to sawn timber (see Appendix I5)

7.3.4. Results and discussion

The results of the modelling of carbon sequestration in Robinia plantations in Europe are displayed in Figure 7.3 and presented in Table 7.3.

Table 7.3 Comparison of carbon stocks and fluxes for industrial plantations of black locust in Europe on three site classes.

- 1) Total stock of carbon at the end of the rotation in biomass and products (Mg C ha⁻¹);
- 2) Total stock of carbon at the end of the rotation in the soil organic matter i.e. litter, dead wood and stable humus (Mg C ha⁻¹);
- 3) Total stock of carbon at the end of the rotation in biomass, forest products and in dead organic material on or in the soil (Mg C ha⁻¹);
- 4) Long-term average stock of carbon in the biomass and the forest products (Mg C ha⁻¹);
- 5) Long-term average stock of carbon in the forest products (Mg C ha⁻¹);
- 6) Long-term average stock of carbon in the soil organic matter (Mg C ha⁻¹);
- 7) Long-term average stock of carbon in the total system of biomass, products and soil organic matter (Mg C ha⁻¹);
- 8) Net accumulated amount of carbon over the first 100 years after afforestation (Mg C ha⁻¹);
- 9) Average net annual carbon flux at the end of the first rotation (Mg C ha⁻¹yr⁻¹).

	1	2	3	4	5	6	7	8	9
good site class (I _m = 12.1 m ³ ha ⁻¹ yr ⁻¹)	189	78	267	142	52	101	242	241	4.12
moderate site class (I _m = 8.9 m ³ ha ⁻¹ yr ⁻¹)	155	66	221	111	40	84	195	189	3.35
site class (I _m = 5.8 m ³ ha ⁻¹ yr ⁻¹)	104	60	164	71	26	67	138	124	2.12

From the results it appears that black locust both sequesters carbon in a high annual rate and stores relatively large amounts of carbon in the forest ecosystem in the long-term. On a moderate site class, the average net annual carbon storage during the first rotation is 3.35 Mg C ha⁻¹yr⁻¹ with a long-term average amount in the living biomass and products of 111 Mg C ha⁻¹. During the total simulation period, the compartment of dead wood, litter and stable humus increases on the moderate site to a long-term average of 84 Mg C ha⁻¹.

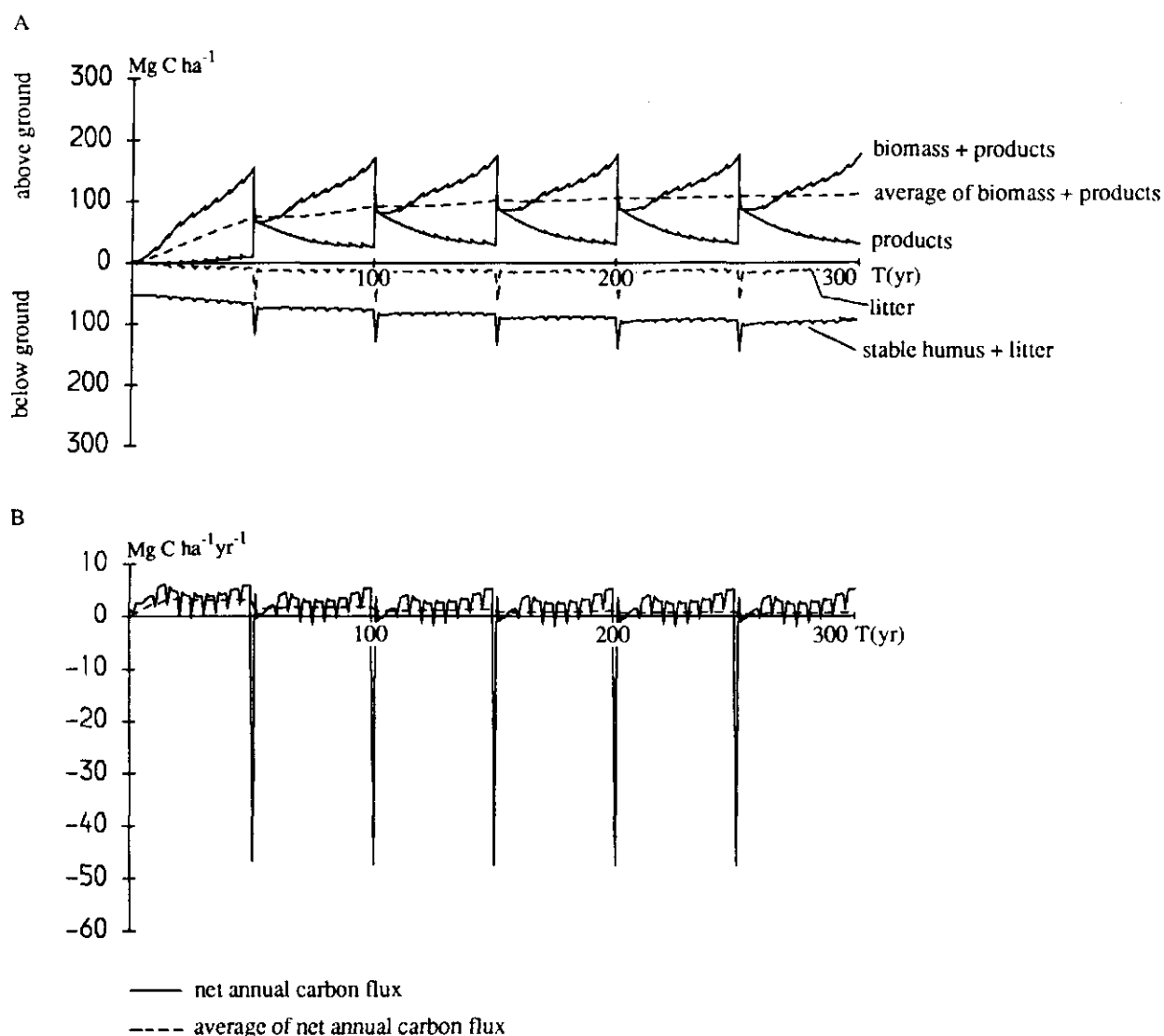


Fig. 7.3 A: Carbon stocks in biomass, forest products and soil organic matter for *Robinia* plantations on moderate sites in rotations of 50 years ($I_m = 8.9 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ at $T = 40$)
 B: Carbon fluxes both on an annual basis and as a running mean (dashed line) ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$).

Some input parameter values are, however, rather uncertain. The volume increment had to be derived from a yield table of the former German Democratic Republic. It is uncertain to what degree these increments can be achieved in more maritime climates on former arable land (Bullfin 1990). No biomass measurements of pure black locust stands were available, so general averages for deciduous forests had to be used.

The humification percentage was set rather high at 10%, because the litter of black locust is of a good quality. The residence time of the litter was thus kept

rather short at 1 year. These parameter values could not be derived from measured values from literature, but had to be kept in accordance with other forest types and climates which were more certain. The accumulation of the stable humus (residence time = 250 years) which results from this is at least within the range of the accumulation that Johnson (1992) mentions after afforestation.

Only the other simulations of the carbon storage in black locust found were in Dixon et al (1991). For afforestations with *Robinia* spp. in China they mention a net annual carbon storage during the first rotation of $8.28 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ and an amount of 149 Mg C ha^{-1} stored in 50 years. This is achieved in rotations of 35 years in which a mean volume increment of $15 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ was achieved. The annual storage rate mentioned by Dixon is very high, but is caused by the much higher growth rate which they use. The total amount stored on a good site in 50 years, is in larger our study than the amount Dixon et al. mention. This is because in our study this criterion coincides with the end of a rotation, whereas they simulate the middle of a rotation at that time.

Concluding it can be stated that because some vital parameter values are still uncertain, the results for this forest type can only be seen as indications. Despite the uncertainties, it can be stated that black locust is a considerable carbon storer, it is a forest type which accumulates relatively large average stock of carbon in the biomass and products. On a moderate site, approximately $3.4 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ are stored during the first rotation with a long term average stock in the biomass and products of 111 Mg C ha^{-1} .

8. INDUSTRIAL PINE PLANTATIONS IN REGIONS WITH A LONG GROWING SEASON.

8.1. Introduction to the forest type.

Industrial pine plantations in subtropical and warm temperate regions of the world cover an extensive area. In suitable conditions the growth is fast and the plantations give a high yield of cheaply produced wood for pulp or softwood sawn timber. Because of the high yields that can be achieved, they seem suitable for carbon storage. The carbon storage potential for four pine species will be presented in this chapter. The species and their regions are: *Pinus radiata* in New Zealand/Australia, *Pinus caribaea* in Brazil/Venezuela, *Pinus taeda* in the southeast of the United States and *Pinus elliottii* in Brazil. Each of the following sections deals with one pine species.

8.2. Carbon dynamics in *radiata* pine plantations.

8.2.1. Sites, climate and silviculture

Radiata pine or Monterey pine (*Pinus radiata*) is native in only three very small localities in California (USA) and on the island of Guadalupe, French West Indies (see Figure 8.1) (Vidakovi 1991). Although its native distribution is very limited, the species is the most widely cultivated of all pines. It is under intensive cultivation in New Zealand, Australia, South Africa and Chile, where it grows rapidly. It succeeds in warmer regions where temperature does not fall much below zero. The native climate is a special kind of Mediterranean type climate. There is little summer rain, but adequate summer moisture comes from frequent sea fogs or mists (Scott 1960). The southeast of Australia has a similar climate, while much of New Zealand has climates which are reasonably suitable.

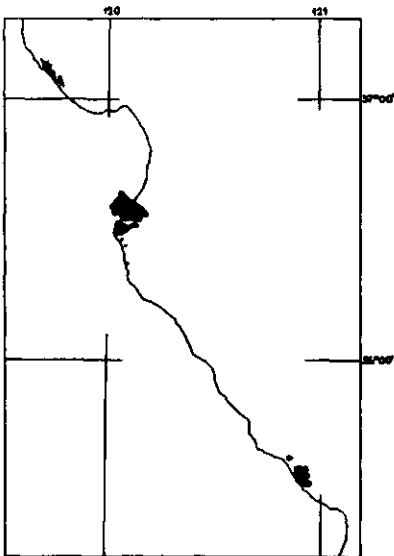


Fig. 8.1 Native range of *Pinus radiata* in the coastal region of California (Vidakovi 1991 after Critchfield & Little).

In New Zealand, the pine is mainly established on podzolized sands on the North Island. The soils are sandy, but hold moisture fairly well. Radiata pine seems to grow best on deep, freely drained sandy loams of moderate fertility (Scott 1960). It does not thrive on wet sites. In Australia the species is mainly planted in the southeast on sandy soils which are relatively poor sites. Growth in Australia is mainly determined by rainfall. Mean annual volume increments at an age of 20 to 30 years may vary from $11 \text{ m}^3 \text{ha}^{-1} \text{yr}^{-1}$ in regions with 580 mm of annual rainfall to $25 \text{ m}^3 \text{ha}^{-1} \text{yr}^{-1}$ in regions with more than 760 mm of annual rainfall (Scott 1960).

Afforestations are usually carried out with 3000 to 4500 plants per hectare, depending on the goal of the plantation. Narrow spacings in short rotations of 16 to 30 years are usually carried out to produce pulpwood, while somewhat wider spacings in rotations up to 50 years are practised to produce timber. Regular thinnings and pruning are carried out when quality sawn logs are to be produced.

8.2.2. Literature data

Data were gathered on the following parameters:

- volumetric growth and standing volume;
- amount of biomass in the different compartments;
- litter fall and forest floor biomass;
- humification factor and residence time of the litter;
- residence time of the stable humus;
- specific gravity of the wood;
- amount of stable humus in the soil;
- thinning ages and product allocation.

Yield tables were available for the main countries in which *Pinus radiata* is grown. Scott (1960) gives a good overview of the available yield tables for New Zealand, Australia, Chile, Spain and South Africa. He cites Lewis who presents mean annual volume increments for New Zealand ranging from 18 to $30 \text{ m}^3 \text{ha}^{-1} \text{yr}^{-1}$ at an age of 40 years. He states that the growth of *Pinus radiata* is approximately the same in Australia as in New Zealand. Lewis in Scott (1960) presents a yield table for Australia in which the mean annual volume increments in rotations of 36 years, range from 17 to $29 \text{ m}^3 \text{ha}^{-1} \text{yr}^{-1}$. The maximum current volume increment is achieved at an age of 12 years and for good, moderate and limited sites is 44, 33 and $25 \text{ m}^3 \text{ha}^{-1} \text{yr}^{-1}$ respectively.

The dry weight of the roots remains rather uncertain from these measurements. An equation is given by Will (1966): He found a linear relation between the branch weight of a radiata stand on a good site and the root weight of the stand. He states that root weight = $0.69 \times$ branch weight.

The annual litter fall in radiata stands is given by Kimmins et al. (1985). They cite Cromer who found figures of 3.5 to $3.9 \text{ Mg ha}^{-1} \text{yr}^{-1}$ for radiata stands aged 15 years in Australia. Bray & Gorham (1964) cite Will, who found an annual total litter fall of 6.3 Mg ha^{-1} for a 28-year-old radiata stand in New Zealand and of $7.4 \text{ Mg ha}^{-1} \text{yr}^{-1}$ for a 40-year-old stand.

The published data on forest floor dry weight of older stands vary considerably. Some data for young stands are given in Table 8.1. Ballard & Will in Kimmins et al. (1985) found 38 Mg ha^{-1} for the stock of fine litter under a radiata stand (age unknown). The woody litter amounted 11.7 Mg ha^{-1} . Kimmins et al. (1985) mention an amount of 60 Mg ha^{-1} dry weight in the forest floor for a 30-year-old stand in California. According to Turner & Lambert (1988) a 42-year-old stand had a forest floor dry weight of 14 Mg ha^{-1} .

No published rates of annual turnover in the forest floor and the stable humus were found, but Turner & Lambert (1988) reported that when the native vegetation of New South Wales, Australia (Eucalyptus) was converted to radiata stands, the amount of soil organic matter increased on less fertile sites when the stand had reached an age of 42 years. On a more fertile site, the amount of soil organic matter had decreased. There is concern about whether the long-term productivity can be maintained under these intensive pine plantation systems (Dyck & Mees 1990). Large-scale clearcuts, windrowing, and burning of the logging slash are reported to result in a short-term increase of available nutrients but also in an increased leaching of elements and thus loss of productivity in the long-term (2 or 3 rotations). Squire et al. (1985) state that when litter and logging slash is left after clearcut, the site productivity can at least be maintained in the second rotation.

The amount of carbon in the stable humus is 93 Mg C ha^{-1} under warm temperate moist forest according to Millemann & Boden (1986). Under subtropical moist forest this is 92 Mg C ha^{-1} . Under Mediterranean shrub or woods in Australia, this figure is 102 Mg C ha^{-1} .

The basic density of the wood of *Pinus radiata* is 420 kg m^{-3} according to Dixon et al. (1991). Scott (1960) mentions a figure of 400 kg m^{-3} .

8.2.3. Model input

Model runs were done for 8 successive rotations of 40 years with radiata pine on sites of good, moderate and limited fertility. At an age of 40 years, mean annual volume increments of 29, 23 and $17 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ were used. Input values were set according to the yield table of Lewis in Scott (1960) (see Appendix D3). The allocation of the Net Primary Production was set in such a way that the results agreed with the biomass measurements of Table 8.1 (see Appendix E). The basic density of the wood was set at 400 kg m^{-3} .

The humification factor of the litter for the good, moderate and limited site was set at 5%, 4% and 3% respectively. The litter residence time was set at 3, 3 and 4 years. The residence time of the stable humus was set at 200, 220 respectively 240 years. These values were kept in agreement with the other forest types and climates (see Appendix H).

Table 8.1 Biomass measurements of Pinus radiata stands obtained by various authors.

stand age	8	9	10	17	22	5	7	9	12	42	12	12	35
Country	NZ	NZ	NZ	NZ	NZ	AU	AU	AU	AU	NZ	NZ	NZ	NZ
reference	1	1	1	1	1	2	2	2	2	3	4	4	5
biomass dry weight (Mg ha ⁻¹)													
stem	28.8	32.7	54.4	236.7	270.5	2.4	23.8	53.8	89.5	129.2	52.9	105.0	*
branch	4.8	5.5	11.4	22.0	27.4	1.2	14.9	9.9	18.7	23.2	15.2	43.9	*
foliage	2.5	3.4	5.8	10.8	9.2	2.1	11.6	8.8	9.5	7.2	8.6	13.2	*
root	*	*	*	*	*	*	9.0	12.9	*	*	*	*	*
total	36.1	41.6	71.6	269.5	307.1	5.7	59.3	85.4	117.7	159.6	76.7	162.1	362.0
forest floor	*	*	*	*	*	1.8	4.7	14.3	17.0	14.0	*	*	*
dead wood	0.0	0.0	0.1	9.0	4.7	*	*	*	*	*	1.4	3.0	*
undergrowth	*	*	*	*	*	*	*	*	*	0.8	*	*	*
NPP (Mg ha ⁻¹ yr ⁻¹)													
stem						1.0	10.7	15.1	11.9		14.1	26.5	
branch						0.5	2.5	2.5	2.5		2.6	14.5	
foliage						0.7	3.4	5.1	4.6		4.7	6.4	
root						*	*	*	*		*	*	
total	*	*	*	*	*	2.2	16.6	22.7	19.0	*	21.4	47.4	*

References: 1: Madgwick et al. 1977;
2: Forrest & Ovington, in Cannell 1982;
3: Turner & Lambert 1988;
4: Beets & Pollock 1987;
5: Kimmins et al. 1985.

The initial value for the amount of stable humus was set rather low at an amount of 150, 130 120 Mg ha⁻¹ dry matter respectively. These values were chosen because the initial situation is assumed to be former agricultural land, not the native (Eucalyptus) forest. It is assumed that the amount of stable humus has been depleted already. Some accumulation after afforestation will therefore occur.

Light thinnings are carried out regularly at ages of 10, 15, 20, 25, 30 and 35 years. Much of the thinning wood is allocated to pulp and at higher ages to particle board and packing wood. The wood from the final cut is mainly allocated to particle board and packing wood (see appendix I4).

8.2.4. Results and discussion

The results of the modelling of carbon sequestration in *Pinus radiata* plantations in New Zealand/Australia are displayed in Figure 8.2 and presented in Table 8.2. Using Appendix J, relative site class as used here can be determined for a particular field situation, in order to estimate the potential for carbon storage.

Table 8.2 *Comparison of carbon stocks and fluxes for Pinus radiata plantations in New Zealand/Australia on three site classes.*

- 1) Total stock of carbon at the end of the rotation in biomass and products (Mg C ha^{-1});
- 2) Total stock of carbon at the end of the rotation in the soil organic matter i.e. litter, dead wood and stable humus (Mg C ha^{-1});
- 3) Total stock of carbon at the end of the rotation in biomass, forest products and in dead organic material on or in the soil (Mg C ha^{-1});
- 4) Long-term average stock of carbon in the biomass and the forest products (Mg C ha^{-1});
- 5) Long-term average stock of carbon in the forest products (Mg C ha^{-1});
- 6) Long-term average stock of carbon in the soil organic matter (Mg C ha^{-1});
- 7) Long-term average stock of carbon in the total system of biomass, products and soil organic matter (Mg C ha^{-1});
- 8) Net accumulated amount of carbon over the first 100 years after afforestation (Mg C ha^{-1});
- 9) Average net annual carbon flux at the end of the first rotation ($\text{Mg C ha}^{-1}\text{yr}^{-1}$).

	1	2	3	4	5	6	7	8	9
good site class ($I_m = 27.0 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$)	198	101	299	154	42	120	274	196	5.28
moderate site class ($I_m = 22.2 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$)	171	86	257	126	35	97	223	151	4.54
limited site class ($I_m = 17.5 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$)	136	81	217	99	27	89	188	118	3.68

From the results it is clear that radiata pine in New Zealand/Australia is a considerable carbon storer assuming that the long-term fertility of the soil does not decrease during consecutive rotations. The main parameter determining the carbon sequestering potential, the volume increment, could be based on an established yield table, which makes the results reliable. This forest type both shows a high annual rate during the first rotation and large long-term average amounts of carbon in the living biomass and products, for example 126 Mg C ha^{-1} on a moderate site.

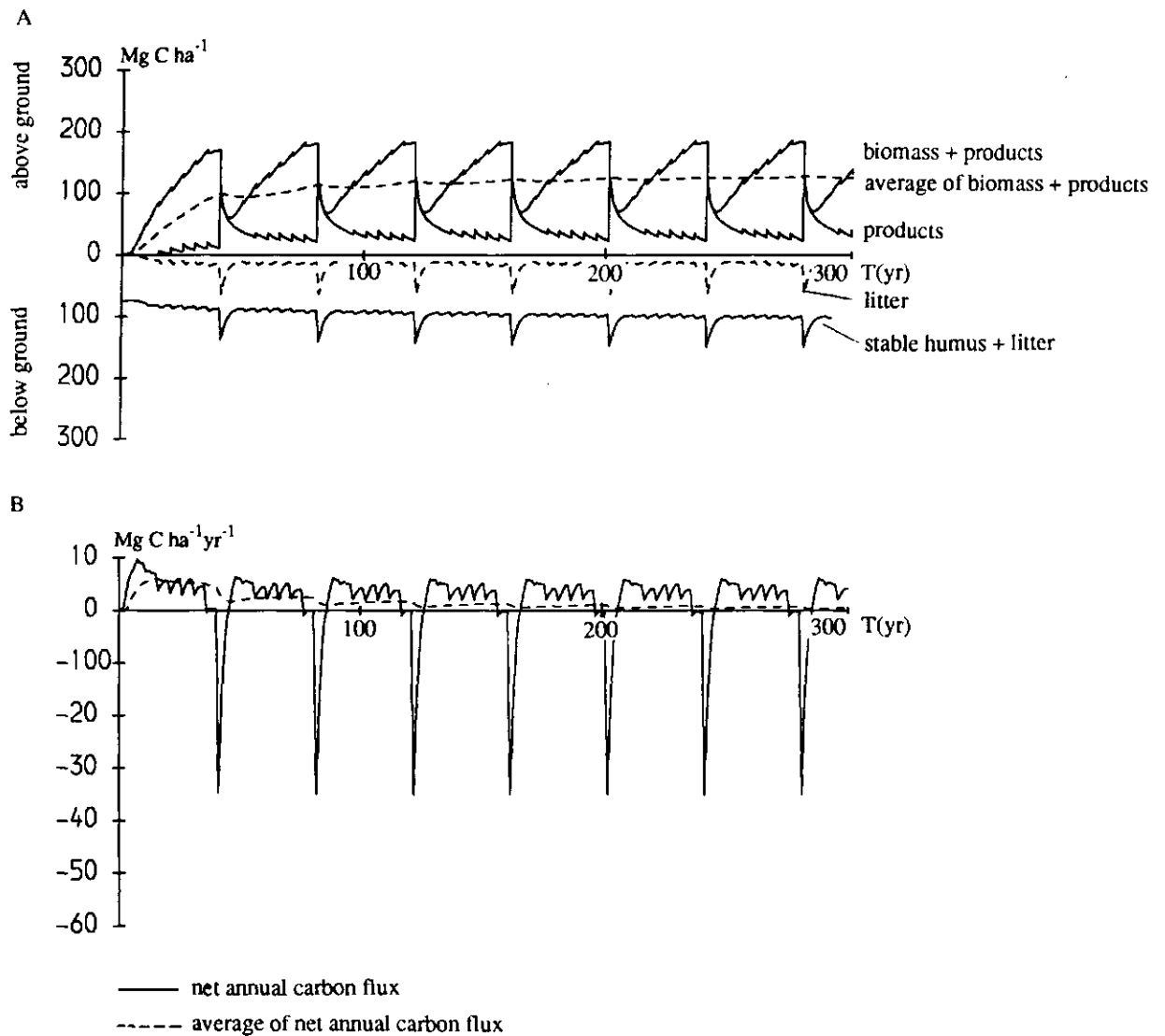


Fig. 8.2 A: Carbon stocks in biomass, forest products and soil organic matter for *Pinus radiata* plantations on moderate sites in a rotation of 40 years

($I_m = 22.2 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ at $T = 40$)

B: Carbon fluxes both on an annual basis and as a running mean (dashed line) ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$).

The degree of accumulation in the stable humus is rather critical. It is assumed here that the initial situation is some kind of impoverished agricultural land, which can accumulate soil humus. If the initial situation starts with higher amounts of stable humus, some decrease in the amount of stable humus is possible, because it may be expected that on the long term, *Pinus radiata* impoverishes the site (Dyck & Mees 1990). The model assumes continuous site productivity which can be achieved on somewhat richer and loamy sites.

On sandy sites this is rather uncertain in the long-term. It is uncertain how much the productivity will decrease after 2 or 3 rotations. However, if the logging slash is treated in an appropriate way, it should be possible to maintain the productivity of the site.

Carbon storage in *Pinus radiata* stands has been modelled before. For *radiata* stands in a rotation of 25 years and a mean annual increment of $25 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ Dixon et al. (1991) mention a net annual storage rate of $8.4 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. Their annual storage is high compared to the results for our average site ($I_m = 23.7$ at $T = 25 \text{ y}$). By modelling short rotations with narrow initial spacings, Dixon obtained very high increments at young ages and thus high storage rates during a very short period.

Concluding it can be stated that *Pinus radiata* in New Zealand and Australia stores carbon at a high annual rate during the first rotation and with reasonable long-term average amounts of carbon in the biomass and products. On a moderate site the net annual storage rate is $4.54 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ during the first rotation with a long-term average stock of 126 Mg C ha^{-1} in the biomass and products. From the dashed line in Figure 8.2.B it can be seen that the net annual carbon flux gradually decreases to zero, although the site productivity has been kept stable. Long-term productivity will strongly depend on management and the initial soil fertility.

8.3. Carbon dynamics in Caribbean pine plantations.

8.3.1. Sites, climate and silviculture

The Caribbean or Cuban pine (*Pinus caribaea*) has its native distribution on the Bahama islands, in western Cuba and along the Caribbean seaboard of central America, from Honduras to Nicaragua (see Figure 8.3). The altitudinal range is from sea level to 1000 m or above, but it is more common in the lower altitudes (Vidakovi 1991). It grows in a climate with summer rainfall and a winter dry season free from frost. It can be found on a variety of soils, usually loams or sandy loams which hold the moisture fairly well. The soil has to be deep and well drained for growth to be good, but the species is also known for its ability to grow on hot, infertile sites (Lamb 1973).

Plantations of *P. caribaea* are usually managed in rotations of 20 to 25 years. The tree can attain heights of 45 m under the best conditions. On suitable sites it can achieve a mean annual increment up to $28 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ in a rotation of 30 years (Lamb 1973). The wood is used for packing wood and pulp and to a lesser degree, for sawn timber (Pandey 1983). Pandey states that at the of the 1980s the area covered by *P. caribaea* in Brazil and Venezuela amounted to some 280 000 ha.

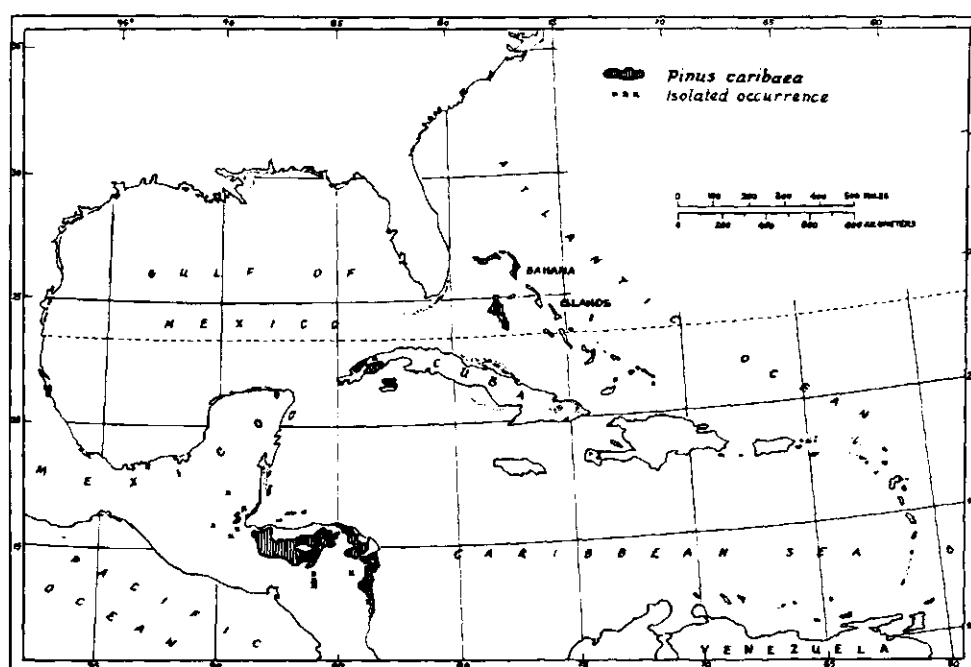


Fig. 8.3 Native range of *Pinus caribaea* (Vidakovi 1991 after Critchfield & Little).

8.3.2. Literature data

Although *P. caribaea* plantations are established on a large scale all over the world, well established yield tables were difficult to find. In his overview Lamb (1973) presents yield tables which are usually only valid for one site class or are rather incomplete. For Brazil he mentions only a set of trial fields recorded only once. These trial fields gave a mean annual increment of $19.1 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ at an age of 11 years. The yield table for Jamaica presents a mean annual increment of $21.4 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ at an age of 20 years. Lamb states that the growth in the Brazilian plots is well above the best growth of Trinidad and reproduces a yield table with mean annual increments of 20, 15 and $11 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ respectively.

Net Primary Productivity can vary considerably in *P. caribaea* plantations. Lugo et al. (1988) show in a graph that at an age of 10 years, the mean annual stemwood biomass increment ranges from $5 \text{ Mg ha}^{-1} \text{ y}^{-1}$ dry matter in a tropical dry climate to $27 \text{ Mg ha}^{-1} \text{ y}^{-1}$ dry matter in the tropical premontane wet climate of Costa Rica.

According to Cuevas et al (1991) the annual litter fall for an 11-year-old *P. caribaea* stand in Puerto Rico is $12.1 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ dry matter. Fine root production was $1.1 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ dry matter.

Table 8.3 *Results of biomass measurements of Pinus caribaea plantations according to various authors.*

stand age	11	6	4	6	7	11-15	16-20	21-30
Country	P. Rico	Nigeria	Brazil			av.	av.	av.
reference	1	2	3	3	3	4	4	4
<hr/>								
biomass dry weight (Mg ha ⁻¹)								
stem	*	47.7	6.0	22.0	28.0	120	143	285
branch	*	9.4	*	*	*	*	*	*
foliage	*	11.5	*	*	*	*	*	*
root	*	17.1	*	*	*	*	*	*
<hr/>								
total	94.9	85.7	*	*	*	*	*	*
forest floor	10.5	*	*	*	*	*	*	*
<hr/>								
NPP (Mg ha ⁻¹ yr ⁻¹)								
stem	6.0	*	5.0	6.8	7.3	*	*	*
branch	*	*	*	*	*	*	*	*
foliage	12.1	2.0	*	*	*	*	*	*
root	2.2	*	*	*	*	*	*	*
<hr/>								
total	20.3	*	*	*	*	*	*	*
<hr/>								
References:	1:	Cuevas et al. 1991 (there was 82 Mg ha ⁻¹ dry matter in the stable humus);						
	2:	Cannell 1982;						
	3:	Lugo et al. 1988;						
	4:	Brown et al 1985.						

The basic density of the Caribbean pine wood is 460 kg m³ according to Schroeder (1992). Dixon et al. (1991) mention a figure of 510 kg m³. Much of the Caribbean pine wood is used for pulp, emballage and board wood. A minor part is used for softwood sawn timber (Lamb 1973).

Lugo & Sanchez (1986) report that when the cropping intensity of tropical soils was reduced, the soil carbon increased in the order of 0.3-0.5 Mg C ha⁻¹yr⁻¹ over a 40-year-period. The higher the sand content, the less the soil carbon accumulation. They report 69.5 Mg C ha⁻¹ in the stable humus in the topsoil of a wet clay in Puerto Rico which had been under pasture for more than 50 years.

8.3.3. Model input

Model runs were done for 12 rotations of 25 years on three site classes in central and northern South America. The yield table from Jamaica (Lamb

1973) was used for the moderate site class, and the growth on the other sites was based on this yield table in combination with the recorded growth in the plots from Brazil (see § 8.3.2). The mean annual increments at an age of 20 years for the good, moderate and limited sites were set at 23.8, 19.6 and 13.9 $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$ respectively (see Appendix D4).

Allocation of the NPP to the distinguished biomass compartments was set in the same way as was done for *P. radiata*, because only very few biomass measurements of all the biomass compartments were found (see Appendices E and F).

For the good, moderate and limited sites, the humification factor was set at 5%, 4% and 3% respectively, in agreement with the other pine plantations. The litter residence time was set at 3, 3 and 4 years, and the stable humus residence time at 200, 220 and 250 years respectively (see Appendix H). The initial value for the stable humus was set at 140, 130 and 110 Mg ha^{-1} dry matter.

Thinnings are carried out at ages of 10, 15 and 20 years, and each time approximately 20% of the standing wood is harvested. For allocation of the harvested wood see appendix I4.

8.3.4. Results and discussion

The results of the modelling of carbon sequestration in *Pinus caribaea* plantations in central and northern South America are displayed in Figure 8.4 and presented in Table 8.4. Using Appendix J, relative site class as used here can be determined for a particular field situation, in order to estimate the potential for carbon storage.

The results show that Caribbean pine in rotations of 25 years, is generally a good carbon storer in terms of its net annual carbon flux during the first rotation. On a moderate site, an annual net carbon flux of 5.12 $\text{Mg C ha}^{-1} \text{yr}^{-1}$ can be achieved. But the average amount stored in the biomass and products is limited. On a moderate site, 89 Mg C ha^{-1} are stored on average in the biomass and products. The total amount of carbon stored after 100 years, however, seems rather positive, but this is because in the *P. taeda* system this arbitrary criterion coincides exactly with the end of a rotation, which is not the case in the other tropical pine plantations.

Table 8.4 Comparison of carbon stocks and fluxes for *Pinus caribaea* plantations in central and northern South America on three site classes.

- 1) Total stock of carbon at the end of the rotation in biomass and products (Mg C ha^{-1});
- 2) Total stock of carbon at the end of the rotation in the soil organic matter i.e. litter, dead wood and stable humus (Mg C ha^{-1});
- 3) Total stock of carbon at the end of the rotation in biomass, forest products and in dead organic material on or in the soil (Mg C ha^{-1});
- 4) Long-term average stock of carbon in the biomass and the forest products (Mg C ha^{-1});
- 5) Long-term average stock of carbon in the forest products (Mg C ha^{-1});
- 6) Long-term average stock of carbon in the soil organic matter (Mg C ha^{-1});
- 7) Long-term average stock of carbon in the total system of biomass, products and soil organic matter (Mg C ha^{-1});
- 8) Net accumulated amount of carbon over the first 100 years after afforestation (Mg C ha^{-1});
- 9) Average net annual carbon flux at the end of the first rotation ($\text{Mg C ha}^{-1}\text{yr}^{-1}$).

	1	2	3	4	5	6	7	8	9
good site class ($I_m = 23.8 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$)	145	91	236	107	40	105	212	182	6.14
moderate site class ($I_m = 19.6 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$)	122	83	205	89	33	90	179	148	5.12
limited site class ($I_m = 13.9 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$)	90	71	161	63	24	75	138	110	3.84

The volume increments used were rather critical in this study. No well established and reliable yield tables were available for the northern region of South America. Only rather fragmented yield tables for some south and central American regions were presented in the overview of Lamb (1973). Therefore, no extreme yields were used either from the upper or from the lower rangew of yields found in literature. Mean annual volume increments were kept in between 14 and $24 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$.

Some accumulation in the stable humus is assumed. The intensive use of the agricultural land has probably resulted in some decrease of the amount of stable humus. Less intensive use after afforestation may result in slow but continuous build-up of the stable humus.

Schroeder (1992) mentions a mean carbon stock of 59 Mg C ha^{-1} in the trees of *P. caribaea* plantations on average sites. He assumes a rotation length of 15 years with a mean annual volume increment of $20 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$. Considering his input values, it can be stated that the results agree with ours, although he finds almost the same average amount of carbon as in our study but now in

shorter rotations. Schroeder probably used higher volume increments at young ages, which result in a relatively high mean increment at a young age.

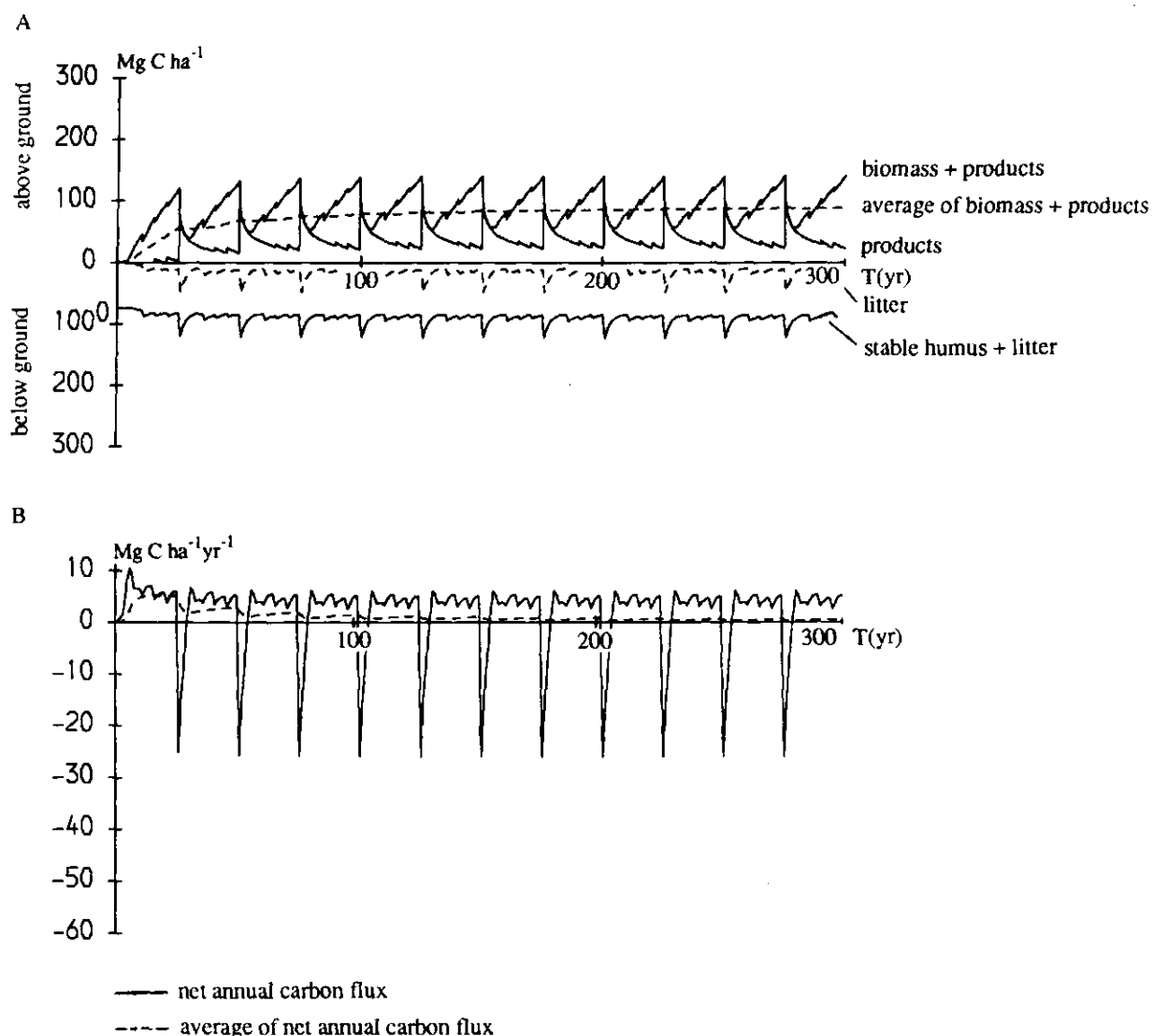


Fig. 8.4 A: Carbon stocks in biomass, forest products and soil organic matter for *Pinus caribaea* plantations on moderate sites in a rotation of 25 years ($I_m = 19.6 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$)
 B: Carbon fluxes both on an annual basis and as a running mean (dashed line) ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$).

Dixon et al. (1991) mention various reforestation schemes with Caribbean pine in Brazil. In rotations of 16 years, with a mean annual increment of $18 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, they suggest a net annual carbon flux of $7.2 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ with 61 Mg C ha^{-1} stored in 50 years, which can only be achieved in narrow spacings with high increments at young ages. Our stored amount after 50 years is higher

(142 Mg C ha⁻¹) because in our study this criterion coincides with the end of the second rotation. For other afforestation schemes with even shorter rotations and higher mean increments, Dixon et al (1991) mention net annual storage rates up to 10 Mg C ha⁻¹yr⁻¹ during the first rotation. These systems, however, result in a strong decline of the site productivity, which results in a release of the stored carbon in the medium term.

Concluding it can be stated that *Pinus caribaea* plantations in central and northern South America store carbon at a high rate over the first rotation, but with limited average amounts in the biomass and products. On a moderate site, *P. caribaea* stores 5.12 Mg C ha⁻¹yr⁻¹ during the first rotation with an average stock of 89 Mg C ha⁻¹ in the biomass and products.

8.4. Carbon dynamics in loblolly pine plantations.

8.4.1. Sites, climate and silviculture.

As a native species, Loblolly pine (*Pinus taeda*) is of lesser importance in the mesic pine communities of the southeastern coastal plains of the USA (see Figure 8.5).

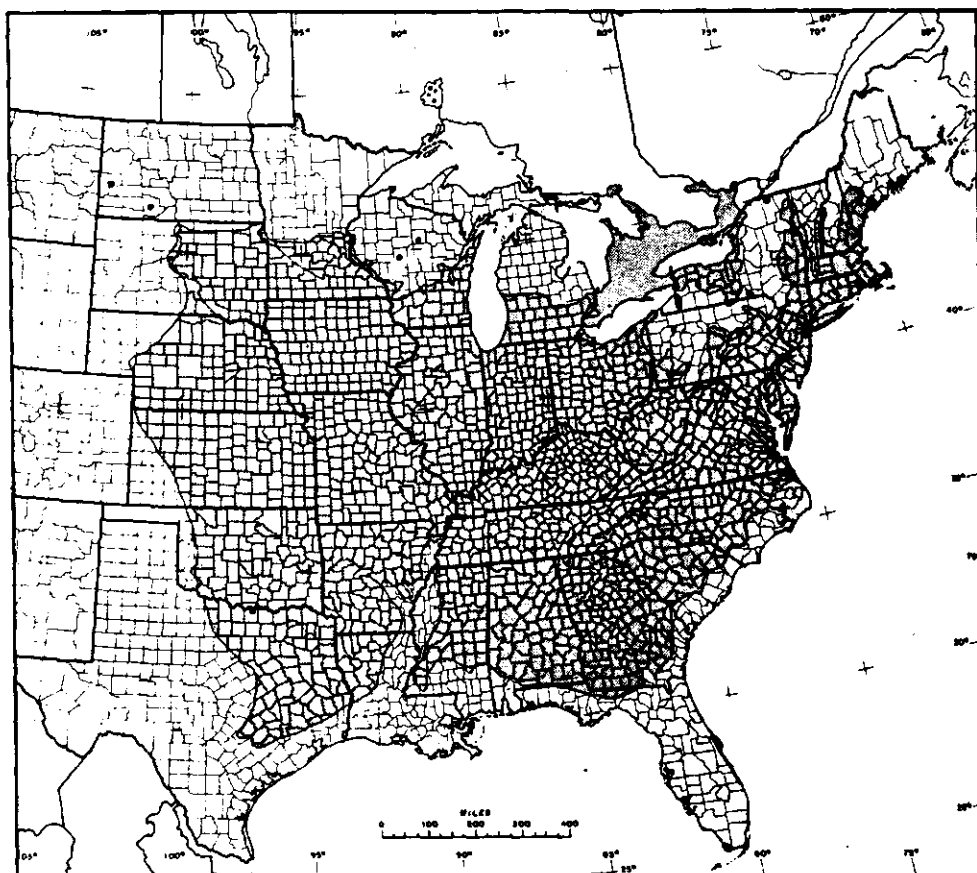


Fig. 8.5 Native distribution of *Pinus taeda* (Vidakovi 1991 after Critchfield & Little).

As an economic species, however, it is very important (Christensen in Barbour & Billings 1988). Its altitudinal distribution ranges from near sea level to 250 m elevation (Vidakovi 1991). It is suitable for cultivation in warm temperate regions on soils which hold the moisture fairly well, but also on drier soils. The main soil types of the coastal plains are Entisols (soils with no profile development on the very well drained sands), Inceptisols (infertile soils on the alluvial plains of varying texture with hardly any profile development), Alfisols (rather fertile soils with a distinct B horizon on the alluvial plains of the Mississippi) and Ultisols (poorer highly weathered soils which occur on a wide scale). Growth of loblolly pine is fast and it is therefore the most important commercial softwood species of the southern United States.

Loblolly pine can be managed in unthinned or thinned stands. If the goal is to produce much pulp, board and emballage wood in a short period, then usually unthinned stands are managed in rotations of 30 years. To produce emballage or softwood timber, rotation length is approximately 45 years with thinnings starting at an age of 15 years, repeated every 7-10 years. Baldwin & Feduccia (1987) state that site indices (height in metres at an age of 25 years) for the western Gulf region (Louisiana, Texas and Arkansas) range from 12 to 24 (originally 40 to 80 ft). In unthinned stands the current volume increment can reach $25 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ at an age of approximately 15 years.

8.4.2. Literature data

Site indices for *P. taeda* (height in feet at age 25) in the southeast of the United States range from 40 to 80. Most plantations, however, lie within the range of indexes 50 to 70 (Baldwin & Feduccia 1987). Baldwin & Feduccia (1987) mention mean annual volume increments between 7.7 and $16.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ for unthinned stands in a rotation of 30 years. In thinned stands in rotations of 50 years, a mean annual volume increment of $13 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ can be achieved. It became clear from the literature that the standing volume and the mean annual increment of a stand depend not only on the site and the climate, but also very much on the planting space and the thinning regime.

The annual litter fall in stands of *P. taeda* of 11-15, 16-17 and 24-27 years according to Wells & Jorgensen (1975) was respectively 7.7, 3.4 and $5.1 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ dry matter. According to them the annual accumulation in the forest floor under *P. taeda* stands between 13 and 16 years was $4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ dry matter, approaching an equilibrium dry matter biomass in the forest floor of 30 Mg ha^{-1} at an age of 30 years. Switzer in Kimmins et al. (1985) mentions dry matter weights in the forest floor under *P. taeda* of 17.9 and 19 Mg ha^{-1} at ages of 15-30 and 30-45 years respectively.

According to Dixon et al. (1991) the basic wood density of loblolly pine is 470 kg m^{-3} . Millemann & Boden (1986) mention a figure of 94 Mg C ha^{-1} for the amount of carbon in the stable humus under warm temperate dry forest in North America. For the amount under warm temperate moist forest, they mention a figure of 60 Mg C ha^{-1} .

8.4.3. Model input

The carbon dynamics of *P. taeda* were modelled for 10 consecutive rotations of 30 years on three site classes. Volume increments were set according to Baldwin & Feduccia (1987) and resulted in mean annual volume increments at an age of 30 years of 13.6, 9.7 and 6.2 m³ha⁻¹yr⁻¹ respectively. Thinnings were not carried out. For allocation of the harvested wood, see the allocation of final cut to product categories in Appendix I4. The basic density of the wood was set at 460 kg m³.

Table 8.5 *Results of biomass measurements of Pinus taeda plantations in the southeast of the United States (N.C.=North Carolina; Ark.=Arkansas; Miss.=Mississippi).*

stand age	16	14	15	11	8	9-10	11	12	30	40
Location	N.C.	N.C.	N.C.	Ark.	N.C.	N.C.	N.C.	N.C.	Miss.	Miss.
reference	1	2	2	3	4	4	4	4	5	5
<hr/>										
biomass dry weight (Mg ha ⁻¹)										
stem	124.8	65.3	74.8	68.9	7.3	40.0	53.0	65.5	*	*
branch	14.6	11.0	11.8	20.7	4.6	16.2	17.4	18.6	*	*
foliage	8.0	5.7	6.0	6.7	4.2	9.2	7.8	6.9	*	*
root	36.3	20.2	21.8	*	2.9	11.9	14.2	16.6	*	*
<hr/>										
total	183.7	102.2	114.4	96.3	19.0	77.3	92.4	107.6	168.0	219.0
forest floor	16.0	*	*	*	*	*	*	*	*	*
<hr/>										
NPP (Mg ha ⁻¹ yr ⁻¹)										
stem	*	9.5	*	*	6.2	5.1	13.7	12.7	*	*
branch	*	6.7	*	*	2.4	2.8	2.2	1.7	*	*
foliage	*	5.4	*	*	2.2	4.0	4.4	3.0	*	*
root	*	9.0	*	*	1.0	1.8	2.9	2.6	*	*
<hr/>										
total	7.5	30.6	*	*	11.8	13.7	23.2	20.0	*	*

References: 1: Wells and Jorgensen 1975;
 2: Ralston, in Cannell 1982;
 3: Pope, in Cannell 1982;
 4: Nemeth, in Cannell 1982;
 5: Switzer et al., in Cannell 1982.

Allocation of the NPP to the distinguished biomass compartments was set in the same way as was done for the other pine species (see Appendices E and F). The results were comparable with the biomass measurements of Table 8.5 (see Appendix H).

For the good, moderate and limited sites, the humification factor was set at 5%, 4% and 3% respectively, in agreement with the other pine plantations.

The litter residence time was set at 3, 4 and 5 years, and the stable humus residence time at 250 years. The initial value for the stable humus was set at 150, 125 and 100 Mg ha⁻¹ dry matter.

8.4.4. Results and discussion

The results of the modelling of carbon sequestration in Pinus taeda plantations in southeastern United States are displayed in Figure 8.6 and presented in Table 8.6. Using Appendix J, relative site class as used here can be determined for a particular field situation, in order to estimate the potential for carbon storage.

Table 8.6 Comparison of carbon stocks and fluxes for Pinus taeda plantations in southeastern United States on three site classes.

- 1) Total stock of carbon at the end of the rotation in biomass and products (Mg C ha⁻¹);
- 2) Total stock of carbon at the end of the rotation in the soil organic matter i.e. litter, dead wood and stable humus (Mg C ha⁻¹);
- 3) Total stock of carbon at the end of the rotation in biomass, forest products and in dead organic material on or in the soil (Mg C ha⁻¹);
- 4) Long-term average stock of carbon in the biomass and the forest products (Mg C ha⁻¹);
- 5) Long-term average stock of carbon in the forest products (Mg C ha⁻¹);
- 6) Long-term average stock of carbon in the soil organic matter (Mg C ha⁻¹);
- 7) Long-term average stock of carbon in the total system of biomass, products and soil organic matter (Mg C ha⁻¹);
- 8) Net accumulated amount of carbon over the first 100 years after afforestation (Mg C ha⁻¹);
- 9) Average net annual carbon flux at the end of the first rotation (Mg C ha⁻¹yr⁻¹).

	1	2	3	4	5	6	7	8	9
good site class (I _m = 13.6 m ³ ha ⁻¹ yr ⁻¹)	122	91	211	78	25	94	172	58	4.14
moderate site class (I _m = 9.7 m ³ ha ⁻¹ yr ⁻¹)	93	77	170	59	19	81	139	46	3.21
limited site class (I _m = 6.2 m ³ ha ⁻¹ yr ⁻¹)	61	61	122	38	12	60	98	28	2.09

From the results it is clear that although loblolly pine has a high net annual carbon flux during the first rotation, the long-term average stock of carbon in the biomass and products is limited. On a moderate site, the net annual carbon flux during the first rotation is 3.21 Mg C ha⁻¹yr⁻¹ with on average only 59 Mg C ha⁻¹ in the biomass and products.

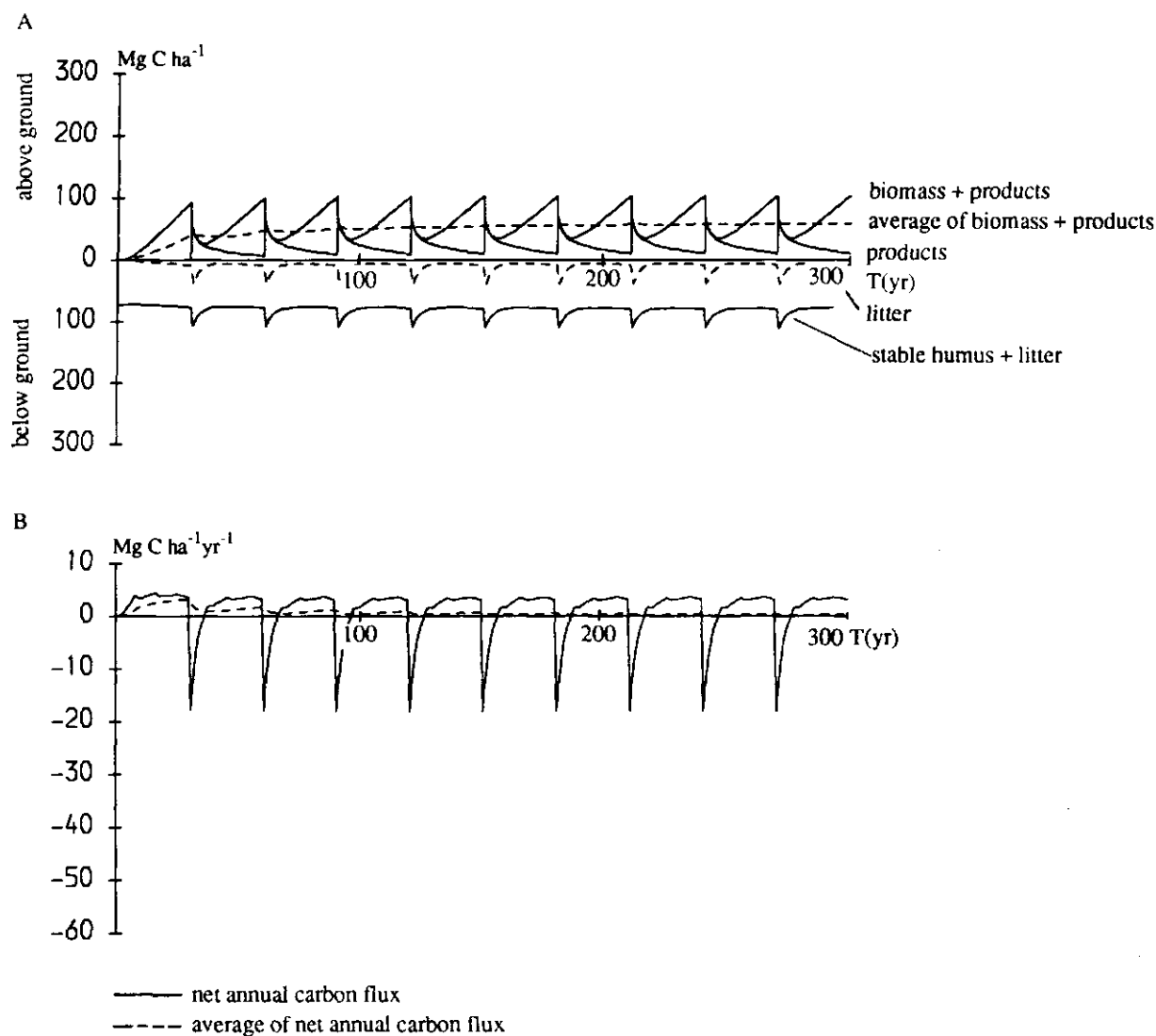


Fig. 8.6 A: Carbon stocks in biomass, forest products and soil organic matter for *Pinus taeda* plantations on moderate sites in a rotation of 30 years ($I_m = 9.7 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$)
 B: Carbon fluxes both on an annual basis and as a running mean (dashed line) ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$).

Although loblolly pine is widely distributed in the southeastern United States, it is difficult to choose volume increments typical of a large part of the loblolly plantations. The site indexes chosen in this study may cover a wide range of sites, but management may have an impact on the growth and standing volume too. It was decided to model 30-year rotations with no thinnings. If a rotation of 50 years with 4 heavy thinnings had been modelled, this would have resulted in larger long-term average stocks of carbon in the biomass and products.

The chosen allocation of the NPP to the distinguished biomass compartments resulted in a stem biomass compartment of 70% of the total living biomass at an age of 30 years. At younger ages, this was approximately 55-60%, which is in agreement with the data of Table 8.5.

Since the rotations are very short with no thinnings, it was assumed that only 10% of the harvested wood is used as sawn timber. The rest is used as pulp, particle board and packing wood. It was also assumed that the amount of stable humus had not decreased because of previous land use, and thus a rather stable amount of humus resulted.

Dixon et al. (1991) present a net annual carbon flux of $5.91 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ during the first rotation when dry cropland is afforested with *P. taeda* in rotations of 45 years. After 50 years an amount of 295 Mg C ha^{-1} is stored. Since they do not mention a growth rate, it is very difficult to compare this figure with our results, but their stored stock does seem very high.

Although the results are only valid for the management regime chosen, it can be concluded that plantations of *P. taeda* are limited carbon storers. The results for the most important criterion, the long-term average stock of carbon in biomass and products is only 59 Mg C ha^{-1} .

8.5. Carbon dynamics in slash pine plantations.

8.5.1. Sites, climate and silviculture

Slash pine (*Pinus elliottii*) is native in the southeast of the United States, where it extends from the southern parts of South Carolina to southern Florida and west to Louisiana (see Figure 8.7). It is found in lowlands and does not exceed 100m elevation (Vidakovi 1991). It needs abundant moisture in the soil! It requires moderate climate and is damaged by frost. Roughly the same soil types as have been described for *P. taeda* are valid for *P. elliottii*.

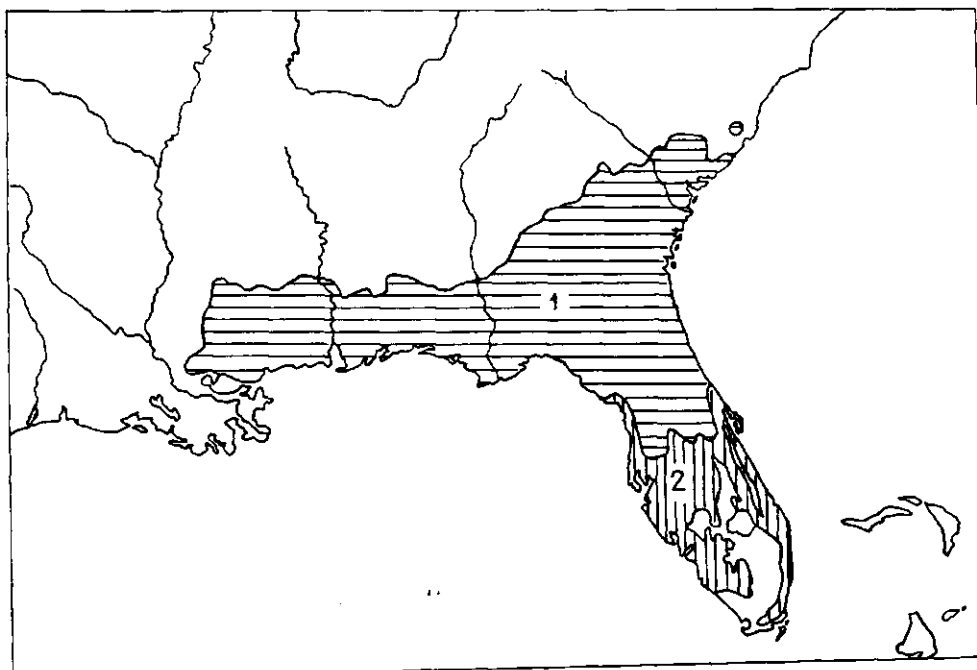


Fig. 8.7 Native distribution of 1: *Pinus elliottii* var. *elliottii* and 2: *Pinus elliottii* var. *densa* (Vidakovi 1991 after Critchfield & Little).

It is a fast growing species, successfully cultivated in plantations of 25-30 years in Africa, South America and Australia. In Brazil the best growth is found on primary and secondary forest sites and abandoned agricultural sites, while the worst growth is recorded on tree, shrub and grass savanna (Bastide & Van Goor 1970). Schneider (1984) mentions optimum rotations of 35 years on the worst site and of 20 years on the best sites. Site indices (mean volume increment at an age of 30 years) for Brazil vary from 22 to 34 $\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$ according to Schneider (1984). The main soil type for Brazil is the Latosol or Ultisol, a strongly weathered deep, clayey tropical soil with a low base saturation.

Afforestations are usually carried out with 4000 plants ha^{-1} , with regular thinnings every 5 years. Thinning wood is often used for pulp and board wood. At higher ages, the wood is used for emballage and softwood timber.

8.5.2. Literature data

Schneider (1984) presents a reliable and well established yield table for *P. elliottii* in Brazil.

Table 8.7 Results of biomass measurements of *P. elliottii* plantations (Jap.=Japan; Flor.=Florida, USA).

stand age	8	8	8	8	8	8	8	7	7	7	?
Country	Jap.	Jap.	Jap.	Jap.	Jap.	Jap.	Jap.	USA	USA	USA	Flor.
reference	1	1	1	1	1	1	1	2	2	2	3
biomass dry weight (Mg ha^{-1})											
stem	37.6	33.7	34.9	40.6	3.8	38.2	72.1	22.8	19.2	30.4	93.0
branch	7.8	6.9	6.6	6.9	0.4	4.1	9.3	6.9	7.5	10.1	7.5
foliage	11.7	10.5	10.6	12.2	1.9	8.7	17.6	8.9	7.5	10.1	5.2
root	*	*	*	*	*	*	*	*	*	*	*
total	57.1	51.1	52.1	59.7	6.1	51.0	99.0	38.6	34.2	50.6	105.7
NPP ($\text{Mg ha}^{-1}\text{yr}^{-1}$)											
stem	6.9	6.4	6.5	8.8	*	5.2	10.1	*	*	*	*
branch	*	*	*	*	*	*	*	*	*	*	*
foliage	*	*	*	*	*	*	*	*	*	*	*
root	*	*	*	*	*	*	*	*	*	*	*
total	*	*	*	*	*	*	*	*	*	*	*

References: 1: NPK fertilizer experiment, in Cannell 1982;
 2: McKee & Shoulders, in Cannell 1982;
 3: West et al., in Kimmins et al. 1985 (there was 5.7 Mg ha^{-1} undergrowth dry weight).

He distinguishes site indices from 22 to 34. The choice of the site indices shifts slowly from the mean volume increment at age 30 on the best site to the mean volume increment at age 15 on the worst site. The maximum of the current volume increment varies from 30.7 on the worst site to 66.7 $\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$ on the best site. These highest increments are usually achieved around an age of 10 years.

Unfortunately no biomass measurements were found for older stands in Brazil. Only volumes could be derived from the yield table of Schneider (1984).

Certain biomass compartments and allocation of the NPP to the compartments distinguished remain uncertain from these measurements. Only general averages for pine species were available. Thus biomass compartment turnover rate and litter fall had to be kept rather general, with averages for pine species.

According to Dixon et al. (1991) basic density of the slash pine wood is 540 kg m^{-3} . Cannell (1984) uses a figure of only 370 kg m^{-3} . The carbon amount in the stable humus under subtropical humid forest in South America is 88 Mg C ha^{-1} (Millemann & Boden 1986). Under tropical dry forest in South America this is 92 Mg C ha^{-1} .

8.5.3. Model input

The carbon dynamics of *P. elliottii* in Brazil were modelled for 10 consecutive rotations of 30 years on varying sites of good, moderate and limited fertility. The yield table of Schneider (1984) for *P. elliottii* in Brazil on three site classes was used. For current increments, see Appendix D4. Thinnings are carried out at ages 10, 15, 20 and 25 years. For good, moderate and limited sites, the mean annual volume increments amount to 34.8, 26.0, and 17.2 $\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$ respectively. Allocation of the NPP to the biomass compartments distinguished was kept the same as for the other pine species, but adapted to the different growth dynamics of slash pine (see Appendix E).

The basic density of the wood was set at 370 kg m^{-3} . Turnover rates of branches, foliage and roots were kept the same as for the other pine species, with turnover times for branches, foliage and roots of 20, 3.3 and 14 years respectively (see Appendix F). Most of the wood from thinnings at younger ages is used as paper; later, more packing and particle board wood is produced (see Appendix I4).

The humification factor, litter residence time and stable humus residence time on the good site were set at respectively 5%, 3 and 200 years, in agreement with the other pine species (see Appendix H). The initial values for soil stable humus on the good, moderate and limited sites were set at 150, 130 and 110 Mg ha^{-1} dry matter respectively.

8.5.4. Results and discussion

The results of the modelling of carbon sequestration in *Pinus elliottii* plantations in Brazil are displayed in Figure 8.8 and presented in Table 8.8. Using Appendix J, relative site class as used here can be determined for a particular field situation, in order to estimate the potential for carbon storage.

Table 8.8: Comparison of carbon stocks and fluxes for *Pinus elliottii* plantations in Brazil on three site classes.

- 1) Total stock of carbon at the end of the rotation in biomass and products (Mg C ha^{-1});
- 2) Total stock of carbon at the end of the rotation in the soil organic matter i.e. litter, dead wood and stable humus (Mg C ha^{-1});
- 3) Total stock of carbon at the end of the rotation in biomass, forest products and in dead organic material on or in the soil (Mg C ha^{-1});
- 4) Long-term average stock of carbon in the biomass and the forest products (Mg C ha^{-1});
- 5) Long-term average stock of carbon in the forest products (Mg C ha^{-1});
- 6) Long-term average stock of carbon in the soil organic matter (Mg C ha^{-1});
- 7) Long-term average stock of carbon in the total system of biomass, products and soil organic matter (Mg C ha^{-1});
- 8) Net accumulated amount of carbon over the first 100 years after afforestation (Mg C ha^{-1});
- 9) Average net annual carbon flux at the end of the first rotation ($\text{Mg C ha}^{-1}\text{yr}^{-1}$).

	1	2	3	4	5	6	7	8	9
good site class ($I_m = 34.8 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$)	139	95	234	143	56	105	248	175	4.88
moderate site class ($I_m = 26.0 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$)	112	80	193	111	44	80	191	115	3.88
limited site class ($I_m = 17.2 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$)	81	67	148	75	30	63	138	62	2.76

Plantations of slash pine are very good carbon storers when only the net annual carbon flux during the first rotation is regarded. The long-term average stock of carbon in the biomass and products is reasonable, assuming that the fertility of the soil can be maintained. On a moderate site, the net carbon flux during the first rotation is $3.88 \text{ Mg C ha}^{-1}\text{yr}^{-1}$, and the long-term average carbon stock in the biomass and products is 111 Mg C ha^{-1} .

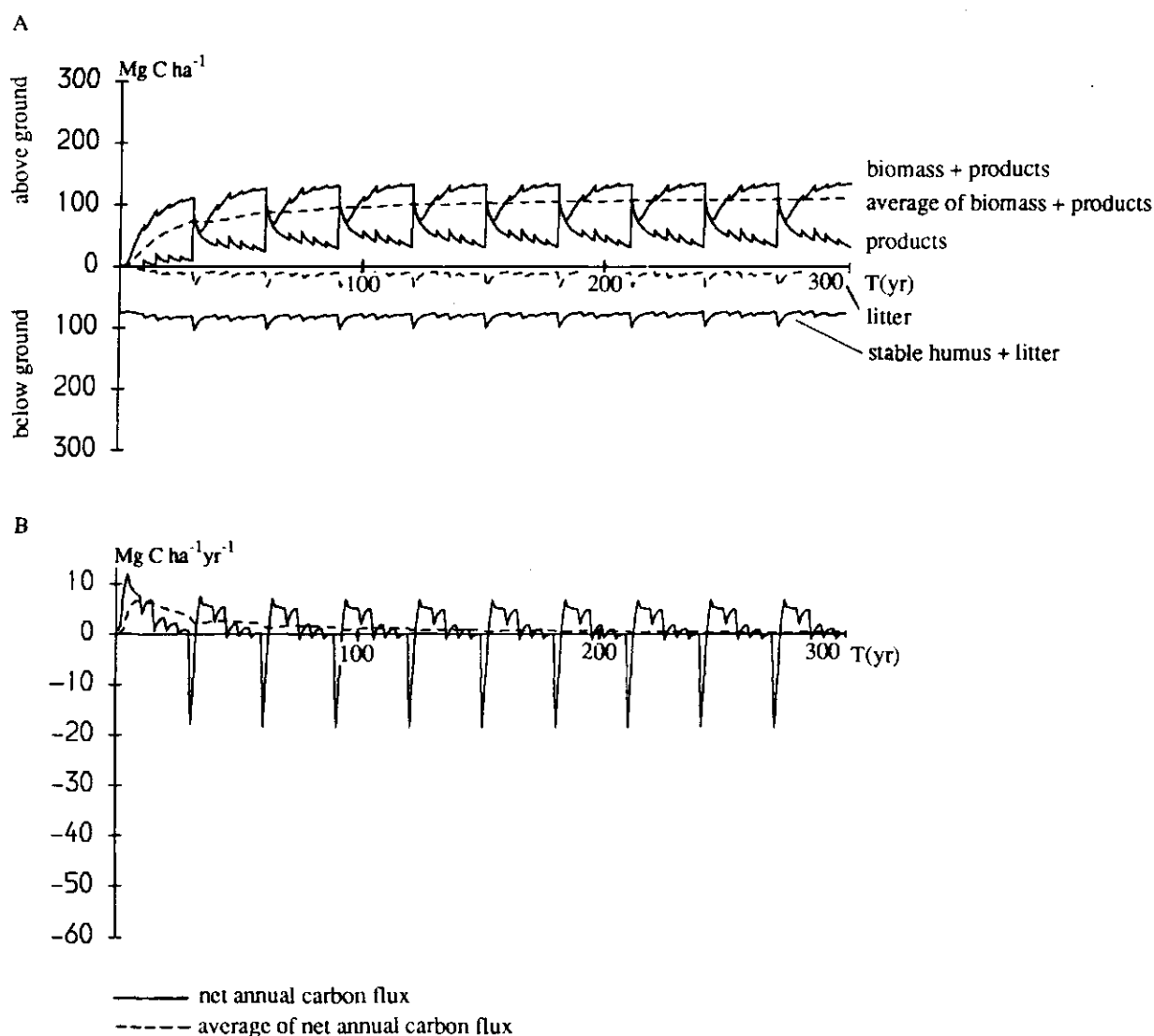


Fig. 8.8 A: Carbon stocks in biomass, forest products and soil organic matter for *Pinus elliottii* plantations on moderate sites in a rotation of 30 years ($I_m = 26.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$)
 B: Carbon fluxes both on an annual basis and as a running mean (dashed line) ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$).

Although a reliable yield table could be used, it remains rather uncertain whether these growth rates can be achieved in the long-term. If the amounts of Ca and Mg in the soil are limited, depletion of the fertility may easily occur after a couple of rotations in these intensive systems (Van Goor 1985). Because adequately fertile soils are not very widespread, it is likely that the highest yields can only be achieved on a limited number of sites. Further depletion of the amount of nutrients on the limited sites may easily result in failing plantations, with erosion and socio-economic setbacks following them.

In the modelling it is assumed that the initial amount of stable humus is approximately the same as under the natural forest and that the amount can be maintained during the rotations. This is critical, however, and the amount of stable humus can easily occur decline under these plantations. Ballard & Gessel (1983) state that stocks of forest floor nutrients were strongly reduced under slash pine plantations when the logging slash was windrowed. If minimal pre-planting site preparations were carried out, the effects on physical, chemical and biological soil properties were negligible.

Dixon et al. (1991) present a net annual storage rate of $13.7 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ during the first rotation for 10-year rotations of slash pine in Brazil with a mean volume increment of $29 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. This can only be achieved during this very short period with much higher planting densities, which result in higher juvenile growth rates. The long-term productivity of the site is at stake, however, in these very intensive systems.

Concluding it can be stated that *Pinus elliottii* (slash pine) plantations in Brazil serve mainly as quick carbon storers in the short-term. A plantation on a moderate site shows a net annual carbon flux of $3.88 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ during the first rotation. The long-term average carbon stock in the biomass and products is considerable with 111 Mg C ha^{-1} .

9. CONCLUDING REMARKS

9.1. Carbon sequestration in forest ecosystems

A summmary of the carbon sequestering potential of the forest types on moderate sites is given in Table 9.1, and a graphical representation of the carbon stock at the end of the rotation on good sites is given in Figure 9.1.

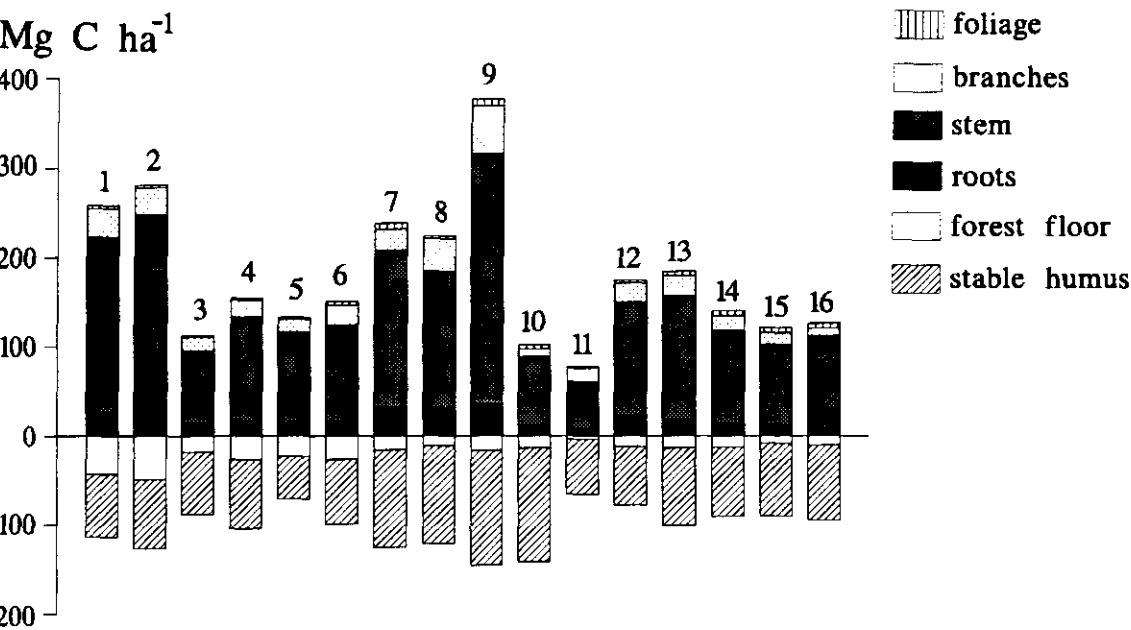


Fig. 9.1 Bar diagram showing the stocks of carbon in each compartment for all 16 forest types at the end of the rotation on good sites. (for legende see Figure S.1).

When comparing the individual forest types in Figure 9.1, it is clear that the carbon stocks in biomass and in soil organic matter at the end of a rotation may vary considerably between the forest types. Douglas fir in the Pacific northwest of America (type 9), shows very large stocks of carbon in the aboveground biomass, which are only approached in the selectively logged, lowland Dipterocarp rainforest (type 2). It is shown also that the stock of carbon at the end of the rotation (or cutting cycle) does not differ al that much when tropical rainforest is selectively logged, or when heavy logging is taking place (comparison of types 1 & 2, and 3 & 4). Other forest types which also contain sizeable stocks of carbon in the biomass at the end of a rotation are Norway spruce (type 7) and mixed oak/beech (type 8) stands in long rotations. Poplar in short rotation (type 11), and boreal spruce contain the smallest amount carbon at the end of a rotation.

The soil organic matter compartments, litter and stable humus, contain considerable amounts of carbon under each forest type. The largest stock is found under Douglas fir (type 9). Boreal spruce (type 10) is the only forest type for which the stock of soil carbon at the end of the rotation still exceeds the amount of carbon in the living biomass. In this case, the stock of carbon in the soil organic matter is the most important pool of carbon in the ecosystem. The large stock of carbon in the litter compartment of the tropical forest types (types 1 to 6), are caused by the natural mortality which is assumed to occur in these forest types. This causes considerable amounts of fallen, dead wood with a relatively long average residence time of decay of 10 years. In case average residence time is less, the resulting amount of litter will be less.

Table 9.1 Summarized presentation of carbon stocks and fluxes for the most important criteria for all 16 forest types, each on the *moderate site class*.

- 1: Long term average amount of carbon in the living biomass and the forest products (stems, branches, foliage, roots, undergrowth and products) (Mg C ha^{-1}).
- 2: Average net annual carbon flux over the first rotation ($\text{Mg C ha}^{-1}\text{yr}^{-1}$) (accumulation through photosynthesis minus decomposition of stable humus, litter, dead wood, logging slash and products).
- 3: Long-term average amount of carbon in the soil organic matter (ie. litter, dead wood and soil stable humus) (Mg C ha^{-1}).
- 4: Area technically suitable and socially available for this forest type, based on estimates by Winjum et al. (1992) after Howlett & Sargent (1991), Brown et al. (1992), Birdsey (1990) (10^6 ha).

Forest type:	1	2	3	4
1. Heavily logged evergreen rainforest	144	2.40	92	5.0
2.. Selectively logged evergr. rainforest	207	2.85	102	2.0
3. Heavily logged semi-evergreen rainforest	76	1.07	76	5.0
4. Selectively logged semi-evergr. rainforest	151	2.03	98	2.0
5. Afforestation of wasteland	121	1.69	67	30.0
6. Logged rainforest hampered by lianas	125	0.79	92	20.0
7. Norway spruce in central Europe	137	2.02	117	0.3
8. Mixed deciduous in central Europe	110	1.35	105	0.2
9. Douglas-fir in northwest USA	196	3.43	143	0.1
10. Norway spruce in boreal zone of Russia	53	1.03	139	30.0
11. Poplar on former agricultural land	62	2.23	75	0.2
12. Black locust on former agricultural land	111	3.35	84	0.1
13. Radiata pine in N. Zealand and Australia	126	4.54	97	0.3
14. Caribbean pine in Brazil and Venezuela	89	5.12	90	0.5
15. Loblolly pine in southeast USA	59	3.21	81	0.2
16. Slash pine in Brazil	111	3.88	80	0.3

Column 1 in Table 9.1 is the main criterion to evaluate the carbon sequestering potential of the investigated forest types, because this is the long-term (at $T = 300$ years) average amount which is permanently withdrawn from the atmosphere and stored in biomass and products. Since this is a long-term running average, it hardly varies anymore after 300 years. The long-term average is arbitrarily chosen at $T = 300$ years. From a trial run of 2400 years, using montane spruce on good sites, it appeared that the result after 300 years was

at 91% of the value which 2400 years. In Table 3.3, a value of 317 Mg C ha^{-1} , is given for the period 0 to 300 years, while this value increased to 348 Mg C ha^{-1} if the model was allowed to run for 2400 years.

The second criterion in Table 9.1 only applies to the first rotation, as net storage is negligible once the system has reached its equilibrium value. The third criterion refers to soil carbon only, and is of lesser importance when carbon storage after afforestation is considered, as this stock of carbon is built up partly during long-term soil formation. Only part the the soil carbon is directly associated with the developing forest ecosystem. Typically, the rate of carbon accumulation in soil organic matter is an order of magnitude less than the rate of accumulation in the living biomass. However, unlike the amount of carbon in the living biomass, the soil pool of carbon may continue to accumulate over longer periods of time.

The fourth column in Table 9.1 is added for evaluation of the possibilities for afforestation from point of view of land-use. A forest type may perform very well according to the long-term average stock of carbon, but when the available area for afforestation is limited, the contribution to the overall carbon sequestration of carbon is limited from technical point of view.

From Table 9.1 it is clear that certain forest types perform well according to the criterion net annual carbon flux, but score less on average amount of carbon in the biomass and in wood products. It is important to distinguish between these two criteria. Fast growing short rotation plantations usually show high net annual carbon fluxes during a short period, but they soon reach their equilibrium biomass, which tends to be rather low because of the short time available for biomass build-up. Thus, on average, the flux of carbon to the vegetation approaches zero relatively soon. Silvicultural systems with long rotations, or tropical selective cutting systems, usually build up large amounts of biomass and produce wood of a high quality, although their net flux over the first rotation may be only modest. In the long run, this results in high stocks of carbon in biomass and products.

From column 1 in Table 9.1 it is clear that the selectively logged tropical lowland evergreen rainforest stores the largest amount of carbon in the biomass and products (206 Mg C ha^{-1}). This is mainly due to the fact that at the end of a rotation only 50% of the biomass is harvested, while in a clearcut system (types 7 to 16), 100% of the biomass is harvested. This difference in management also explains why selectively logged rainforest performs best on average stocks, but not on carbon stocks at the end of a rotation (see Figure 9.1). It is also clear from these data that through a selective instead of a heavy logging system, the average stock of carbon can be increased substantially. The selectively logged evergreen forest contains on average 206 Mg C ha^{-1} , while the heavily logged evergreen forest contains on average 144 Mg C ha^{-1} . The evergreen forest in which no clearing and underplanting is carried out and which is hampered by lianes (type 6), contains on average only 125 Mg C ha^{-1} . It should be noted however, that the figure for selectively logged rainforest is still less than the stock of carbon in the virgin tropical rainforest on these sites (250 Mg C ha^{-1}). The selective logging system appears to be able to keep more carbon in the system of biomass and products, but any logging and

exploitation reduces the amount of carbon in the system.

Generally speaking, long rotation management systems outperform short rotation systems according to the criterion average stock of carbon in biomass and products. Douglas fir performs the best with 196 Mg C ha^{-1} , followed by montane spruce in Europe with 137 Mg C ha^{-1} . The 40 year rotation system with radiata pine performs however also very well with 126 Mg C ha^{-1} . The short rotation forest types outperform long rotation systems when net annual carbon flux during the first rotation is considered, although Douglas fir may perform well on both criteria. The highest net annual carbon flux is achieved with Caribbean pine in Brazil with a storage rate of $5.12 \text{ Mg C ha}^{-1} \text{ y}^{-1}$ during the first rotation. The slow growing boreal forest performs rather poorly on both criteria.

The long-term average stock of carbon in the soil organic matter is the largest under Douglas fir in the Pacific northwest of America (143 Mg C ha^{-1}) followed by the amount under boreal forests. Under boreal forest, the average stock of soil carbon exceeds by far the amount in the biomass and products.

Based on the main criterion for carbon storage in forest ecosystems, that is the long-term average amount of carbon in the biomass and products, it is concluded that selectively cut lowland evergreen tropical rainforest and Douglas fir forest in the Pacific northwest of America sequester most carbon. Both ecosystems may store on average some 200 Mg C ha^{-1} .

9.2. Uncertainties associated with carbon storage in forest ecosystems

Uncertainties in the outcome of the calculations as presented here may result from a number of different causes: i) uncertainties in the input parameters caused by measurement error or lack of sufficiently detailed information; ii) uncertainties in the correctness of the simulation model used (the model may contain wrong assumptions, and programming errors may lead to wrong model results); iii) uncertainties associated with predicting forest growth and forest development under future site conditions.

The first uncertainty can to some extent be dealt with using formal sensitivity and uncertainty analysis (Jansen et al. 1992a & 1992b, Van de Voet & Mohren 1993). Such an uncertainty analysis using Monte Carlo sampling of the parameter space, specified from information on the variation in parameter estimates, was carried out for the model CO2FIX, and the results will be discussed in the following sections. The second uncertainty can only be evaluated by looking at the model formulations in detail; in fact, this uncertainty has to be dealt with by the authors of the model, when outlining the potential and limitations of a particular model. This will not be dealt with any further here. The third uncertainty is directly associated with the use of a dynamic model, in which a limited number of assumptions is brought together, for predictions into the future. The predictions made in this report concerning carbon sequestering and total carbon storage in forest ecosystems rely on the validity of several assumptions, e.g. concerning the stability of site conditions for growth. The simulation runs for periods of 300 years assume that the site conditions

remain the same as in the initial situation throughout the whole period. Thus, it is assumed that site productivity is maintained (also under short rotation pine plantations), that soil acidification or global climate change does not interfere with the predictions, and that no major disturbances disrupt the ecosystem. The validity of some of these assumptions can be disputed, e.g. when severe soil acidification is expected to lead to large scale changes in growing conditions, if allowed to continue (Heij et al. 1991, Mohren 1991). At present, a number of recent publications indicate that the growth rates over large areas in western Europe are higher than previously expected (e.g. Kauppi et al. 1992). These phenomena have not been accounted for in the analysis as presented here, but may turn out to be highly relevant for the application of the results reported in this report.

The outcome of the uncertainty analysis carried out with the model CO2FIX, together with an extended account of the methods used, is described in detail in Appendix K. As the main criterion for the uncertainty analysis is taken the average amount of carbon stored in the total ecosystem (including the soil) at the end of the 300 year simulation period. In general, the results indicate that the model is highly sensitive to the uncertainty associated with turnover of soil organic matter (humification and decomposition coefficients used), to elementary parameter values such as basic density of the wood, and the carbon content of biomass dry matter, and to the tabulated growth rates that are used to force the dynamics of the model.

The following interpretation can be given to these results: **Concerning soil organic matter turnover:** It has been stated already in the introduction that it is uncertain to what extent soil organic matter will increase or decrease following changes in land-use, e.g. through afforestation. It was decided here to concentrate on carbon in the live biomass, as this pool builds up rather rapidly compared to soil organic matter, and also because reliable data on growth rates and biomass amounts were available. At the same time, it is clear from the results that carbon in forest soils present a significant storage pool that may be worth exploring. Therefore the uncertainty associated with soil carbon is recognized, and both the size and relevance of the pool, and the sensitivity of the model results to uncertainties associated with lack of understanding and lack of detailed data, warrant further research in this area. The consequence of this for the use of the results presented in this report, is that evaluation and comparison of forest types is best done using data of carbon in the biomass, as large uncertainties are associated with soil carbon results. **Concerning elementary parameter values (constants):** It is clear from the model formulations that any uncertainty in e.g. basic density or carbon content of the biomass are linearly related to uncertainties in the model outcome, as the criteria as used here (total carbon in the system at the end of the simulation period) is mainly determined by the amount of wood, with wood volume in $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$ as the basic entry. This type of uncertainty is easily reduced by using site specific or regional data that can be obtained either in the laboratory or from technological literature (e.g. Laming et al., 1978, or the local equivalent).

Concerning growth rates used as forcing functions: This result was to be expected from the basic assumptions underlying the approach and subsequently also underlying the simulation model. This can be interpreted as an

indication that under the assumptions used here, stem volume increment indeed determines to a large extent how much carbon will be stored in the biomass of a forest ecosystem. Obviously, any decrease or increase in growth rate will have direct consequences for carbon fluxes and total carbon storage. As mentioned in earlier Chapters, stem volume increment rates are quite well known for the major economic tree species in temperate forest, but are much more uncertain for tropical trees and forests. As the uncertainty analysis described in Appendix K was carried out for a Central European Norway spruce stand, it is not unlikely that the result will be quite different when uncertainties of model inputs for tropical forests would have been used. Most likely, in case of tropical forests, the contribution of growth rate in the uncertainty of the model outcome is much larger than for Norway spruce. In case of growth rates, there is an additional uncertainty comparable to the uncertainty associated with predictions into the future, and that is that for a particular site, the expected growth rate has to be known or estimated. This cannot be dealt with here, but it is relevant when applying the results of the calculations here to a particular site.

Concerning the uncertainty analysis it is worth noting which input variables apparently do not lead to major uncertainties in the model outcome. As it turns out here, the model is only little sensitive to the uncertainties in the allocation coefficients used for estimating needle, branch, and root growth from stem volume increment. From this it can be concluded that although there are large uncertainties about the exact value of carbon in biomass components other than stems, these uncertainties do not blur the results from the simulations as apparently the contribution of these biomass components to the final result is only minor. The same holds for values used for average product life-time: the model appears to be relatively insensitive to product use and product decomposition (a conclusion also drawn by Dewar & Cannell, 1992).

9.3. Possibilities for increasing the potential for carbon sequestering

Marland (1988) and Cooper (1983) suggest that not only planting trees, but also managing forests more intensively could result in faster growth and increased rates of carbon sequestration. Schroeder (1991) examined this option more closely and analyzed the impact of three management practices on carbon sequestration: thinning, fertilization and control of competing vegetation. He concluded that the stock of carbon in the standing biomass at 35 year decreased through thinning, that carbon storage may increase through fertilization, mainly on the poorer sites, and that control of competing ground vegetation increased the growth of the stand and thus the carbon storage.

Table 9.2 *Comparison of results of carbon sequestering potential for montane spruce in Europe on good sites, when managed in rotations of 120 years or 80 years and for poplar on moderate sites when managed in rotations of 45 or 20 years.*

	<ol style="list-style-type: none"> 1) Total stock of carbon at the end of the rotation in biomass and products (Mg C ha^{-1}); 2) Total stock of carbon at the end of the rotation in the soil organic matter i.e. litter, dead wood and stable humus (Mg C ha^{-1}); 3) Total stock of carbon at the end of the rotation in biomass, forest products and in dead organic material on or in the soil (Mg C ha^{-1}); 4) Long-term average stock of carbon in the biomass and the forest products (Mg C ha^{-1}); 5) Long-term average stock of carbon in the forest products (Mg C ha^{-1}); 6) Long-term average stock of carbon in the soil organic matter (Mg C ha^{-1}); 7) Long-term average stock of carbon in the total system of biomass, products and soil organic matter (Mg C ha^{-1}); 8) Net accumulated amount of carbon over the first 100 years after afforestation (Mg C ha^{-1}); 9) Average net annual carbon flux at the end of the first rotation ($\text{Mg C ha}^{-1}\text{yr}^{-1}$). 								
	1	2	3	4	5	6	7	8	9
spruce; 120-year rot.	272	125	397	191	48	126	317	274	2.37
spruce; 80-year rot.	241	122	363	155	39	123	278	128	3.13
poplar; 45-year rot.	93	62	155	62	15	75	137	49	2.23
poplar; 20-year rot.	104	59	163	60	25	84	144	139	5.41

Table 9.2 presents the results of shortening the rotation length of montane spruce in Europe from 120 to 80 years, together with the result of shortening the rotation length of poplar from 45 to 20 years, as has been done in Chapter 7. Shortening the rotation of Norway spruce resulted in a decrease of the stock of carbon at the end of the rotation in biomass and products from 272 to 241 Mg C ha^{-1} . The long-term average stock in biomass and products also decreased from 191 to 155 Mg C ha^{-1} . Only the net annual flux over the first rotation increased considerable, but this rate now only applies to a period of 80 years. Shortening the rotation of poplar from 45 to 20 years, also included the application of a denser planting space and in the application of a different management scheme. In the 45-year rotation one heavy thinning is applied, while no thinning is applied in the 20-year rotation. Therefore the stock of carbon in biomass and products at the end of the rotation is higher in the 20-year rotation system. The long-term average stock is approximately the same in the two systems. The net annual flux over the first rotation increased considerable when a 20-year rotation was applied.

Intensifying the management of stands and thus assuming a larger proportion of saw wood from the final cut, resulted only in minor changes in the long-term stock of carbon the forest products in all forest types, mainly because carbon in forest products makes up only a moderate fraction of total carbon removed from the atmosphere (20-30%). In conclusion, it appears that the options for increasing carbon storage through forest management of existing stands has only limited perspective, compared to the gain involved in changing to e.g. mixed deciduous stands that may achieve a high equilibrium biomass. Growth rates and biomass in equilibrium conditions are strongly determined by overall site factors such as climate, water availability and soil fertility, and can only marginally be augmented through forest management.

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APPENDICES

APPENDIX A: project members and review board

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APPENDIX B: Definitions.

- Afforestation:** planting of tree saplings and thus establishment of forest on land that was previously not used as forest.
- Assimilate allocation:** assimilates produced in the tree foliage during photosynthesis are divided (allocated) in certain ratios over roots, stem, branches and foliage and used for respiration or production of organic material.
- Basic wood density:** density of wood expressed as weight of dry wood per original fresh volume. Expressed in kg m^{-3} .
- Biomass:** all the organic material in a certain ecosystem produced by autotrophic plants, expressed in dry weight per unit of area, usually Mg ha^{-1} ($= 10^6 \text{ g ha}^{-1}$; $= \text{ton ha}^{-1}$). Sometimes a distinction is made between living biomass (the living trees and undergrowth) and dead biomass (dead wood, litter and stable humus). Living biomass is the same as standing biomass.
- Biomass compartments:** the biomass of forests and trees consists of different parts (organs) such as foliage, branches, stems, roots, undergrowth, forest floor, litter and stable humus.
- Board wood:** a certain kind of use of the stem wood of trees in which the wood is chipped and pressed into boards, soft woods of a bad quality are usually used.
- Carbon sequestering potential:** the amount of carbon that can be stored, in this case in a certain forest type including living biomass, forest products and soil organic matter. The carbon sequestering potential of a forest type can be evaluated by a set of criteria and is expressed in Mg C ha^{-1} ($= 10^6 \text{ g C ha}^{-1}$; $= \text{ton C ha}^{-1}$) or $\text{Mg C ha}^{-1} \text{ yr}^{-1}$.
- Carbon sequestration:** this term is better than carbon storage. The withdrawal of carbon dioxide from the atmosphere in this case through photosynthesis and storage of the carbon as organic matter in compartments like the stem, branches, foliage, roots, forest products, litter and stable humus.
- Carbon stock:** the amount of carbon or content of carbon in a certain forest type, biomass compartment, forest product or soil organic matter compartment at a certain time or time interval. Expressed in Mg C ha^{-1} .
- Current annual volume increment (CAI):** increase of all tree volumes of a certain stand in the year of recording, expressed in $\text{m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$.
- Decomposition:** dead organic material which accumulates on the mineral soil in a litter layer or forest floor, is broken down by soil fauna and fungi at a certain rate and used for their respiration. Carbon in the organic matter is oxidized to carbon dioxide. The rate at which this process takes place is mainly determined by the quality of the soil and the climate. Expressed as the fraction of the litter that decomposes each year.
- Dead wood:** organic matter in stem wood of dead trees as a result of natural mortality in unmanaged natural forests. Stands thinned regularly contain hardly any dead wood. Dead wood is part of the litter compartment and can be part of the forest floor.
- Energy wood:** a certain kind of use of the stem wood of trees in which the wood is burned either for warmth or to cook or to produce electricity. Poor quality wood is usually used.

Final cut: at the end of a rotation when the mean annual increment starts to decline, all the trees of a certain stand are harvested. The branches and foliage are usually left on the site, which is subsequently reforested.

Forest floor: also called ect-organic layers. Organic matter on top of the mineral soil which has accumulated here because the rate of litter fall exceeds the rate of decomposition. The thickness of the forest floor can vary from less than 1 cm up to 50 cm.

Forest products: harvested wood is used in some kind of wood product, varying from energy to high quality sawn timber. In this case only woody products are included but in general a wide range of products is included (e.g. fruits, nuts and medicines). The original area of production as unit of surface area.

Forest type: class of forests which are comparable in terms of tree species, region and management.

Forestry: management of forests to maintain the forest and to achieve sustainable yields e.g. wood, nature conservation, scenery, recreation and conservation of groundwater reserves.

Gross Primary Production (GPP): the total production of assimilates during photosynthesis, part of which is used for respiration of the varying biomass compartments and another part is used for build-up of organic matter.

Humification: a small part of the litter in the forest floor is degraded to stable humus and usually incorporated into the mineral soil by activity of soil fauna.

Litter: all kinds of dead organic material either standing in the forest, in the forest floor or as dead roots in the mineral soil. Litter thus includes a wider set of dead organic materials than for example "forest floor".

Logging slash: organic material like branches, minor stems and foliage which is left at a site to decompose after a thinning or a final cut. It is also part of the litter compartment and of the forest floor compartment.

Mean annual volume increment (MAI): the average of the current volume increment to the time of recording. Expressed in $\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$.

Net annual carbon flux: the net uptake or emission of carbon through withdrawal of carbon from the atmosphere for photosynthesis minus emission of carbon through respiration, decomposition of litter, logging slash, stable humus and forest products.

Net Ecosystem Production: total annual increase or decrease of the biomass of an ecosystem, expressed in $\text{Mg dry weight ha}^{-1}$.

Net Primary Production (NPP): total annual production of living biomass, expressed in $\text{Mg dry weight ha}^{-1}$. Usually measured as the sum of litter fall and the increase of the standing biomass.

Packing wood: a certain kind of use of the stem wood of trees in which the wood is used to produce crates and pallets for the packing industry, usually softwoods of a reasonable sawing quality are used.

Paper wood: a certain kind of use of the stem wood of trees in which the wood is used to produce pulp for paper; softwoods of poor quality are usually used.

Photosynthesis: a process in green leaves or needles through which carbon dioxide from the atmosphere and water together with energy from sunlight are transformed into sugars, which can be used for respiration and build-up of organic matter.

Production level: the term site class is preferable. A way to distinguish sites according to the maximum production of wood of a certain species that can be reached. Usually used in an absolute way.

- Reforestation: establishment of forest on a site on which the full-grown stand was cut or on a site which was covered with forest in the near past.
- Residence time: Characteristic time-coefficient used in first order decay functions describing decomposition processes of the type $dW/dt = 1/k \times W$ with k the residence time in years, W the state variable (e.g. carbon in litter, carbon in a particular product category, in Mg ha^{-1}) and dW/dt the decomposition rate in $\text{Mg ha}^{-1}\text{yr}^{-1}$.
- Rotation: period in which the cycle of establishment to final cut of the stand is gone through.
- Silviculture: the management of forests to obtain the desired goals.
- Site: the place at which a tree grows including all the site factors which influence the growth and activity of a tree such as precipitation, temperature, soil fertility, moisture availability and radiation.
- Site class: a degree which presents the quality of a site for a certain tree species. An absolute site class uses the maximum of the mean annual volume increment to distinguish the class (expressed in $\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$), while the relative site class uses the Roman numeral I to indicate the best site class and subsequent numerals for sites of inferior quality.
- Soil organic matter: (or: soil organic material) a compartment which includes litter, dead wood and stable humus. Standing dead wood is also included, but living roots, although in the soil, are not included.
- Stable humus: litter which has been degraded to humus with a long residence time and which is incorporated into the mineral soil. The amount of stable humus mainly depends on climate and soil type.
- Yield table: a table valid for stands, usually of one species and one age, divided into site classes in which basal area, stand volume, volume increments and thinning volumes at certain ages are presented. A certain thinning regime is simulated.

APPENDIX C: Basic wood density for the main species considered.

Taken from Laming et al. (1978), Dixon et al. (1991), USDA Forest Service (1987), Cannell (1984), Schroeder (1992), Dewar and Cannell (1992).

tree species (scientific name)	tree species (common name)	Basic density (dry weight per fresh volume, in kg m ⁻³)
Shorea sp.	sal	560
Albizia falcataria	*	320
Picea abies	Norway spruce	410
Quercus robur	pedunculate oak	635
Fagus sylvatica	European beech	560
Pseudotsuga menziesii	Douglas-fir	450
Populus x euramericana	poplar hybrids	340
Robinia pseudoacacia	black locust	630
Pinus radiata	radiata pine	400
Pinus caribaea	Caribbean pine	460
Pinus taeda	loblolly pine	460
Pinus elliottii	slash pine	370

Appendix D: Current volume increments ($\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$) used as input for each forest type.

Table D1:

logg I, II, III:	regrowing heavily logged evergreen tropical lowland dipterocarp forest on good, moderate, and limited sites respectively;
logg IV:	regrowing semi-evergreen tropical lowland rainforest on moderate sites.
lianas:	regrowing evergreen tropical lowland rainforest on moderate sites, hampered by the vigorous growth of lianas.
albdipt:	Albizia as a pioneer on wasteland, heavily thinned after 10 years and underplanted with Dipterocarps.
selcut I, II, III:	regrowing selectively logged evergreen tropical lowland dipterocarp rainforest on good, moderate and limited sites respectively;
selcut IV:	regrowing selectively logged semi-evergreen tropical lowland rainforest on moderate sites.

forest type:

age	loggI	loggII	loggIII	loggIV	age	lianes	age	albdipt
0	3.0	2.0	1.0	0.2	0	2.0	0	0.25
1	3.5	2.5	1.5	0.3	1	2.5	2	3.5
20	20.0	12.0	10.0	5.0	10	4.0	6	15.5
30	25.0	21.0	16.0	11.0	20	7.0	10	16.0
40	24.0	21.0	17.0	11.0	30	9.0	11	8.0
70	18.0	13.0	10.5	7.0	40	10.0	20	12.0
					70	10.0	40	10.0
					90	9.5	60	9.0
					110	9.0	90	8.0
					140	8.0		

forest type:

age	selcutI	selcutII	selcutIII	selcutIV
0	4.0	3.0	2.0	1.0
1	6.0	4.0	3.0	2.0
5	16.0	15.0	14.0	12.0
10	23.0	19.0	16.0	14.0
40	25.0	18.0	14.0	12.0
70	19.0	15.0	12.0	10.0

Table D2:

spr I,II,III:	Norway spruce in Central Europe on three site classes.
dec I,II,III:	Mixed deciduous stands in central Europe on three site classes.
bor I,II,III:	Norway spruce in the Boreonemoral zone on three site classes.
dgl I,II,III:	Douglas-fir stands in the Pacific Northwest of the USA on three site classes.

forest type:

age	sprI	sprII	sprIII	decI	decII	decIII	borI	borII	borIII	dglI	dglII	dglIII
10	6.0		0.2	2.7	1.0	0.4				8.0	3.0	2.0
15				5.0	1.3	0.8				16.0	5.7	4.0
20	17.2	2.4	1.0	5.7	1.8	1.4	1.6	0.8	0.5	21.0	13.6	7.8
25	19.2	7.0	1.6	6.0	2.5	1.6	2.8	1.3	0.9	25.0	18.5	12.4
30	19.4	9.8	2.8	6.5	3.0	2.0	5.0	2.4	1.4	25.4	20.3	15.0
35	19.4	12.4	4.4				6.7	4.0	2.0	25.0	20.8	15.8
40	19.1	14.4	6.4	7.1	4.0	2.5	7.6	5.7	2.8	24.3	20.6	16.1
45	18.6	15.4	7.6				8.4	6.4	3.8	23.7	19.6	15.8
50	18.1	14.8	8.6	8.0	5.3	3.2	8.7	7.1	5.0	22.9	19.0	15.4
55	17.4	14.0	9.2				9.0	7.4	5.7	22.6	18.5	15.0
60	17.0	13.6	9.2	9.0	7.0	5.0	8.9	7.5	6.0	21.8	19.0	14.6
65	16.4	13.0	9.0				8.8	7.4	6.0	20.9	17.8	13.9
70	15.8	12.2	8.8	9.6	7.7	6.1	8.6	7.3	5.7	20.5	17.1	14.4
75	15.2	11.8	8.6				8.4	7.1	5.4	20.1	16.3	13.6
80	14.6	10.8	8.4	9.9	7.9	6.3	8.1	6.8	4.9	19.4	17.5	12.9
85	14.4	10.6	8.2				7.7	6.4	4.5	19.0	16.1	12.2
90	13.8	10.0	8.0	9.8	7.6	6.0	7.3	6.0	4.1	18.5	15.1	12.7
95	13.2	9.6	7.8				6.9	5.6	3.8	18.0	14.2	12.0
100	12.6	9.4	7.6	9.8	7.2	5.6	6.5	5.1	3.5	17.5	14.8	11.2
105	12.1	9.2	7.0									
110	11.6	8.4	6.2	9.8	6.8	5.2						
115	11.0	8.2	5.6									
120	10.6	8.0	4.8	9.7	6.4	4.9						
125												
130				9.6	6.1	4.7						
135												
140				9.4	6.0	4.5						
145												
150				9.2	5.9	4.3						

Table D3:	
pop I,II,III:	Poplar on former agricultural land of three site classes in Europe.
pop (20 y):	Poplar on moderate sites in Europe in a rotation of 20 years.
rob I,II,III:	Robinia on former agricultural land of three site classes in Europe.
prad I,II,III:	Industrial pine plantation of <i>P. radiata</i> in New Zealand/ Australia on three site classes.

forest type:										
<hr/>										
age	popI	popII	popIII	pop(20 y)	robI	robII	robIII	pradI	pradII	pradIII
<hr/>										
5	4.5	2.7	0.6	4.7				23.0	15.0	12.0
10	20.9	12.6	4.7	21.5	9.0	5.2	2.4	40.0	31.0	23.0
15	33.5	20.7	8.1	35.2	12.0	9.4	5.2	38.0	32.0	24.6
20	22.2	22.9	9.2	38.9	13.0	9.6	6.4	34.6	29.4	23.1
25	20.3	12.7	8.6		13.5	9.8	6.6	31.0	27.0	22.2
30	10.6	10.6	7.2		14.0	10.8	7.2	25.9	24.1	21.0
35	8.2	8.2	5.6		15.0	11.2	7.6	16.5	16.0	12.0
40	6.1	6.1	4.2		17.0	12.4	8.4	10.0	8.0	5.0
45	4.4	5.1	3.0		16.3	12.6	9.0			
50					15.0	12.8	10.0	8.5	6.5	3.5

Table D4:

pcar I,II,III: Industrial pine plantation of *P. caribaea* in Brazil/Venezuela on three site classes.

ptae I,II,III: Industrial pine plantation of *P. taeda* in southeast USA on three site classes.

pell I,II,III: Industrial pine plantation of *P. elliottii* in Brazil on three site classes.

forest type:

age	pcar-I	pcar-II	pcar-III	ptae-I	ptae-II	ptae-III	pell-I	pell-II	pell-III
5	18.0	15.0	5.0	4.5	3.5	2.5	60.7	43.6	11.6
10	32.0	26.0	20.0	14.0	10.1	6.3	55.5	40.6	29.0
15	34.3	28.3	22.3	19.0	14.0	9.0	44.3	35.0	27.0
20	27.3	23.3	17.3	18.5	13.6	8.7	28.8	23.2	17.0
25	18.0	15.0	9.0	16.5	12.2	7.6	17.6	15.5	11.5
30				12.6	9.6	6.6	12.0	9.7	5.8

APPENDIX E: Assimilate allocation during stand development, relative to stem dry weight increment.

Forest type:

1 to 6.	age:	0	10	20	30	40	50	60	70	80	90
	foliage	0.7	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5
	branches	0.6	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5
	roots	0.7	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5
7.	stand age	0	10	20	30	40	60	80	100	150	999
	foliage	1.0	1.0	0.75	0.65	0.65	0.7	0.75	0.85	1.0	1.2
	branches	1.0	0.4	0.25	0.23	0.3	0.35	0.5	0.6	0.65	0.7
	roots	1.0	0.8	0.6	0.6	0.65	0.8	1.0	1.2	1.4	1.6
8.	stand age	0	10	30	60	80	100	120	150	200	999
	foliage	2.5	2.0	1.5	0.8	1.0	1.0	1.0	1.2	1.3	1.4
	branches	1.5	1.2	0.7	0.4	0.3	0.4	0.6	0.7	0.8	0.9
	roots	2.0	1.5	0.8	0.5	0.4	0.5	0.55	0.7	0.8	0.9
9.	stand age	0	10	20	30	40	60	80	100	150	999
	foliage	1.0	0.8	0.6	0.4	0.4	0.5	0.7	1.0	1.2	1.2
	branches	1.0	0.4	0.25	0.11	0.08	0.1	0.2	0.3	0.4	0.5
	roots	1.0	0.6	0.4	0.4	0.5	0.5	0.6	0.6	0.6	0.6
10.	stand age	0	10	20	30	40	60	80	100	150	999
	foliage	1.0	1.0	0.75	0.65	0.65	0.65	0.7	0.8	1.0	1.2
	branches	1.0	0.4	0.25	0.23	0.22	0.21	0.2	0.2	0.2	0.3
	roots	1.0	0.9	0.8	0.6	0.6	0.5	0.5	0.5	0.5	0.5
11.	stand age	0	5	10	20	30	40	50	60	80	999
	foliage	2.5	1.0	0.3	0.5	0.8	0.9	1.2	1.4	1.6	1.8
	branches	1.5	0.8	0.2	0.35	0.4	0.5	0.5	0.6	0.7	0.9
	roots	2.0	0.8	0.1	0.3	0.35	0.4	0.5	0.6	0.7	0.9
12.	stand age	0	5	10	20	30	40	50	60	80	999
	foliage	2.5	1.0	0.6	0.45	0.5	0.55	0.6	0.65	0.7	1.4
	branches	1.5	0.8	0.4	0.3	0.2	0.2	0.3	0.4	0.5	0.9
	roots	2.0	0.8	0.45	0.4	0.3	0.3	0.4	0.5	0.6	0.9

13.	stand age	0	6	10	14	18	22	25	30	40	50
	foliage	0.8	0.6	0.2	0.15	0.15	0.2	0.25	0.3	0.6	0.8
	branches	0.8	0.5	0.2	0.15	0.15	0.2	0.3	0.4	0.7	0.9
	roots	0.9	0.6	0.3	0.25	0.25	0.3	0.4	0.6	0.8	1.0
14.	stand age	0	6	10	14	18	22	25	30	40	50
	foliage	0.8	0.4	0.2	0.15	0.15	0.2	0.25	0.3	0.6	0.8
	branches	0.8	0.5	0.2	0.15	0.15	0.2	0.3	0.4	0.7	0.9
	roots	0.9	0.6	0.3	0.25	0.25	0.3	0.4	0.6	0.8	1.0
15.	stand age	0	2	4	6	8	18	20	22	25	30
	foliage	0.8	0.7	0.6	0.5	0.15	0.15	0.2	0.3	0.6	0.8
	branches	0.8	0.7	0.6	0.5	0.15	0.15	0.2	0.3	0.6	0.8
	roots	0.9	0.7	0.6	0.5	0.25	0.25	0.3	0.4	0.7	0.9
16.	stand age	0	6	10	14	18	22	25	30	40	50
	foliage	0.5	0.2	0.1	0.2	0.3	0.4	0.5	0.8	0.9	1.0
	branches	0.6	0.15	0.05	0.10	0.12	0.15	0.17	0.2	0.22	0.3
	roots	0.6	0.15	0.05	0.1	0.12	0.15	0.17	0.2	0.22	0.3

APPENDIX F: Turnover rates of biomass compartments (yr⁻¹):

forest type:	foliage	branches	roots
1. heavily logged evergreen rainforest	0.5	0.05	0.06
2. selectively logged evergreen rainforest	0.5	0.05	0.06
3. heavily logged semi-evergreen rainforest	0.5	0.05	0.06
4. selectively logged semi-evergreen rainf.	0.5	0.05	0.06
5. Albizia + Dipterocarps on wasteland	0.5	0.05	0.06
6. heavily logged evergreen with lianas	0.5	0.05	0.06
7. Spruce in montane Europe	0.3	0.05	0.10
8. Mixed deciduous in montane Europe	1.0	0.025	0.04
9. Douglas-fir in Pacific Northwest of USA	0.3	0.03	0.10
10. Spruce in Boreonemoral zone of Russia	0.3	0.03	0.07
11. Hybrid poplar on former agricultural land	1.0	0.06	0.1
12. Black locust on former agricultural land	1.0	0.04	0.07
13. Radiata pine in N. Zealand and Australia	0.3	0.05	0.07
14. Caribbean pine in Brazil and Venezuela	0.3	0.05	0.07
15. Loblolly pine in southeast of USA	0.3	0.05	0.07
16. Slash pine in Brazil	0.3	0.05	0.07

APPENDIX G: Average residence times (years) of wood products.

Energy wood	Paper wood	Packing wood	Particle Board	Sawn timber
<hr/>	<hr/>	<hr/>	<hr/>	<hr/>
1	2	3	20	35

APPENDIX H: Average residence times of dead wood (on the forest floor), litter and stable humus, and humification factors, in various regions.

	site class	residence time dead wood (yr)	humific. factor	residence time litter (yr)	residence time stable humus (yr)
evergreen rain-forest	I	10	0.1	1	100
	II	10	0.1	1	110
	III	10	0.1	1	120
semi-evergreen		10	0.08	1	160
tropical coniferous	I	10	0.05	3	200
	II	10	0.04	3	220
	III	10	0.03	4	250
temperate hardwoods	I	30	0.1	1	250
	II	30	0.08	1.2	275
	III	30	0.06	2	350
temperate softwood	I	10	0.1	1	275
	II	10	0.1	1	275
	III	10	0.1	1	275
montane coniferous	I	20	0.03	2	320
	II	20	0.02	3	350
	III	20	0.02	3.5	350
temperate coniferous	I	20	0.06	2	250
	II	20	0.06	2	250
	III	20	0.06	2	300
boreal coniferous	I	30	0.02	5	550
	II	30	0.02	6	550
	III	30	0.02	8	600

APPENDIX I: Partitioning of wood from thinnings and final cut.**Table I1:**

Softwoods in a long rotation (Douglas-fir and boreal and temperate spruce):

age of thinning	dead wd (litter)	energy	paper	packing wood	particle board	sawn timber
20	1.0	0.0	0.0	0.0	0.0	0.0
30	0.2	0.0	0.8	0.0	0.0	0.0
40	0.2	0.0	0.8	0.0	0.0	0.0
50	0.1	0.0	0.9	0.0	0.0	0.0
60	0.1	0.0	0.0	0.1	0.8	0.0
70	0.1	0.0	0.0	0.1	0.6	0.2
80	0.1	0.0	0.0	0.1	0.5	0.3
90	0.1	0.0	0.0	0.1	0.4	0.4
100	0.1	0.0	0.0	0.1	0.3	0.5
110	0.1	0.0	0.0	0.0	0.2	0.7
120 (final cut)	0.1	0.0	0.0	0.0	0.1	0.8

Table I2:

Softwoods in a short rotation (poplar hybrids):

age of thinning	dead wd (litter)	energy	paper	packing wood	particle board	sawn timber
17	0.2	0.0	0.6	0.0	0.2	0.0
21	0.2	0.0	0.4	0.0	0.4	0.0
27	0.1	0.0	0.5	0.2	0.2	0.0
45 (final cut)	0.1	0.0	0.2	0.3	0.3	0.1

Table I3:

Softwoods in very short rotation (poplar hybrids in 20-year rotation):

age of thinning	dead wd (litter)	energy	paper	packing wood	particle board	sawn timber
20 (final cut)	0.1	0.0	0.2	0.3	0.3	0.1

Table I4:

Tropical and subtropical pine plantations (radiata pine, Caribbean pine, Loblolly pine, and slash pine):

age of thinning	dead wd (litter)	energy	paper	packing wood	particle board	sawn timber
10	1.0	0.0	0.0	0.0	0.0	0.0
15	0.2	0.0	0.6	0.0	0.2	0.0
20	0.2	0.0	0.4	0.0	0.4	0.0
25	0.1	0.0	0.4	0.2	0.3	0.0
30	0.1	0.0	0.2	0.3	0.4	0.0
35	0.1	0.0	0.2	0.3	0.4	0.0
40 (final cut)	0.1	0.0	0.2	0.3	0.3	0.1

Table I5:

Temperate mixed deciduous forests in a long rotation (mixed oak/beech), and black locust in 50-year rotation:

age of thinning	dead wd (litter)	energy	paper	packing wood	particle board	sawn timber
20	1.0	0.0	0.0	0.0	0.0	0.0
30	0.2	0.8	0.0	0.0	0.0	0.0
40	0.2	0.8	0.0	0.0	0.0	0.0
50	0.1	0.7	0.0	0.1	0.0	0.1
60	0.1	0.7	0.0	0.1	0.0	0.1
70	0.1	0.4	0.0	0.3	0.0	0.2
80	0.1	0.3	0.0	0.3	0.0	0.3
90	0.1	0.2	0.0	0.4	0.0	0.3
100	0.1	0.2	0.0	0.3	0.0	0.4
110	0.1	0.2	0.0	0.2	0.0	0.5
120	0.1	0.1	0.0	0.2	0.0	0.6
130	0.1	0.1	0.0	0.2	0.0	0.6
140	0.1	0.0	0.0	0.2	0.0	0.7
150 (final cut)	0.1	0.0	0.0	0.1	0.0	0.8

Table I6:

Tropical heavily logged evergreen and semi-evergreen rainforests. Logged over each 70 years and thinned 20 and 40 years afterwards

age of thinning	dead wd (litter)	energy	paper	packing wood	particle board	sawn timber
20	0.5	0.5	0.0	0.0	0.0	0.0
40	0.5	0.3	0.0	0.0	0.0	0.2
70	0.5	0.2	0.0	0.0	0.0	0.3

Table 17:

Tropical selectively logged evergreen and semi-evergreen rainforests. Logged over every 70 years and thinned 5 and 20 years afterwards

age of thinning	dead wd (litter)	energy	paper	packing wood	particle board	sawn timber
5	0.3	0.5	0.0	0.0	0.2	0.0
20	0.3	0.3	0.0	0.0	0.2	0.2
70	0.3	0.2	0.0	0.0	0.1	0.4

Table 18:

Tropical heavily logged evergreen rainforests. Logged over every 140 years because the regrowth is hampered by lianas and thinned 10, 20 and 90 years afterwards.

age of thinning	dead wd (litter)	energy	paper	packing wood	particle board	sawn timber
10	0.5	0.5	0.0	0.0	0.0	0.0
20	0.5	0.5	0.0	0.0	0.0	0.0
90	0.5	0.3	0.0	0.0	0.2	0.0
140	0.3	0.3	0.0	0.0	0.1	0.3

Table 19:
Afforestations of waste lands with a short rotation (10 yr) of Albizia spp. followed by underplanting with Dipterocarpaceae. Heavy thinning in Albizia at T=10, followed by two thinnings in the dipterocarps at T= 20 and 30 years, and a heavy logging at T=90 yr. Following rotations are 70 years.

age of thinning	dead wd (litter)	energy	paper	packing wood	particle board	sawn timber
10	0.1	0.0	0.0	0.4	0.5	0.0
20	0.6	0.0	0.0	0.0	0.4	0.0
30	0.5	0.0	0.0	0.0	0.4	0.1
90	0.3	0.0	0.0	0.0	0.2	0.5
10	0.6	0.0	0.0	0.0	0.4	0.0
20	0.5	0.0	0.0	0.0	0.4	0.1
70	0.3	0.0	0.0	0.0	0.2	0.5

APPENDIX J: Stand parameters to determine the relative site class

(see next page for explanation of the forest type number)

forest type	age (years)	average height (m)	basal area (m ² ha ⁻¹)
1	30	*	34
2	30	*	24
3	30	*	20
4	30	*	14
5	30	*	13
6	40	16	36
7	40	13	30
8	40	7	21
9	40	15	± 19
10	40	11	± 15
11	40	8	± 11
12			
13			
14			
15	40	7	21
16	40	5	18
17	40	4	15
18	20	29,5	16
19	20	25	23 (no thinning yet!)
20	20	18	12
21	15	19,5	24
22	30	18	20
23	30	16	16
24	30	14	11
25	*	*	*
26	20	24	56
27	*	*	*
28	10	19	28 (after thinning)
29	10	17	22 (after thinning)
30	15	16	21 (after thinning)
31	15	15	31
32	15	13	26
33	15	11	20
34	10	17	29 (one heavy thinning)
35	10	14	30 (one light thinning)
36	10	11	34 (no thinning yet)

Explanation of the forest types in Appendix J:

- 1: Regrown heavily logged tropical lowland evergreen Dipterocarp rainforest on good sites.
- 2: Regrown heavily logged tropical lowland evergreen Dipterocarp rainforest on moderate sites.
- 3: Regrown heavily logged tropical lowland evergreen Dipterocarp rainforest on limited sites.
- 4: Regrown heavily logged tropical lowland semi-evergreen rainforest on moderate sites.
- 5: Afforestations of tropical wasteland of moderate fertility with *Albizia* spp. as a pioneer, followed by Dipterocarps.
- 6: Norway spruce forest on good sites in Central Europe.
- 7: Norway spruce forest on moderate sites in Central Europe.
- 8: Norway spruce forest on limited sites in Central Europe.
- 9: Mixed oak/beech forest on good sites in Central Europe.
- 10: Mixed oak/beech forest on moderate sites in Central Europe.
- 11: Mixed oak/beech forest on limited sites in Central Europe.
- 12: Douglas-fir forest on good sites in the Pacific Northwest of North America.
- 13: Douglas-fir forest on moderate sites in the Pacific Northwest of North America.
- 14: Douglas-fir forest on limited sites in the Pacific Northwest of North America.
- 15: Norway spruce forest on relatively good sites in the Boreonemoral zone of Russia.
- 16: Norway spruce forest on relatively moderate sites in the Boreonemoral zone of Russia.
- 17: Norway spruce forest on relatively limited sites in the Boreonemoral zone of Russia.
- 18: Poplar plantations on good sites on former agricultural land in Europe.
- 19: Poplar plantations on moderate sites on former agricultural land in Europe.
- 20: Poplar plantations on limited sites on former agricultural land in Europe.
- 21: Poplar plantations on moderate sites on former agricultural land in Europe.
- 22: Black locust plantations on good sites on former agricultural land in Europe.
- 23: Black locust plantations on moderate sites on former agricultural land in Europe.
- 24: Black locust plantations on limited sites on former agricultural land in Europe.
- 25: Industrial radiata pine plantation on good sites in New Zealand and Australia.
- 26: Industrial radiata pine plantation on moderate sites in New Zealand and Australia.
- 27: Industrial radiata pine plantation on limited sites in New Zealand and Australia.
- 28: Industrial Caribbean pine plantation on good sites in Brazil and Venezuela.
- 29: Industrial Caribbean pine plantation on moderate sites in Brazil and Venezuela.
- 30: Industrial Caribbean pine plantation on limited sites in Brazil and Venezuela.
- 31: Industrial loblolly pine plantation on good sites in the southeast of the USA.
- 32: Industrial loblolly pine plantation on moderate sites in the southeast of the USA.
- 33: Industrial loblolly pine plantation on limited sites in the southeast of the USA.
- 34: Industrial slash pine plantation on good sites in Brazil.
- 35: Industrial slash pine plantation on moderate sites in Brazil.
- 36: Industrial slash pine plantation on limited sites in Brazil.

APPENDIX K: UNCERTAINTY ANALYSIS OF THE MODEL CO2FIX

By: H. van der Voet (GLW-DLO)

The model CO2FIX was developed to predict carbon fixation by forests over long periods, e.g. 300 years. The model can be used to make predictions for specific combinations of forest type and management regime. A proper appreciation of the model predictions requires an understanding of (a) the mathematical description of the modelled system, and (b) the uncertainties associated with the model predictions even if the mathematical description is believed to be sufficiently close to reality. Uncertainty analysis is concerned with the latter aspect, and the resulting uncertainties should consequently be interpreted as lower boundaries if one is not sure about the exactness of the model equations.

Uncertainty analysis was performed using simple error propagation formulas relating 173 inputs of the model to the main model output, which is the predicted CO₂-fixation averaged over 300 years (CTOTAV, measured in Mg C ha⁻¹). The general strategy was the same as that applied earlier to the FORGRO 3.0 model (Van der Voet & Mohren 1993):

1. Choice of relevant model outputs and inputs, and of suitable transformations;
2. Specification of the input uncertainties in the form of a simultaneous input distribution;
3. Generation of a sample of input values from the input distribution;
4. Simulations with the model using the generated input values;
5. Description of the output distribution (histogram, summary statistics);
6. Determination of most influential inputs (uncertainty contributions).

The prediction of CTOTAV is calculated from inputs describing (a) species characteristics like growth and decomposition constants, and (b) stand and management characteristics concerned with e.g. initial biomass and allocation of stemwood to product categories. The data used as an example in this note (spruce under central European conditions) are reproduced in Table K9.

Uncertainty about model inputs is the consequence of (a) unmodelled natural variability, and/or (b) lack of knowledge about natural constants. Natural variability is dependent upon the unit of modelling: e.g. average initial biomass is more variable for units of 1 ha than for units of 100 ha. In the present study a typical stand was used as the natural unit. All uncertainties of model inputs and outputs should therefore be taken as referring to stand averages.

The method used assumes a multivariate normal distribution of the inputs. To ensure this to be reasonable, input transformations were applied wherever appropriate according to the following scheme: inputs with necessarily nonnegative values were transformed using a natural logarithm, inputs representing a fraction were transformed using the logistic function, and multiple inputs necessarily summing to 1 were transformed using the log-ratio transformation given by Aitchison (1986). Addition of a small value $\epsilon = 10^{-6}$ was used if necessary to prevent numerical problems. Values from samples drawn from the multivariate normal distribution on the transformed scale, were backtransformed to

provide inputs for the CO2FIX model program. In this way impossible values (e.g. negative biomass) were prevented.

Many inputs are given to the model in the form of tables describing piecewise linear relations, e.g. allocation factors in relation to age. By allowing only strictly coupled changes in the elements of any table, only one entry in each table was taken as a basic model input to be independently varied. The total number of independently varied inputs was thus reduced from 173 to 32. The central values and uncertainty limits for these 32 model inputs were assessed subjectively, and are given in part C of Table K10. For the remaining 141 tabular inputs only central values were given (part D of Table K10), and each was linked to one of the 32 basic inputs. In the simulations each of these 'slaved' inputs was then given an equal change from the central value (on the transformed scale) as the chosen basic input.

Assessments of correlation between the 32 basic inputs were made on the transformed scale. Among 32 inputs 496 bivariate correlations exist, but only 40 were assumed to have non-zero values (part E of Table K10). Values ± 0.3 , ± 0.5 and ± 0.8 were used to indicate small, moderate or large correlations (there was no restriction on choosing other values). Internally the uncertainty specification by means of upper or lower limits and inter-input correlations is converted to a description in the form of a covariance matrix of the transformed inputs.

In the subjective assessment of uncertainty it easily occurs that the resulting covariance matrix is negative definite, which means that it is incompatible with any underlying data set. For example, if two inputs are each assumed to have correlation 0.8 with a third, it cannot be true that these two inputs have no correlation among themselves. A negative definite matrix Σ can be detected by the presence of negative eigenvalues in the eigenvalue decomposition $\Sigma = V\Lambda V'$. We tried to detect the most problematic correlation structures by the following procedure. A 'corrected' version of the covariance matrix was reconstructed from the eigenvalue decomposition by deleting the columns of V and Λ corresponding to negative eigenvalues. Then both the original and the 'corrected' version were transformed to correlation matrices, and the difference matrix was formed. Large elements in this matrix of differences indicated which inputs were the primary source of trouble, and for a submatrix with these inputs the correlations were reassessed subjectively, while continuously checking on the presence of negative eigenvalues in the decomposition of the submatrix.

In the present study the first version of the covariance matrix Σ had 30 positive and 2 negative eigenvalues. According to the procedure outlined above, a submatrix of 6 inputs was identified as the main source of inconsistency. Table K1 gives both the original and reassessed versions of the correlation matrix for these inputs. Table K10 contains already the modifications made.

Table K1:
Original and reassessed versions of the correlation matrix between 6 inputs.

a. Original assessment						b. Reassessment							
cc	1					cc	1						
tedht	0	1				tedht	0.3	1					
humc	0.8	0.3	1			humc	0.5	0.3	1				
teldec	0.5	0.8	-0.3	1		teldec	0.5	0.5	0.3	1			
tchdec	0	0.8	-0.3	0.5	1	tchdec	0.3	0.3	0.3	0.5	1		
cchum	0.8	0	-0.3	0	0.8	1	cchum	0.5	0	0.3	0	0.5	1
cc	tedht	humc	teldec	tchdec	cchum	cc	tedht	humc	teldec	tchdec	cchum		

Simulations with the model CO2FIX were done for a sample of 100 sets of input values. The sample was obtained by applying Latin hypercube sampling (McKay et al. 1979) to uncorrelated linear combinations constructed from correlated multivariate normal distributed variables (Iman & Conover 1982). A schematic representation of programs and files used is shown in Table K11.

The raw result of an uncertainty analysis using representative sampling is the empirical distribution of predictions. If simple enough, this distribution can be summarized by e.g. a measure of central value (mean, geometric mean or median) on the one hand, and a measure of spread (standard deviation or coefficient of variation) on the other. It may also be useful to calculate a confidence interval. In the following we have analyzed the natural logarithm of CTOTAV, in line with our general strategy to transform variables with necessarily non-negative values. However, omitting the transformation, and analyzing CTOTAV directly gives virtually identical results, illustrating that the choice is unimportant when values are 'far away from zero'.

A second point of interest may be the ordering of inputs with respect to their influence on the output. This can only be done if we have a simple metamodel relating the model output to the model inputs, for example a linear or quadratic regression equation. The squared coefficient of multiple correlation (r^2) might be a convenient guide to judge the fit of a metamodel. A problem arises if there are non-zero correlations. Should the influence of input x_1 on output y include the indirect influence via another input x_2 with which x_1 is correlated? Another problem is to find an easily interpretable criterion to summarize the effects per input. Among other possibilities we focus on the following four measures in the case of a sufficiently well fitting linear metamodel:

1. RRV, the relative reduction in variance to be attained if the uncertainty in one specific input could be eliminated. An RRV of 57% for model input CC for example means that the total uncertainty about the model output (expressed in our case as the variance of $\ln(\text{CTOTAV})$) would be more than halved if CC were to become constant and perfectly known.
2. RSV, the relative specific variance, measures how much of the total uncertainty would remain, if all other inputs except the one under considerations were to

become constant and perfectly known. In the absence of correlations between inputs, RRV and RSV are equal.

3. CVMARG, the coefficient of variation (relative standard deviation) of the model output, induced by the input under consideration, and including indirect effects via other correlated inputs (technically we look at the marginal distribution, i.e. we look only at the variation of y as a function of x_1 , ignoring the existence of other inputs in the regression analysis, though not in the simulations). We define CVMARG to be signed with the sign of the marginal correlation between input and output, thus showing the direction of the relation.
RRV and CVMARG measure the same thing in a different way, their relation is $RRV = (1/v) * \ln(CVMARG^2 + 1)$, where v is the total variance of the transformed output, $\ln(CTOTAV)$ in our case. CVMARG was also used in Van der Voet & Mohren (1993).
4. CVCOND, the coefficient of variation (relative standard deviation) of the model output, induced by the input under consideration, but conditioning on fixed values of all other inputs. Indirect effects are therefore not included. We define CVCOND to be signed with the sign of the conditional regression coefficient. If all correlations are zero CVMARG and CVCOND are equal.

Finally it can be noted that RRV and RSV (but not CVMARG and CVCOND) can be calculated also for quadratic metamodells. For more information about these measures see Van der Voet (1991). CVMARG and CVCOND are related to the measures in that note by $CVMARG = \pm \sqrt{\{\exp(MUC^2) - 1\}}$ and $CVCOND = \pm \sqrt{\{\exp(CUC^2) - 1\}}$, which are the usual approximations to translate a variance on the logarithmic scale (the scale of the linear metamodel) to a relative standard deviation on the original scale.

Results

The CO2FIX model, using the central input values from Table K10, predicts for spruce under central European conditions an average CO_2 fixation of 316 Mg C ha^{-1} . The uncertainty analysis shows the precision of this prediction in the light of the uncertainties about the model inputs (remember that the model equations are assumed to be a correct representation of reality). The empirical distribution of 100 simulated predictions is shown in Figure 1. The median prediction is 320 Mg C ha^{-1} with a relative standard deviation of 12%. A 95% confidence interval for the prediction (again, assuming error free model equations) is $254\text{--}403 \text{ Mg C ha}^{-1}$.

Technical note: summary statistics like median, relative standard deviation and confidence limits can be calculated in different ways. In the above we have used values based on the linear error propagation model relating the natural logarithm of CTOTAV to the transformed basic inputs. This way of calculation requires of course that this linear metamodel fits sufficiently close the data. In the present case there were no problems, in view of the squared correlation coefficient (r^2) of 0.99. An alternative way of calculation is to use only the empirical predictions. For the present example we obtain a median of 315, a relative standard deviation of 12%, and a 95%-confidence interval of $261\text{--}405$, all very close to the values above.

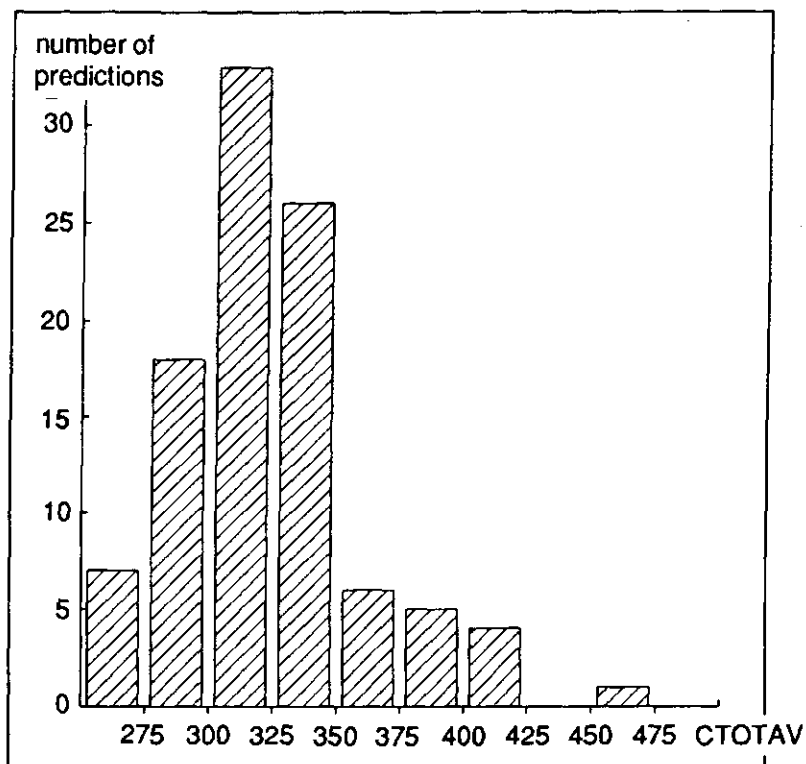


Figure K1. Distribution of 100 simulated predictions for CTOTAV.

Some insight into the sources of the total uncertainty in CTOTAV is obtained by inspection of Table K2, which lists the uncertainty specification of the 32 basic inputs together with the 4 measures RRV, RSV, CVMARG and CVCOND. The model inputs here are ordered according to decreasing values of RRV (and of the absolute values of CVMARG). All measures are based on the linear error propagation model, so a sufficiently close fit ($r^2=0.99$ in this case) is a prerequisite for the calculation of interpretable uncertainty contribution measures.

Note: Remember that some basic inputs (e.g. GROPTB_25) are strictly coupled to other tabular inputs (the rest of the second line of table GROPTB, in this case, see Appendices 1a, 2D), so that measures in Table K2 may actually show the combined effect of changing a complete tabular input (the complete second line of table GROPTB).

Table K2:

Results of uncertainty analysis output CTOTAV of model CO2FIX for spruce under central European conditions.

median: 320.1	cv: 11.6%	r ² : 0.99
95% confidence interval:	254.2 - 402.9	

Uncertainty contributions:

input	cent	limit	rrv%	rsv%	cvmarg%	cvcond%
tcldec	2.000	4.000	56.43	3.37	8.73	5.75
cc	0.480	0.450	55.68	0.64	8.68	2.53
humc	0.030	0.050	44.02	5.07	7.71	3.33
tchdec	320.000	500.000	36.78	0.90	7.05	2.72
tcdht	20.000	10.000	20.30	0.22	5.23	0.87
cchum	0.580	0.650	19.44	0.07	5.12	1.03
baden	410.000	450.000	4.40	3.27	2.43	3.52
blc	0.050	0.040	1.94	0.01	-1.62	-0.52
groptb_25	19.400	21.300	1.83	0.48	1.57	3.62
humus	190.000	210.000	1.49	0.14	1.42	0.93
thuse_12_5	0.300	0.500	1.11	1.11	1.22	1.22
rlc	0.100	0.150	0.33	0.14	-0.67	-1.20
tczaag	35.000	40.000	0.25	0.25	0.58	0.58
flc	0.300	0.250	0.20	0.02	-0.51	-0.43
mort	0.020	0.030	0.11	0.01	0.38	0.26
thuse_12_2	0.010	0.100	0.06	0.06	-0.28	-0.28
tcenrg	1.000	2.000	0.06	0.06	-0.28	-0.28
thuse_12_3	0.100	0.200	0.05	0.05	-0.26	-0.26
tcembl	3.000	10.000	0.04	0.04	0.23	0.23
thuse_12_1	0.010	0.100	0.04	0.04	-0.23	-0.23
dhout	1.000	2.000	0.04	0.00	0.22	0.03
tcpap	2.000	5.000	0.03	0.03	0.21	0.21
fctb_25	0.650	0.800	0.03	0.20	0.20	0.88
litter	1.000	2.000	0.03	0.00	-0.20	-0.10
rctb_25	0.650	0.800	0.02	0.42	0.18	1.26
teplaa	20.000	25.000	0.02	0.02	0.16	0.16
bctb_25	0.300	0.400	0.02	0.23	0.16	0.93
bw	0.500	3.000	0.02	0.00	0.16	0.15
fw	3.000	10.000	0.02	0.00	0.15	0.14
svol	1.000	5.000	0.01	0.00	0.13	0.00
rw	0.500	5.000	0.01	0.00	-0.10	-0.14
thuse_12_4	0.480	0.750	0.00	0.00	-0.03	-0.03

The first four entries in Table K2 are TCLDEC (time coefficient for litter decomposition), CC (carbon content of dry matter), HUMC (humification coefficient) and TCHDEC (time coefficient for humus decomposition) with RRV values around 50%. This means that absolute knowledge of any of these inputs would approximately

halve the uncertainty variance of the model output. The same fact can also be seen in the CVMARG values: uncertainty about CC alone induces a relative standard deviation of 9% in CTOTAV (remember that the total uncertainty was 12%, so that the residual unexplained by CC is about $\sqrt{(12^2 - 9^2)} = 8\%$). Although it may seem that CC, HUMC, TCLDEC and TCHDEC are important sources of uncertainty, neither of them is very specific as testified by the RSV values, which are 5% at most. This means that no single input can be identified as a major source of uncertainty. The large values of RRV and CVMARG are therefore mainly due to indirect effects: a different value for CC, for example, implies that also the values for correlated inputs (HUMC, TCLDEC, TCHDEC, TCDHT, CCHUM) are expected to be different, which implies, that also values for inputs correlated with *these* inputs are expected to be different, which implies ..., etc. The resulting change in model output is then a consequence of this cascade of changed expected values.

Entries 5 and 6 in Table K2 are TCDHT (mean time of presence of CO₂ after fixation in natural forests) and CCHUM (carbon content of humus). These entries have RRV values of about 20%, and a CVMARG of about 5%. The next entry, BADEN (basic density), is perhaps remarkable for a relative large RSV value (3%), together with HUMC (5%), and TCLDEC (3%), in comparison to all other inputs (1% at most). It can be noted that all important uncertainty contributions as measured by our criteria are species characteristics, whereas all stand/management characteristics (as well as the remaining species characteristics) show no important influence whatsoever.

Not too much value should be attached to the precise values of criteria, and the precise ranking in Table K2. The subjective assessment of input uncertainty and correlations (Table K10) is itself of course fraught with uncertainties. Some insight into the robustness of the results against other uncertainty assessments can be obtained by trying a few variations of the input uncertainty specification. Unintentionally simple random sampling instead of Latin hypercube sampling has been used in these calculations, but this is not expected to give importantly different results (only the efficiency might be somewhat lower). Tables K3-8 show some results of the robustness studies. In Tables K3 and K4, the analysis from Table K2 is repeated with two simple random samples of inputs. Happily we note that differences are small. Tables K5, K6 and K7 document the results from analyses where correlations are altered in respectively a slight, a moderate, and a severe degree (see Table captions). In general, if less correlation is assumed between inputs, RRV values decrease and RSV values increase, because indirect effects become less prominent. With only a small change in correlations (Table K5) the differences in output remain small too. If correlations would be attenuated more or even be absent (Tables K6, K7), also BADEN (basic density) and GROPTB (growth in m³yr⁻¹ in relation to age) would show up as relative important sources of uncertainty. The uncertainty analysis in Table K8 checks that the specification of the last digit for the CC limit value is not very critical: a limit 0.46 instead of 0.45 (with a central value 0.48) does not give very different results.

Some final remarks

1. The uncertainty in most inputs will often reflect natural variability more than lack of knowledge about an exact constant of nature. If this is the case for the major contributors of uncertainty as found above, a reduction of prediction uncertainty should be accomplished by modelling the corresponding aspect of reality in an alternative way. If a better model is more detailed, this may require more parameters (model inputs), about which probably less knowledge exists. Therefore there is an optimum in the amount of detail the model should have. This optimum is dependent on the availability of data, and can be shifted in the direction of more detailed modelling by performing appropriate experiments on inputs suggested by e.g. an uncertainty analysis. For example, carbon content (CC) is considered as a species-specific natural constant. The analysis indicates that more experimentation to obtain more precise estimates may be fruitful.
2. In this note the uncertainty about model predictions as such is evaluated. However, it may be that the real interest lies more in comparisons of scenarios: for example, can we better plant spruce or oak for a maximal CO₂ fixation? The uncertainty about the difference between two predictions might be radically different from the uncertainty about the predictions themselves. It is therefore then sensible to apply uncertainty analysis to a supermodel consisting of two runs of CO2FIX with specific inputs, and then forming a difference.

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Table K3:

Results of uncertainty analysis output CTOTAV of model CO2FIX for spruce under central European conditions Robustness study: simple random sample.

median: 320.3 cv: 11.5% r^2 : 0.99
 95% confidence interval: 255.2 - 402.1

Uncertainty contributions:

input	cent	limit	rrv%	rsv%	cvmarg%	cvcond%
cc	0.480	0.450	54.23	0.53	8.45	2.28
tcldc	2.000	4.000	51.53	2.75	8.24	5.13
humc	0.030	0.050	43.98	5.36	7.61	3.38
tchdec	320.000	500.000	41.73	0.97	7.41	2.78
cchum	0.580	0.650	24.64	0.23	5.69	1.82
tcdht	20.000	10.000	18.50	0.09	4.93	0.55
baden	410.000	450.000	4.69	2.76	2.48	3.20
groptb_25	19.400	21.300	2.07	0.21	1.65	2.39
humus	190.000	210.000	1.99	0.07	1.62	0.64
blc	0.050	0.040	1.09	0.07	-1.20	-1.61
thuse_12_5	0.300	0.500	0.90	0.90	1.09	1.09
tczaag	35.000	40.000	0.45	0.45	0.77	0.77
thuse_12_1	0.010	0.100	0.29	0.29	-0.62	-0.62
rctb_25	0.650	0.800	0.24	0.44	0.56	1.28
dhout	1.000	2.000	0.15	0.05	0.44	0.42
thuse_12_4	0.480	0.750	0.12	0.12	-0.40	-0.40
tcembl	3.000	10.000	0.10	0.10	0.36	0.36
fctb_25	0.650	0.800	0.09	0.04	0.34	0.38
thuse_12_2	0.010	0.100	0.08	0.08	-0.32	-0.32
litter	1.000	2.000	0.07	0.01	-0.31	-0.22
tcenrg	1.000	2.000	0.06	0.06	0.29	0.29
tcpap	2.000	5.000	0.06	0.06	0.27	0.27
rlc	0.100	0.150	0.04	0.01	-0.23	-0.37
fw	3.000	10.000	0.02	0.10	-0.16	-0.70
tcplaa	20.000	25.000	0.02	0.02	0.14	0.14
bw	0.500	3.000	0.01	0.09	0.11	0.66
flc	0.300	0.250	0.01	0.01	0.09	0.34
thuse_12_3	0.100	0.200	0.01	0.01	-0.08	-0.08
rw	0.500	5.000	0.00	0.02	-0.08	-0.28
bctb_25	0.300	0.400	0.00	0.12	0.06	0.65
mort	0.020	0.030	0.00	0.03	0.05	0.54
svol	1.000	5.000	0.00	0.02	0.03	0.30

Table K4:
Results of uncertainty analysis output CTOTAV of model CO2FIX for spruce under central European conditions. Robustness study: simple random sample with other seed of random generator.

median: 319.9 cv: 11.9% r ² : 0.98						
95% confidence interval: 252.7 - 404.9						
Uncertainty contributions:						
input	cent	limit	rrv%	rsv%	cvmarg%	cvcond%
tclddec	2.000	4.000	57.56	3.97	9.03	6.39
cc	0.480	0.450	52.71	0.34	8.64	1.88
humc	0.030	0.050	43.83	5.37	7.88	3.50
tchdec	320.000	500.000	40.27	1.02	7.55	2.96
cchum	0.580	0.650	20.55	0.14	5.39	1.47
tcldht	20.000	10.000	18.82	0.10	5.16	0.60
baden	410.000	450.000	4.10	3.16	2.41	3.54
gproptb_25	19.400	21.300	2.42	0.50	1.85	3.79
humus	190.000	210.000	1.60	0.12	1.50	0.89
thuse_12_5	0.300	0.500	1.24	1.24	1.33	1.33
b1c	0.050	0.040	0.80	0.00	1.07	0.10
tcembl	3.000	10.000	0.30	0.30	0.65	0.65
thuse_12_2	0.010	0.100	0.12	0.12	-0.41	-0.41
thuse_12_1	0.010	0.100	0.12	0.12	-0.40	-0.40
rctb_25	0.650	0.800	0.10	0.58	0.38	1.52
tczaag	35.000	40.000	0.08	0.08	0.34	0.34
tcplaa	20.000	25.000	0.07	0.07	0.31	0.31
fctb_25	0.650	0.800	0.05	0.49	0.26	1.40
bctb_25	0.300	0.400	0.03	0.22	0.21	0.93
litter	1.000	2.000	0.03	0.10	-0.20	-0.65
tcenrg	1.000	2.000	0.02	0.02	-0.18	-0.18
rlc	0.100	0.150	0.01	0.06	-0.11	-0.81
tcpap	2.000	5.000	0.01	0.01	0.10	0.10
thuse_12_3	0.100	0.200	0.01	0.01	0.10	0.10
mort	0.020	0.030	0.00	0.03	-0.07	-0.59
bw	0.500	3.000	0.00	0.01	0.06	0.20
flc	0.300	0.250	0.00	0.00	-0.03	-0.05
dhout	1.000	2.000	0.00	0.01	0.00	0.23
fw	3.000	10.000	0.00	0.00	0.00	0.00
svol	1.000	5.000	0.00	0.00	0.00	-0.03
rw	0.500	5.000	0.00	0.00	0.00	-0.14
thuse_12_4	0.480	0.750	0.00	0.00	0.00	0.00

Table K5:
Results of uncertainty analysis output CTOTAV of model CO2FIX for spruce under central European conditions. Robustness study: all correlations $\pm 0.5 \rightarrow \pm 0.4$.

median: 320.5 cv: 11.1% r ² : 0.99						
95% confidence interval: 257.2 – 399.4						
Uncertainty contributions:						
input	cent	limit	rrv%	rsv%	cvmarg%	cvcond%
tcldec	2.000	4.000	47.31	6.21	7.64	4.97
cc	0.480	0.450	45.26	1.79	7.47	2.45
humc	0.030	0.050	44.26	4.80	7.39	3.39
tchdec	320.000	500.000	38.63	2.78	6.90	3.21
cchum	0.580	0.650	21.10	0.82	5.10	1.50
tedht	20.000	10.000	15.07	0.04	4.31	0.37
baden	410.000	450.000	5.23	2.46	2.54	3.30
groptb_25	19.400	21.300	2.11	0.18	1.61	2.55
humus	190.000	210.000	1.64	0.33	1.42	0.79
blc	0.050	0.040	1.30	0.06	-1.26	-1.57
thuse_12_5	0.300	0.500	0.86	0.86	1.03	1.03
tczaag	35.000	40.000	0.34	0.34	0.65	0.65
thuse_12_1	0.010	0.100	0.28	0.28	-0.59	-0.59
rctb_25	0.650	0.800	0.21	0.37	0.51	1.27
thuse_12_4	0.480	0.750	0.15	0.15	-0.44	-0.44
dhout	1.000	2.000	0.11	0.02	0.37	0.25
tcenrg	1.000	2.000	0.09	0.09	0.33	0.33
fctb_25	0.650	0.800	0.08	0.05	0.32	0.45
tcembl	3.000	10.000	0.07	0.07	0.29	0.29
thuse_12_2	0.010	0.100	0.07	0.07	-0.29	-0.29
litter	1.000	2.000	0.07	0.01	-0.29	-0.15
rlc	0.100	0.150	0.06	0.02	-0.28	-0.48
tcpap	2.000	5.000	0.06	0.06	0.28	0.28
fw	3.000	10.000	0.02	0.10	-0.15	-0.68
thuse_12_3	0.100	0.200	0.01	0.01	-0.11	-0.11
flc	0.300	0.250	0.01	0.02	0.10	0.42
bctb_25	0.300	0.400	0.01	0.10	0.10	0.67
mort	0.020	0.030	0.01	0.02	0.10	0.44
bw	0.500	3.000	0.01	0.07	0.10	0.57
tcplaa	20.000	25.000	0.01	0.01	0.09	0.09
rw	0.500	5.000	0.00	0.02	-0.08	-0.30
svol	1.000	5.000	0.00	0.03	0.06	0.38

Table K6:

Results of uncertainty analysis output CTOTAV of model CO2FIX for spruce under central European conditions. Rubustness study: all non-zero correlations 0.3 closer to 0 ($\pm 0.8 \rightarrow \pm 0.5$, $\pm 0.5 \rightarrow \pm 0.2$, $\pm 0.3 \rightarrow \pm 0.0$).

median: 319.7 cv: 10.8% r^2 : 0.99
 95% confidence interval: 258.0 - 396.0

Uncertainty contributions:

input	cent	limit	rrv%	rsv%	cvmarg%	cvcond%
tclddec	2.000	4.000	38.19	22.42	6.68	5.48
tchdec	320.000	500.000	16.98	7.42	4.45	3.09
cc	0.480	0.450	16.18	3.94	4.34	2.30
humc	0.030	0.050	12.79	9.49	3.86	3.40
baden	410.000	450.000	11.80	11.80	3.71	3.71
groptb_25	19.400	21.300	11.48	11.48	3.66	3.66
cchum	0.580	0.650	5.93	1.33	2.63	1.33
rctb_25	0.650	0.800	2.89	2.89	1.84	1.84
tcdht	20.000	10.000	2.42	0.28	1.68	0.58
humus	190.000	210.000	1.59	0.98	1.36	1.09
rlc	0.100	0.150	1.57	0.66	-1.35	-1.11
bctb_25	0.300	0.400	1.34	1.34	1.25	1.25
blc	0.050	0.040	0.81	0.06	-0.97	-0.35
flc	0.300	0.250	0.75	0.04	-0.94	-0.28
fbctb_25	0.650	0.800	0.75	0.75	0.94	0.94
thuse_12_5	0.300	0.500	0.75	0.75	0.93	0.93
mort	0.020	0.030	0.46	0.01	0.73	0.14
thuse_12_1	0.010	0.100	0.32	0.32	-0.61	-0.61
tczaag	35.000	40.000	0.29	0.29	0.58	0.58
tcplaa	20.000	25.000	0.13	0.13	0.39	0.39
tcembl	3.000	10.000	0.09	0.09	0.33	0.33
bw	0.500	3.000	0.06	0.08	0.25	0.38
thuse_12_2	0.010	0.100	0.05	0.05	-0.23	-0.23
tcenrg	1.000	2.000	0.05	0.05	0.23	0.23
tcpap	2.000	5.000	0.04	0.04	0.20	0.20
fw	3.000	10.000	0.03	0.13	-0.19	-0.49
thuse_12_4	0.480	0.750	0.02	0.02	-0.15	-0.15
svol	1.000	5.000	0.02	0.01	0.13	0.15
rw	0.500	5.000	0.01	0.00	0.10	0.08
dhout	1.000	2.000	0.00	0.01	0.07	0.09
thuse_12_3	0.100	0.200	0.00	0.00	0.06	0.06
litter	1.000	2.000	0.00	0.00	0.00	-0.03

Table K7:

Results of uncertainty analysis output CTOTAV of model CO2FIX for spruce under central European conditions. Robustness study: all correlations zero.

median: 319.6 cv: 9.9% r^2 : 0.99
 95% confidence interval: 262.9 - 389.1

Uncertainty contributions:

input	cent	limit	rrv%	rsv%	cvmarg%	cvcond%
toldec	2.000	4.000	30.97	30.97	5.52	5.52
baden	410.000	450.000	14.12	14.12	3.72	3.72
groptb_25	19.400	21.300	14.00	14.00	3.71	3.71
humc	0.030	0.050	12.15	12.15	3.45	3.45
tchdec	320.000	500.000	10.29	10.29	3.18	3.18
cc	0.480	0.450	5.71	5.71	2.37	2.37
rctb_25	0.650	0.800	3.39	3.39	1.82	1.82
cchum	0.580	0.650	1.81	1.81	1.33	1.33
bctb_25	0.300	0.400	1.58	1.58	1.25	1.25
rlc	0.100	0.150	1.40	1.40	-1.17	-1.17
humus	190.000	210.000	1.27	1.27	1.12	1.12
fctb_25	0.650	0.800	0.87	0.87	0.92	0.92
thuse_12_5	0.300	0.500	0.77	0.77	0.87	0.87
tcdht	20.000	10.000	0.30	0.30	0.54	0.54
thuse_12_1	0.010	0.100	0.27	0.27	-0.52	-0.52
tczaag	35.000	40.000	0.22	0.22	0.46	0.46
tcplaa	20.000	25.000	0.19	0.19	0.43	0.43
bw	0.500	3.000	0.16	0.16	0.40	0.40
blc	0.050	0.040	0.14	0.14	-0.37	-0.37
tcembl	3.000	10.000	0.13	0.13	0.36	0.36
flc	0.300	0.250	0.06	0.06	-0.25	-0.25
thuse_12_2	0.010	0.100	0.04	0.04	-0.21	-0.21
fw	3.000	10.000	0.04	0.04	-0.19	-0.19
tcenrg	1.000	2.000	0.04	0.04	0.19	0.19
thuse_12_4	0.480	0.750	0.02	0.02	-0.15	-0.15
svol	1.000	5.000	0.02	0.02	0.14	0.14
mort	0.020	0.030	0.01	0.01	0.11	0.11
tcpap	2.000	5.000	0.01	0.01	0.10	0.10
thuse_12_3	0.100	0.200	0.00	0.00	0.05	0.05
dhout	1.000	2.000	0.00	0.00	0.03	0.03
litter	1.000	2.000	0.00	0.00	-0.03	-0.03
rw	0.500	5.000	0.00	0.00	0.00	0.00

Table K8:

Results of uncertainty analysis output CTOTAV of model CO2FIX for spruce under central European conditions. Robustness study: limit CC 0.46 instead of 0.45.

median: 320.3 cv: 10.9% r²: 0.99
 95% confidence interval: 258.4 - 397.1

Uncertainty contributions:

input	cent	limit	rrv%	rsv%	cv marg%	cv cond%
tcldc	2.000	4.000	51.72	3.06	7.80	5.11
cc	0.480	0.460	48.75	0.23	7.57	1.41
humc	0.030	0.050	43.73	6.01	7.17	3.38
tchdec	320.000	500.000	43.47	1.10	7.15	2.80
cchum	0.580	0.650	23.49	0.25	5.25	1.80
tedht	20.000	10.000	18.56	0.10	4.67	0.55
baden	410.000	450.000	5.24	3.09	2.48	3.20
groptb_25	19.400	21.300	2.32	0.24	1.65	2.39
humus	190.000	210.000	2.23	0.08	1.62	0.66
blc	0.050	0.040	1.22	0.08	-1.20	-1.61
thuse_12_5	0.300	0.500	1.00	1.00	1.08	1.08
tczaag	35.000	40.000	0.49	0.49	0.76	0.76
thuse_12_1	0.010	0.100	0.32	0.32	-0.61	-0.61
rctb_25	0.650	0.800	0.27	0.50	0.56	1.28
dhout	1.000	2.000	0.16	0.05	0.43	0.42
thuse_12_4	0.480	0.750	0.14	0.14	-0.40	-0.40
tcembl	3.000	10.000	0.11	0.11	0.36	0.36
fctb_25	0.650	0.800	0.10	0.04	0.34	0.37
thuse_12_2	0.010	0.100	0.09	0.09	-0.32	-0.32
litter	1.000	2.000	0.08	0.02	-0.30	-0.23
tcenrg	1.000	2.000	0.07	0.07	0.29	0.29
tcpap	2.000	5.000	0.06	0.06	0.28	0.28
rlc	0.100	0.150	0.05	0.02	-0.23	-0.37
fw	3.000	10.000	0.02	0.11	-0.16	-0.71
tcplaa	20.000	25.000	0.02	0.02	0.15	0.15
bw	0.500	3.000	0.01	0.10	0.11	0.66
flc	0.300	0.250	0.01	0.01	0.09	0.35
thuse_12_3	0.100	0.200	0.01	0.01	-0.08	-0.08
rw	0.500	5.000	0.00	0.02	-0.08	-0.28
bctb_25	0.300	0.400	0.00	0.13	0.06	0.65
mort	0.020	0.030	0.00	0.03	0.05	0.54
svol	1.000	5.000	0.00	0.02	0.03	0.30

Table K9:
Example input files for model CO2FIX

a. SPRUCE14.SPE:

```

*****
* SPRUCE14.SPE
* FIJNSPAR, on braunerde Im = 14.5 at T= 100 jaar, central Europa
* versie 13-11-1992 t.b.v. FACE; door IBN-DLO
* input file voor programma CO2.FOR
* gegevens: soorten parameters: groeiselheden, drogestof gehalte etc.
* CO2.FOR leest mbv MOFILP
*****
* boomsoort (max. 10 characters):
* SPECS:
  'spruce 14'
*-----
* GROPTB (25 getalparen): 0. site class
* aanwas volgens opbrengsttabel, Im = 14 at T=100. (Mitscherlich 1979)
* eerste regel: leeftijd; tweede regel: aanwas in m3 p.j.
  0., 10., 20., 25., 30., 35., 40., 45., 50., 55., 60., 65., 70.,
  75., 80., 85., 90., 95., 100., 105., 110., 115., 120., 150., 200.
  0., 6.0, 17.2, 19.2, 19.4, 19.4, 19.1, 18.6, 18.1, 17.4, 17.0, 16.4, 15.8,
  15.2, 14.6, 14.4, 13.8, 13.2, 12.6, 12.1, 11.6, 11.0, 10.6, 8.0, 6.0
*-----
* dichtheid van het hout (BADEN)
* koolstofgehalte van de drogestof (CC)
* BADEN:      CC:
  410.      ,   0.50
*-----
* assimilaten verdeling in relatie tot leeftijd. Hoeveelheid drogestof-
* groei in naalden, takken en wortels in verhouding tot stamaanwas.
* naalden (FCTB, 10 getalparen):
  0.0 , 10. , 20. , 30. , 40. , 60. , 80. , 100. , 150. , 999.
  1.0 , 1.0 , 0.75 , 0.65 , 0.65 , 0.7 , 0.75 , 0.85 , 1.0 , 1.2
* takken (BCTB, 10 getalparen):
  0. , 10. , 20. , 30. , 40. , 60. , 80. , 100. , 150. , 999.
  1.0 , 0.4 , 0.25 , 0.23 , 0.3 , 0.35 , 0.5 , 0.6 , 0.65 , 0.7
* wortels (RCTB, 10 getalparen):
  0. , 10. , 20. , 30. , 40. , 60. , 80. , 100. , 150. , 999.
  1.0 , 0.8 , 0.6 , 0.6 , 0.65 , 0.8 , 1.0 , 1.2 , 1.4 , 1.6
*-----
* turnover van verschillende biomassa componenten:
* naalden (FLC)
* takken (BLC)
* wortels (RLC)
* FLC:      BLC:      RLC:
  0.3      , 0.05      , 0.10
*-----
* mortaliteit/zelfdunning in geval van natuurbos (USE=0)
* MORT als fraktie per jaar:
* MORT:

```

0.02

*
* gemiddelde verblijftijd vastgelegd CO2 in stamhout:
* bij achterlating in het bos (natuurbosvariant, geen export: TCDHT):
* bij gebruik voor energie opwekking (TCENRG)
* bij gebruik als papier en karton (TCPAP)
* bij gebruik als emballage (TCEMBL)
* bij gebruik als plaathout (TCPLAA)
* bij gebruik als zaaghout (TCZAAG)
* TCDHT: TCENRG: TCPAP: TCEMBL: TCPLAA: TCZAAG:
20. , 1. , 2. , 3. , 20. , 35.

*
* humificatie en decompositie coëfficiënten (j-1):
* HUMC: TCLDEC: TCHDEC:
0.03 , 2.0 , 320.

*
* koolstofgehalte van humus:
* CCHUM
0.58

b. SPRUCE14.STA

```

*****
* SPRUCE14.STA
* Spruce on fertile braunerde Im = 14 at T = 100 in Europa
* versie 13-11-1992, t.b.v. FACE; door IBN-DLO
* input file voor programma CO2.FOR;;
* gegevens: standplaats parameters: boniteit, etc.
* CO2.FOR leest mbv MOFILP
*****
* omlooptijd (jr), aantal omlopen (jr), uitvoerinterval (jr),
* aanduiding of simulatie een (MCYCLE=0.) of opeenvolgende (MCYCLE=1.)
* groeicycli omvat (voor MCYCLE slechts 0 of 1 invullen), en parameter
* die bepaalt of er direct na dunning een extra uitvoer moet plaats-
* vinden (PARDUN=1: extra uitvoer, PARDUN=0.: geen extra uitvoer):
* CYCLE:   NCYCLE:   PRDEL:   MCYCLE:   PARDUN:
120.      , 3.      , 1.      , 1.      , 1.
* LET OP: Bij spontaan bos, zonder kap en afvoer van hout, wordt CYCLE
* alleen gebruikt om de simulatieperiode vast te stellen (= 2*CYCLE)
*-----
* correctie assimilatenverdeling naar blad, takken, en wortels in
* relatie tot groeiplaats (relatief t.o.v. optimale groei):
* SCFC:   | SCBC:   | SCRC:
1.0      , 1.0      , 1.2
*-----
* indication of self-thinning or mortality (INTEGER):
*
* USE=0: self-thinning according to percentage specified in ITREES.SPE
* USE=1: no self-thinning, possible thinning management specified in
*        tables THAGE, THVOL and THUSE
* USE:
1
*-----
* initiele biomassa (ton/ha)
* FW:      BW:      RW:      SVOL:
3.        , 0.5     , 0.5     , 1.
*-----
* initiele waarden voor dood hout, strooisel en stabiele humus (Mgha-1):
* DHOUT:   LITTER:   HUMUS:
0.        , 0.        , 190.
*-----
* leeftijden waarop een dunning wordt uitgevoerd:
* THAGES:
*
25. , 30. , 35. , 40. , 45. ,
50. , 55. , 60. , 65. , 70. ,
75. , 80. , 85. , 90. , 95. ,
100. , 105. , 110. , 999. , 999. ,
999. , 999. , 999. , 999. , 999.
*
* fractie van het totale stamvolume dat verwijderd wordt:
* FVOLTH:
*
0.07, 0.09, 0.09, 0.09, 0.08,
0.08, 0.07, 0.07, 0.07, 0.07,

```

0.07, 0.07, 0.07, 0.07, 0.07,
 0.08, 0.08, 0.08, 0.00, 0.00,
 0.00, 0.00, 0.00, 0.00, 0.00

*

* allocation of stemwood in thinning to product categories, including
 * dead wood left in the forest, for each of 25 thinnings:

*

* NOTE: last line (line 26) contains use of products at final harvest!!

*

DWOOD:	ENERGY:	PAPER:	EMBAL:	BOARD:	CONSWD:	THAGES
1.0	, 0.0	, 0.0	, 0.0	, 0.0	, 0.0	! 25
0.2	, 0.0	, 0.8	, 0.0	, 0.0	, 0.0	! 30
0.2	, 0.0	, 0.8	, 0.0	, 0.0	, 0.0	! 35
0.2	, 0.0	, 0.8	, 0.0	, 0.0	, 0.0	! 40
0.2	, 0.0	, 0.8	, 0.0	, 0.0	, 0.0	! 45
0.1	, 0.0	, 0.9	, 0.0	, 0.0	, 0.0	! 50
0.1	, 0.0	, 0.9	, 0.0	, 0.0	, 0.0	! 55
0.1	, 0.0	, 0.0	, 0.1	, 0.8	, 0.0	! 60
0.1	, 0.0	, 0.0	, 0.1	, 0.8	, 0.0	! 65
0.1	, 0.0	, 0.0	, 0.1	, 0.6	, 0.2	! 70
0.1	, 0.0	, 0.0	, 0.1	, 0.6	, 0.2	! 75
0.1	, 0.0	, 0.0	, 0.1	, 0.5	, 0.3	! 80
0.1	, 0.0	, 0.0	, 0.1	, 0.5	, 0.3	! 85
0.1	, 0.0	, 0.0	, 0.1	, 0.4	, 0.4	! 90
0.1	, 0.0	, 0.0	, 0.1	, 0.4	, 0.4	! 95
0.1	, 0.0	, 0.0	, 0.1	, 0.3	, 0.5	! 100
0.1	, 0.0	, 0.0	, 0.1	, 0.3	, 0.5	! 105
0.1	, 0.0	, 0.0	, 0.0	, 0.2	, 0.7	! 110
0.0	, 0.0	, 0.0	, 0.0	, 0.0	, 0.0	! 999
0.0	, 0.0	, 0.0	, 0.0	, 0.0	, 0.0	! 999
0.0	, 0.0	, 0.0	, 0.0	, 0.0	, 0.0	! 999
0.0	, 0.0	, 0.0	, 0.0	, 0.0	, 0.0	! 999
0.0	, 0.0	, 0.0	, 0.0	, 0.0	, 0.0	! 999
0.0	, 0.0	, 0.0	, 0.0	, 0.0	, 0.0	! 999
0.0	, 0.0	, 0.0	, 0.0	, 0.0	, 0.0	! 999
0.1	, 0.0	, 0.0	, 0.0	, 0.1	, 0.8	! final

*-----

Table K10:
Specification of inputs: central values, uncertainties, and correlations

SPECIFICATION OF INPUT UNCERTAINTY DISTRIBUTION FOR INPUTS CO2FIX

Version: SPRUCE14

Files: 1 species data (e.g. SPRUCE14.SPE)
2 stand data (e.g. SPRUCE14.STA)

Types: 1 normal distribution
(for unrestricted inputs)
2 normal distribution after log transformation
(for inputs >=0)
3 normal distribution after logistic transformation
(for inputs >=0 and <=1)
>=4 normal distribution after logratio transformation
(for components of a composition vector with values
0<=x<=1 and sum(x)=1);
all inputs with the same type index (within categories C and D
separately) belong to one composition vector;
1-SUM(x) is the reference class value

cen = (backtransformed) central value
lim = (backtransformed) upper or lower limit of 95% confidence interval

Sampling method: 0 systematic sample
n simple random sample with n runs
-n Latin hypercube sample on orthogonalized variables
with n runs

A. General:

seed for random generator	epsilon (for transformations close to 0 or 1)	Sampling method (nruns)	reduction factor for uncertainties
1221312	1E-6	-100	1

B. Basic input specification files:

1 - species inputs 2 - stand inputs
'spruce14.spe' 'spruce14.sta'

C. individual inputs

identification:

file #	name	type	cen	lim
1	30 groptb_25	2	19.4	21.3
1	51 baden	2	410	450
1	52 cc	2	0.48	0.45
1	67 fctb_25	2	0.65	0.8
1	87 bctb_25	2	0.30	0.4
1	107 rctb_25	2	0.65	0.8
1	113 flc	2	0.3	0.25
1	114 blc	2	0.05	0.04
1	115 rlc	2	0.10	0.15
1	116 mort	3	0.02	0.03
1	117 tcdht	2	20.	10.
1	118 tcenrg	2	1.	2.
1	119 tcpap	2	2.	5.
1	120 tcembl	2	3.	10.
1	121 tcplaa	2	20.	25.
1	122 tczaag	2	35.	40.
1	123 humc	2	0.03	0.05
1	124 tcldec	2	2.0	4.0
1	125 tchdec	2	320.	500.
1	126 cchum	2	0.58	0.65
2	10 fw	2	3.	10.
2	11 bw	2	0.5	3.
2	12 rw	2	0.5	5.
2	13 svol	2	1.	5.
2	14 dhout	2	1.	2.
2	15 litter	2	1.	2.
2	16 humus	2	190.	210.
2	134 thuse_12_1	4	0.01	0.10
2	135 thuse_12_2	4	0.01	0.10
2	136 thuse_12_3	4	0.1	0.20
2	137 thuse_12_4	4	0.48	0.75
2	138 thuse_12_5	4	0.3	0.5

D. strictly coupled ('slaved') inputs

identification	coupled to:	type	cen
file # name	file # name		
1	26 groptb_21	1 30 groptb_25	2 0.0
1	27 groptb_22	1 30 groptb_25	2 6.0
1	28 groptb_23	1 30 groptb_25	2 17.2
1	29 groptb_24	1 30 groptb_25	2 19.2
1	31 groptb_26	1 30 groptb_25	2 19.4
1	32 groptb_27	1 30 groptb_25	2 19.1
1	33 groptb_28	1 30 groptb_25	2 18.6
1	34 groptb_29	1 30 groptb_25	2 18.1

1	35	groptb_210	1	30	groptb_25	2	17.4
1	36	groptb_211	1	30	groptb_25	2	17.0
1	37	groptb_212	1	30	groptb_25	2	16.4
1	38	groptb_213	1	30	groptb_25	2	15.8
1	39	groptb_214	1	30	groptb_25	2	15.2
1	40	groptb_215	1	30	groptb_25	2	14.6
1	41	groptb_216	1	30	groptb_25	2	14.4
1	42	groptb_217	1	30	groptb_25	2	13.8
1	43	groptb_218	1	30	groptb_25	2	13.2
1	44	groptb_219	1	30	groptb_25	2	12.6
1	45	groptb_220	1	30	groptb_25	2	12.1
1	46	groptb_221	1	30	groptb_25	2	11.6
1	47	groptb_222	1	30	groptb_25	2	11.0
1	48	groptb_223	1	30	groptb_25	2	10.6
1	49	groptb_224	1	30	groptb_25	2	8.0
1	50	groptb_225	1	30	groptb_25	2	6.0
1	63	fctb_21	1	67	fctb_25	2	1.0
1	64	fctb_22	1	67	fctb_25	2	1.0
1	65	fctb_23	1	67	fctb_25	2	0.75
1	66	fctb_24	1	67	fctb_25	2	0.65
1	68	fctb_26	1	67	fctb_25	2	0.7
1	69	fctb_27	1	67	fctb_25	2	0.75
1	70	fctb_28	1	67	fctb_25	2	0.85
1	71	fctb_29	1	67	fctb_25	2	1.0
1	72	fctb_210	1	67	fctb_25	2	1.2
1	83	bctb_21	1	87	bctb_25	2	1.0
1	84	bctb_22	1	87	bctb_25	2	0.4
1	85	bctb_23	1	87	bctb_25	2	0.25
1	86	bctb_24	1	87	bctb_25	2	0.23
1	88	bctb_26	1	87	bctb_25	2	0.35
1	89	bctb_27	1	87	bctb_25	2	0.5
1	90	bctb_28	1	87	bctb_25	2	0.6
1	91	bctb_29	1	87	bctb_25	2	0.65
1	92	bctb_210	1	87	bctb_25	2	0.7
1	103	rctb_21	1	107	bctb_25	2	1.0
1	104	rctb_22	1	107	bctb_25	2	0.8
1	105	rctb_23	1	107	bctb_25	2	0.6
1	106	rctb_24	1	107	bctb_25	2	0.6
1	108	rctb_26	1	107	bctb_25	2	0.8
1	109	rctb_27	1	107	bctb_25	2	1.0
1	110	rctb_28	1	107	bctb_25	2	1.2
1	111	rctb_29	1	107	bctb_25	2	1.4
1	112	rctb_210	1	107	bctb_25	2	1.6
2	68	thuse_1_1	2	134	thuse_12_1	4	0.01
2	74	thuse_2_1	2	134	thuse_12_1	5	0.01
2	80	thuse_3_1	2	134	thuse_12_1	6	0.01
2	86	thuse_4_1	2	134	thuse_12_1	7	0.01
2	92	thuse_5_1	2	134	thuse_12_1	8	0.01
2	98	thuse_6_1	2	134	thuse_12_1	9	0.01
2	104	thuse_7_1	2	134	thuse_12_1	10	0.01
2	110	thuse_8_1	2	134	thuse_12_1	11	0.01

2	116	thuse_9_1	2	134	thuse_12_1	12	0.01
2	122	thuse_10_1	2	134	thuse_12_1	13	0.01
2	128	thuse_11_1	2	134	thuse_12_1	14	0.01
2	140	thuse_13_1	2	134	thuse_12_1	15	0.01
2	146	thuse_14_1	2	134	thuse_12_1	16	0.01
2	152	thuse_15_1	2	134	thuse_12_1	17	0.01
2	158	thuse_16_1	2	134	thuse_12_1	18	0.01
2	164	thuse_17_1	2	134	thuse_12_1	19	0.01
2	170	thuse_18_1	2	134	thuse_12_1	20	0.01
2	218	thuse_26_1	2	134	thuse_12_1	21	0.01
2	69	thuse_1_2	2	135	thuse_12_2	4	0.01
2	75	thuse_2_2	2	135	thuse_12_2	5	0.76
2	81	thuse_3_2	2	135	thuse_12_2	6	0.76
2	87	thuse_4_2	2	135	thuse_12_2	7	0.76
2	93	thuse_5_2	2	135	thuse_12_2	8	0.76
2	99	thuse_6_2	2	135	thuse_12_2	9	0.86
2	105	thuse_7_2	2	135	thuse_12_2	10	0.86
2	111	thuse_8_2	2	135	thuse_12_2	11	0.01
2	117	thuse_9_2	2	135	thuse_12_2	12	0.01
2	123	thuse_10_2	2	135	thuse_12_2	13	0.01
2	129	thuse_11_2	2	135	thuse_12_2	14	0.01
2	141	thuse_13_2	2	135	thuse_12_2	15	0.01
2	147	thuse_14_2	2	135	thuse_12_2	16	0.01
2	153	thuse_15_2	2	135	thuse_12_2	17	0.01
2	159	thuse_16_2	2	135	thuse_12_2	18	0.01
2	165	thuse_17_2	2	135	thuse_12_2	19	0.01
2	171	thuse_18_2	2	135	thuse_12_2	20	0.01
2	219	thuse_26_2	2	135	thuse_12_2	21	0.01
2	70	thuse_1_3	2	136	thuse_12_3	4	0.01
2	76	thuse_2_3	2	136	thuse_12_3	5	0.01
2	82	thuse_3_3	2	136	thuse_12_3	6	0.01
2	88	thuse_4_3	2	136	thuse_12_3	7	0.01
2	94	thuse_5_3	2	136	thuse_12_3	8	0.01
2	100	thuse_6_3	2	136	thuse_12_3	9	0.01
2	106	thuse_7_3	2	136	thuse_12_3	10	0.01
2	112	thuse_8_3	2	136	thuse_12_3	11	0.10
2	118	thuse_9_3	2	136	thuse_12_3	12	0.10
2	124	thuse_10_3	2	136	thuse_12_3	13	0.10
2	130	thuse_11_3	2	136	thuse_12_3	14	0.10
2	142	thuse_13_3	2	136	thuse_12_3	15	0.10
2	148	thuse_14_3	2	136	thuse_12_3	16	0.10
2	154	thuse_15_3	2	136	thuse_12_3	17	0.10
2	160	thuse_16_3	2	136	thuse_12_3	18	0.10
2	166	thuse_17_3	2	136	thuse_12_3	19	0.10
2	172	thuse_18_3	2	136	thuse_12_3	20	0.01
2	220	thuse_26_3	2	136	thuse_12_3	21	0.01
2	71	thuse_1_4	2	137	thuse_12_4	4	0.01
2	77	thuse_2_4	2	137	thuse_12_4	5	0.01
2	83	thuse_4_4	2	137	thuse_12_4	6	0.01
2	89	thuse_3_4	2	137	thuse_12_4	7	0.01
2	95	thuse_5_4	2	137	thuse_12_4	8	0.01
2	101	thuse_6_4	2	137	thuse_12_4	9	0.01

2	107	thuse_7_4	2	137	thuse_12_4	10	0.01
2	113	thuse_8_4	2	137	thuse_12_4	11	0.77
2	119	thuse_9_4	2	137	thuse_12_4	12	0.77
2	125	thuse_10_4	2	137	thuse_12_4	13	0.58
2	131	thuse_11_4	2	137	thuse_12_4	14	0.58
2	143	thuse_13_4	2	137	thuse_12_4	15	0.48
2	149	thuse_14_4	2	137	thuse_12_4	16	0.38
2	155	thuse_15_4	2	137	thuse_12_4	17	0.38
2	161	thuse_16_4	2	137	thuse_12_4	18	0.30
2	167	thuse_17_4	2	137	thuse_12_4	19	0.30
2	173	thuse_18_4	2	137	thuse_12_4	20	0.20
2	221	thuse_26_4	2	137	thuse_12_4	21	0.10

2	72	thuse_1_5	2	138	thuse_12_5	4	0.01
2	78	thuse_2_5	2	138	thuse_12_5	5	0.01
2	84	thuse_3_5	2	138	thuse_12_5	6	0.01
2	90	thuse_4_5	2	138	thuse_12_5	7	0.01
2	96	thuse_5_5	2	138	thuse_12_5	8	0.01
2	102	thuse_6_5	2	138	thuse_12_5	9	0.01
2	108	thuse_7_5	2	138	thuse_12_5	10	0.01
2	114	thuse_8_5	2	138	thuse_12_5	11	0.01
2	120	thuse_9_5	2	138	thuse_12_5	12	0.01
2	126	thuse_10_5	2	138	thuse_12_5	13	0.20
2	132	thuse_11_5	2	138	thuse_12_5	14	0.20
2	144	thuse_13_5	2	138	thuse_12_5	15	0.30
2	150	thuse_14_5	2	138	thuse_12_5	16	0.40
2	156	thuse_15_5	2	138	thuse_12_5	17	0.40
2	162	thuse_16_5	2	138	thuse_12_5	18	0.48
2	168	thuse_17_5	2	138	thuse_12_5	19	0.48
2	174	thuse_18_5	2	138	thuse_12_5	20	0.67
2	222	thuse_26_5	2	138	thuse_12_5	21	0.77

:

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E. non-zero correlations between transformed inputs category C
(specify at least 1 correlation)

=====

identif. 1	identif. 2	correlation
file # name	file # name	
1	30 groptb_25 1	51 baden -0.3
1	30 groptb_25 1	67 fctb_25 -0.3
1	30 groptb_25 1	87 bctb_25 -0.3
1	30 groptb_25 1	107 rctb_25 -0.3
1	30 groptb_25 1	113 flc 0.3
1	30 groptb_25 1	115 rlc 0.3
1	30 groptb_25 1	116 mort 0.3
1	30 groptb_25 1	117 tedht -0.3
1	30 groptb_25 1	117 tezaag -0.3
1	30 groptb_25 1	124 teldec -0.3
1	30 groptb_25 1	125 tchdec , -0.3
1	52 cc	1 117 tedht 0.3
1	52 cc	1 123 humc 0.5

1	52	cc	1	124	teldec	0.5
1	52	cc	1	125	tchdec	0.3
1	52	cc	1	126	cchum	0.5
1	113	flc	1	114	blc	0.8
1	113	flc	1	115	rlc	0.8
1	113	flc	1	116	mort	0.8
1	114	blc	1	115	rlc	0.8
1	114	blc	1	116	mort	0.8
1	115	rlc	1	116	mort	0.8
1	117	tedht	1	123	humc	0.3
1	117	tedht	1	124	teldec	0.5
1	117	tedht	1	125	tchdec	0.3
1	123	humc	1	124	teldec	0.3
1	123	humc	1	125	tchdec	0.3
1	123	humc	1	126	cchum	0.3
1	124	teldec	1	125	tchdec	0.5
1	125	tchdec	1	126	cchum	0.5
1	126	cchum	2	16	humus	0.5
2	10	fw	2	11	bw	0.8
2	10	fw	2	12	rw	0.8
2	10	fw	2	13	svol	0.8
2	11	bw	2	12	rw	0.8
2	11	bw	2	13	svol	0.8
2	12	rw	2	13	svol	0.8
2	14	dhout	2	15	litter	0.8
2	14	dhout	2	16	humus	0.3
2	15	litter	2	16	humus	0.3

Table K11: Implementation of uncertainty analysis: diagram of procedures. Use is made of VAX/VMS command files (*.COM), Genstat programs (*.GEN) and Fortran programs (*.EXE). The most important files for input and output are boxed. The command @batch 1 performs the upper part of the calculations and gives files SIMY1.DAT, SIMX1.DAT and SIMP1.DAT. The command gf reg,s=10 then asks for the index number (here 1) and performs the regression analysis.

