

Interception and water recharge following afforestation

Experiences from oak and norway spruce chronosequences in Denmark, Sweden and The Netherlands

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Published in Environmental effects of Afforestation in north-western Europe - From field experiments to decision support - edited by Gerrit W. Heil, Bart Muys and Karin Hansen, (2006), 53-77, Springer, The Netherlands

CHAPTER 3

INTERCEPTION AND WATER RECHARGE FOLLOWING AFFORESTATION: EXPERIENCES FROM OAK AND NORWAY SPRUCE CHRONOSEQUENCES IN DENMARK, SWEDEN AND THE NETHERLANDS

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Abstract. The long-term effects of afforestation on hydrological fluxes were investigated using a series of forests of different age planted on comparable soils (chronosequences) in Sweden, Denmark and the Netherlands. Rainfall, throughfall, soil moisture contents and groundwater dynamics were monitored at two oak chronosequences and four spruce chronosequences during a period of one to two years. At all chronosequences, the hydrological fluxes were simulated using a hydrological simulation model. The model was validated on measured throughfall data, soil water contents and CI fluxes. Afforestation has a clear influence on the water recharge of the considered sites. Water recharge is generally lower under spruce compared to oak. In the spruce stands 5–30% of the incoming precipitation leads to water recharge to ground and surface water, whereas water recharge in the oak stands ranges between 20–35% of the precipitation. In general, water recharge declined with an increase of the stand age. At the oak stands leaching decreased from 35 to 20% of the precipitation in the first 30 years. In the spruce stands the water recharge varied considerable between the four investigated chronosequences but in general, the decline in water recharge was approximately 100–150 mm (10–20%). In both oak and spruce stands, losses by soil evaporation slightly declined. Transpiration slightly increased in the oak stands and transpiration remained fairly stable in the spruce stands. It can be concluded that afforestation leads to a reduction in water recharge compared to agricultural use. This reduction is mainly due to an increase in interception

evaporation. The strongest reduction is found when sites are afforested with dense spruce forests. The smallest impact is found in open deciduous forest, which has lower interception evaporation.

1. INTRODUCTION

Afforestation may have adverse environmental effects such as the reduction of water recharge to groundwater and surface water due to higher transpiration of forest compared to agricultural land. Several studies were carried out to investigate the effects of changes in forest cover on the water recharge (Bosch & Hewlett 1982; Blackie 1993, Sahin & Hall 1996). These studies indicate that water recharge declines with an increase in forest cover. The decline in recharge is generally larger for coniferous forest compared to deciduous forests. The reductions in recharge strongly differ from site to site due to differences in climate, site characteristics and field layer. Most of the results are based on clear cut experiments in paired catchments and strongly focus on the difference between a mature forest stand and a clear cut. Much less information is available on changes in the water balance in the years between initial afforestation and mature forest. Moreover, data on the changes in the contribution of the various hydrological fluxes to the water balance, such as interception losses, soil evaporation and transpiration are relatively scarce.

The above mentioned studies indicated that afforestation strongly influences the hydrology of the afforested area. To make decisions on afforestation of former agricultural areas in Europe more information on the impact of afforestation on hydrological fluxes is needed. In order to increase the knowledge on the long-term effects of afforestation a series of forests of different age planted on comparable soils (chronosequences) were investigated in the AFFOREST project.

This chapter describes the results of two oak chronosequences and four spruce chronosequences. At all chronosequences, the hydrological fluxes were simulated using a hydrological simulation model. Simulated throughfall fluxes, water contents and groundwater levels were compared with monthly measured values at the different sites. The specific objectives were i) to estimate interception and water recharge after afforestation of former arable land, and ii) to determine the differences in these hydrological fluxes for coniferous and deciduous tree species.

2. METHODS

2.1. General approach

Chronosequences of oak and spruce were selected in Denmark, southern Sweden and the Netherlands (Chapter 1). At each chronosequence, hydrological conditions were measured monthly during a period of one to two years. Soil hydrological fluxes were modeled using a dynamic simulation model. The model was validated on measured throughfall data and soil water contents. The simulated hydrological fluxes were used to calculate Chloride (Cl) leaching fluxes at the bottom of the root zone (section 2.5). The calculated Cl budgets were used as a final validation of the calculated fluxes.

2.2. Study sites

The hydrology of six chronosequences was studied. Two of these chronosequences were afforested with oak and four with Norway spruce. The oak forests were located in Denmark on a clay soil and in the Netherlands on a sandy soil. The spruce chronosequences were located in Sweden (sandy soil), Denmark (one on a sandy soil and one on a clay soil) and the Netherlands (sandy soil). A description of the sites is given in Chapter 1 and on the AFFOREST website (www.sl.kvl.dk/afforest).

Throughfall was measured using 10-15 collectors at each site. Precipitation was measured in an open field within a distance of 2 km from the sites. Soil water contents were measured using TDR equipment and used for validation of the hydrological model. In Sweden and Denmark, the TDR probes (PRENART) were located within fixed depth intervals of 0-20 cm, 0-50 cm, and for Denmark only, within 0-90 cm. In the Netherlands, soil moisture contents were measured from 10-100 cm depth at an interval of 10 cm using a portable TDR probe (TRIME-T3) which was lowered in to plastic access tubes (TECANAT). TDR measurements were carried out once a month at 3-9 points within each plot (see details on www.sl.kvl.dk/afforest). The height of the groundwater table was measured once a month at the Dutch sites where the groundwater table was within 3 m of the soil surface.

2.3. Model description

The water balance of a forest stand can be described as:

$$P = E + R + D + Q + \Delta S \quad (1)$$

in which P is the precipitation, E is the evapotranspiration, Q is the vertical leaching flux (recharge) to the groundwater, R is runoff, D is the lateral drainage and ΔS is the change in the amount of water in the soil profile. Evapotranspiration is divided in interception evaporation (E_i), transpiration (E_t) and soil evaporation (E_s) according to:

$$E = E_i + E_t + E_s \quad (2)$$

The various terms of the water balance were calculated using the Darcy model SWAP (Van Dam et al. 1997). This model provides a finite difference solution to the Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(K(h) \left(\frac{\partial h}{\partial z} + 1 \right) \right) - S(h) \quad (3)$$

where θ ($\text{m}^3 \text{m}^{-3}$) is the volumetric water content, t (d) is time, z (m) the vertical position in the soil, h (m) soil water pressure head, K (m d^{-1}) hydraulic conductivity and S (d^{-1}) the sink term accounting for root water uptake (actual transpiration).

The potential loss of water by evapotranspiration is calculated using the Penman-Monteith equation (Monteith 1981):

$$E_{pm} = \frac{1}{\lambda} \frac{s R_n + \rho C_p \delta q / r_a}{s + \gamma(1 + r_s / r_a)} f_s \quad (4)$$

where E_{pm} is the potential evapotranspiration (mm d^{-1}), λ is the specific heat of evaporation (J kg^{-1}), s is the slope of the saturated water vapour curve ($\text{hPa } ^\circ\text{K}^{-1}$), R_n is the net radiation (W m^{-2}), ρ is the density of air (kg m^{-3}), C_p is the specific heat capacity of the air ($\text{J g}^{-1} ^\circ\text{K}^{-1}$), δq is the water vapour deficit (hPa), r_a and r_s are the aerodynamic and the crop resistances (s m^{-1}), γ is a psychrometer coefficient ($\text{mbar } ^\circ\text{C}^{-1}$) and f_s is the number of seconds per day.

The potential evapotranspiration is divided into interception evaporation, potential soil evaporation and potential transpiration. When the canopy is wet, r_s is zero and the Penman-Monteith equation reduces to:

$$E_{wet} = \frac{\frac{1}{\lambda} (s R_n + \rho C_p / r_a \delta q)}{(s + \gamma)} \quad (5)$$

Potential transpiration is calculated from the potential evapotranspiration, given by Eq. 4, by reducing the evapotranspiration during rainfall with the calculated interception evaporation according to:

$$E_t^* = \frac{(s + \gamma)}{(s + \gamma (1 + r_c / r_a))} (E_{wet} - E_i) \quad (6)$$

The total amount of interception (E_i) is calculated according to Gash (1995):

$$E_i = sc P \quad (7)$$

when $P < P_s$, or as:

$$E_i = sc P_s + sc \frac{E_{avg}}{R_{avg}} (P - P_s) \quad (8)$$

when $P > P_s$, where sc is the soil cover fraction(-), R_{avg} is the average rainfall rate (mm hr^{-1}), E_{avg} the average daily evaporation rate during rainfall (mm hr^{-1}), P the daily precipitation (mm d^{-1}) and P_s (mm d^{-1}) is the amount of rainfall to saturate the canopy:

$$P_s = \frac{R_{avg}}{E_{avg}} S_{max} sc \ln \left(1 - \frac{E_{avg}}{R_{avg}} \right) \quad (9)$$

where S_{max} is the storage capacity of the crown (mm). Lateral drainage to a local drainage network (ditches) was calculated by:

$$q_d = \frac{\Phi_{avg} - \Phi_d}{\gamma_d} \quad (10)$$

where q_d ($\text{m}^3 \text{m}^{-2} \text{d}^{-1}$) is the flux of water to the local drainage system, Φ_d (m) is hydraulic head of drainage system, and γ_d (d) is drainage resistance. In order to distribute the discharge rates over the soil layers, first a discharge layer is determined by considering a travel-time distribution. The most important assumption in this computational procedure is that lateral discharge occurs parallel to equidistant water courses (distance L_k (m)), cf. Van Dam et al. 1997). Within this discharge layer, the lateral drainage from soil layer i to the local drainage system, $R_{d,L,i}$, is calculated with the equation (see Eq. 3 for symbols):

$$R_{d,L,i} = \frac{q_d}{\Delta z_i} \frac{K_i \Delta z_i}{\sum (K_i \Delta z_i)} \quad (11)$$

2.4. Model parameters

The model SWAP needs meteorological data, abiotic characteristics of the site (soil physical characteristics, drainage characteristics) and vegetation dependant parameters (crop resistance, LAI, parameters to calculate interception, tree height, root distribution) in order to calculate the hydrological fluxes.

2.4.1. Meteorological data

The model needs input of a set of daily meteorological data on precipitation, net radiation, temperature, wind speed and relative humidity. These data were not collected on the site but taken from nearby meteorological stations (Table 3.1).

Table 3.1. *Origin of the meteorological data used in the model calculations.*

Site	Location	Distance
Tönnersjöheden, S	Torup	25 km
	Göteborg ¹⁾	120 km
Vestskoven, DK	Højbakkegård	4 km
	Værløse ²⁾	8 km
Gejlvang, DK	Billund	11 km
Sellingen, NL	Nieuw Beerta	30 km
Drenthe, NL	Eelde ³⁾	20-30 km

¹⁾ All meteorological data were derived from Torup except global radiation, which was derived from Göteborg.

²⁾ Data from the beginning of 1996 to May 2001 are from Højbakkegård. Data from May 2001 to the end of 2002 are from grid cell Værløse.

³⁾ For the 14 yr old spruce stand at Drenthe, data from Nieuw Beerta were used.

Precipitation may vary considerably over short distances, leading potentially to large differences in daily precipitation between data from a (nearby) meteorological station and the actual measured precipitation at the site. To obtain the best estimate of the daily precipitation at the site, daily precipitation data were corrected based on the measured precipitation at the open field close to forest sites according to:

$$P_{i,site} = P_{i,station} \cdot \frac{P_{period,site}}{P_{period,station}} \quad (12)$$

where $P_{i,site}$ is the daily precipitation at the site, $P_{i,station}$ is the daily precipitation measured at the meteorological station, $P_{period,site}$ is the measured precipitation at the site during a period of one month and $P_{period,station}$ is the precipitation measured at the meteorological station during this period.

2.4.2. Abiotic characteristics

The model SWAP uses information on the physical characteristic of the soil, data on the hydrological conditions at the bottom boundary and drainage characteristics (cf. groundwater and drainage).

Water retention characteristics and conductivity data for Drenthe, Vestskoven and Gejlvang were selected from the Staring soil series (Wösten et al. 1994). For Tönnersjöheden, data were based on the HYPRES (Hydraulic properties of European soils) database (Wösten et al. 1999). For all sites, water retention characteristics for the organic layer were based on data from a Dutch Douglas fir site (Tiktak & Bouten 1994).

At Sellingen, water retention characteristics were measured in the mineral soil at 15-20 cm, 40-45 cm and 80-85 cm depth. These data were allocated to the different layer sin the soil profile (Table 3.2). At some sites measured saturated water

contents were calibrated on measured maximum water contents in the field during the winter period (cf. section 3.1). Data on saturated conductivity were based on the Staring soil series (Wösten et al. 1994).

Table 3.2. Soil hydrological characteristics for the Dutch oak sites at Sellinger.

Depth	θ_{res}	Θ_{sat}	α	n	K_{sat}	l
Oak, Sellinger, NL: 4 years						
0-40	0.052	0.36	0.010	2.29	32.2	-0.983
40-60	0.023	0.34	0.013	2.02	63.9	0.039
> 60	0.023	0.34	0.015	1.91	63.9	0.039
Oak, Sellinger, NL: 8 years						
0-1*	0.000	0.5	0.100	1.25	800	0.0178
1-40	0.064	0.36	0.009	2.44	32.2	-0.983
40-60	0.039	0.34	0.011	2.02	63.9	0.039
> 60	0.005	0.34	0.013	2.14	63.9	0.039
Oak, Sellinger, NL: 11 years						
0-2*	0.000	0.5	0.100	1.25	800	0.0178
2-40	0.042	0.36	0.009	2.14	32.2	-0.983
40-60	0.018	0.34	0.012	2.20	63.9	0.039
> 60	0.000	0.34	0.014	1.73	63.9	0.039
Oak, Sellinger, NL: 18 years						
0-3*	0.000	0.5	0.100	1.25	800	0.0178
3-40	0.028	0.36	0.012	2.04	32.2	-0.983
40-60	0.007	0.34	0.011	2.17	63.9	0.039
> 60	0.005	0.34	0.012	2.13	63.9	0.039

Depth = depth of soil layer, [cm]

θ_{res} = Residual water content, [$cm^3 cm^{-3}$]

Θ_{sat} = Saturated water content, [$cm^3 cm^{-3}$]

α = Shape parameter of main drying curve, [cm^{-1}]

n = Shape parameter, [-]

K_{sat} = Saturated hydraulic conductivity, [$cm d^{-1}$]

l = Exponent in hydraulic conductivity function, [-]

* = Organic litter layer

Free drainage of the soil profile was assumed as the groundwater level was deeper than 3 meters at most sites except from the Dutch oak sites at Sellinger and the two youngest Dutch spruce sites. At these sites with shallow groundwater tables, the fluxes at the bottom of the soil profile were calculated as a function of the groundwater level (Ernst & Feddes 1979):

$$Q_{bot} = a e^{b\phi_{avg}} \quad (13)$$

with Q_{bot} is the flux at the bottom boundary, a (cm d^{-1}) and b (cm^{-1}) are parameters. Values for the parameters a and b (Table 3.3) are based on literature data (De Visser & De Vries 1989).

Table 3.3. Bottom boundary conditions, parameters $a = [\text{cm d}^{-1}]$ and $b = [\text{cm}^{-1}]$.

Site	a	b
Sellingeng	-0.7	-0.03
Drenthe (8 yr old)	-0.2	-0.01
Drenthe (13 yr old)	-0.4	-0.02

The Dutch oak stands were drained by ditches. Lateral drainage to the ditches at these sites was calculated using data on drainage resistance, the spacing, depth and water level of the ditches (Table 3.4). Water level of ditches was measured monthly and used as input for the model. Drainage resistances were calibrated on measured groundwater levels and soil moisture contents.

Table 3.4. Drainage characteristics for the oak stands at Sellingeng, the Netherlands.

Parameter	Unit	4 years	8 years	11 years	18 years
Drainage resistance	d	150	300	1200	800
Ditch spacing	m	300	600	1000	1000
Depth of the ditches	cm	-140	-148	-166	-182
Average water level in ditches ¹	cm	-121 (± 5)	-131 (± 5)	-146 (± 5)	-161 (± 5)

¹ Average water level over the measurement period in cm below the soil surface

2.4.3. Vegetation characteristics.

The most important crop parameters used by the model are tree height, canopy resistance, leaf area index (LAI), storage capacity of the canopy ($S_{\max}$), soil cover (sc) and root distribution. Tree height and LAI were based on measurements (Table 3.5 & Table 3.6). Root distribution data were estimated based on visual examination of the soil profile and literature data on average root distribution for spruce and oak (De Visser & De Vries 1989). Parameters describing the interception were calibrated on measured throughfall data (Table 3.5 & Table 3.6).

Table 3.5. *The most important stand characteristics for the oak stands used in the model calculations.*

Site	Age in 2002	Years after afforest.	Height (m)	LAI ($\text{m}^{-2} \text{m}^2$)	Canopy resistance (s m^{-1})	Interception parameters	
						$S_{\max}$ (cm)	Sc (-)
Vestskoven, DK	9	9	2.6	2.9	60	0.05	0.68
Vestskoven, DK	14	14	6.0	4.5	60	0.08	0.75
Vestskoven, DK	23	23	11.0	5.1	60	0.14	0.77
Vestskoven, DK	25	25	10.1	4.4	60	0.09	0.81
Vestskoven, DK	32	32	13.8	5.3	60	0.14	0.79
Sellingén, NL	6	4	3.2	3.6	85	0.05	0.20
Sellingén, NL	10	8	6.3	3.6	85	0.10	0.30
Sellingén, NL	14	11	7.6	4.3	85	0.15	0.50
Sellingén, NL	21	18	10.3	3.3	85	0.15	0.60

Table 3.6. *The most important stand characteristics for the spruce stands used in the model calculations.*

Site	Age in 2002	Years after afforest.	Height (m)	LAI ($\text{m}^{-2} \text{m}^2$)	Canopy resistance (s m^{-1})	Interception parameters	
						$S_{\max}$ (cm)	Sc (-)
Tönnersjöheden, S	19	19	10.1	5.6	50	0.07	0.91
Tönnersjöheden, S	30	30	15.5	5.8	50	0.32	0.95
Tönnersjöheden, S	65	65	19.3	3.4	80	0.26	0.83
Tönnersjöheden, S	74	74	24.1	3.3	80	0.20	0.71
Tönnersjöheden, S	92	92	35.7	3.4	80	0.38	0.82
Vestskoven, DK	5	5	1.9	3.5	60	0.10	0.60
Vestskoven, DK	12	12	6.1	5.7	60	0.15	0.75
Vestskoven, DK	14	14	8.4	5.4	60	0.15	0.67
Vestskoven, DK	29	29	13.3	7.1	60	0.22	0.79
Vestskoven, DK	33	33	17.8	8.5	60	0.25	0.90
Gejlvang, DK	8	8	1.8	6.7	60	0.22	0.86
Gejlvang, DK	21	21	10.0	8.8	60	0.35	0.99
Gejlvang, DK	26	26	12.9	7.2	60	0.24	0.86
Gejlvang, DK	42	42	16.5	8.1	60	0.25	0.95
Drenthe, NL	11	8	6	5.6	140	0.17	0.85
Drenthe, NL	16	13	8	4.3	140	0.23	0.97
Drenthe, NL	17	14	7	5.1	140	0.40	0.99

2.5. Calibration and validation

Interception was calibrated on measured rainfall and throughfall data by adjusting the estimated parameters for soil cover (sc) and storage capacity of the canopy (S_{max}). Initial values for soil cover were based on field estimates and data for the storage capacity of the crown were based on a literature review (De Vries et al. 2001). Normally, parameter values for the storage capacity and the soil cover are derived from analyses of data from single storms using the analysis method by Leyton (Leyton et al. 1967). Such an analysis could not be made for these study sites as only monthly throughfall data were available.

Soil water fluxes were calibrated on measured groundwater levels and water contents. The simulated soil water contents are influenced by both the hydraulic characteristics, drainage characteristics, and the crop characteristics. Parameters were adjusted when clear deviations between measured and simulated water contents did occur. For example, when measured water contents in winter were systematically overestimated, the hydraulic characteristics were adapted. When measured water contents in summer were systematically lower than simulated water contents, crop resistances were increased to reduce the transpiration. At the shallow drained Dutch sites, drainage parameters (Table 3.4) affected the simulated groundwater level and water contents most strongly. These parameters were adjusted on basis of the winter period when transpiration can be neglected. The other parameters were calibrated later on using the full simulation period.

A final check on the validity of the calculated hydrological fluxes can be made by calculating Cl balances for the considered plots. Chloride is considered to behave as a conservative element in the soil solution and the long-term output of Cl by leaching should thus be equal to the long-term input of Cl by throughfall. In practice, substantial deviations in the Cl budgets may occur due to changes in water storage and uncertainties in Cl concentrations in both input and output. This uncertainty is particularly large when short time periods (< 3 years) are considered. For example, at the Solling spruce stand in Germany the Cl budgets for a period of 13 year was 0.7 kg ha⁻¹ yr⁻¹, whereas budgets for individual years ranged from -20 to 30 kg ha⁻¹ yr⁻¹ (van der Salm et al. 2004). At the chronosequences, the monitoring period was 2 years or less. This period is too short to use the budgets for fine tuning of the hydrological model. However, the budgets may give a rough indication of the reliability of the calculated fluxes.

3. RESULTS

3.1. Simulated interception

Calibrated values for soil cover of the oak stands increased from 0.2 to 0.8 with an increase in age (Table 3.5). Values for soil cover were considerably higher for the Danish sites compared to the Dutch sites. The storage capacity of the oak trees increased from 0.05 to 0.15 cm. Calibrated values for storage capacity were generally lower in Denmark than in the Netherlands. The differences in calibrated

parameter values between the Dutch and Danish sites do not correspond with differences in stem density and LAI between the Netherlands and Denmark. On average, stem density was lower in Denmark (average approx. 2900 stems/ha) compared to the Netherlands (average approx. 6000 stems/ha) and LAI was somewhat higher in Denmark (average 4.4) compared to the Netherlands (average 3.7). The different values obtained for the Netherlands and Denmark are caused by the fact that the parameters soil cover and storage capacity can not be calibrated independently on monthly measured throughfall data. Lower values for soil cover together with higher values for storage capacity may lead to comparable simulated throughfall fluxes. This is not a serious problem when studying the long-term effects of afforestation, as long as the obtained values for soil cover and storage capacity are used in combination. For a more detailed analysis of the hydrology on a daily-weekly scale, derivation of the parameters according to the method described by Leyton et al. (1967) is advised.

In the spruce stands, the calibrated values for the soil cover were higher than in the oak stands and increased from 0.60 to 0.99. The storage capacity of the crown was also considerably higher and ranged from 0.1 in the youngest stand to 0.4 in the older spruce stands.

Yearly simulated interception fluxes were generally within 5% of the measured values in 2002 (Figure 3.1). Substantial deviations were found in the youngest spruce stand at Vestskoven where interception losses are underestimated by 50% (70 mm) and the youngest oak stand in Sellingeren where interception was overestimated by 68% (60 mm).

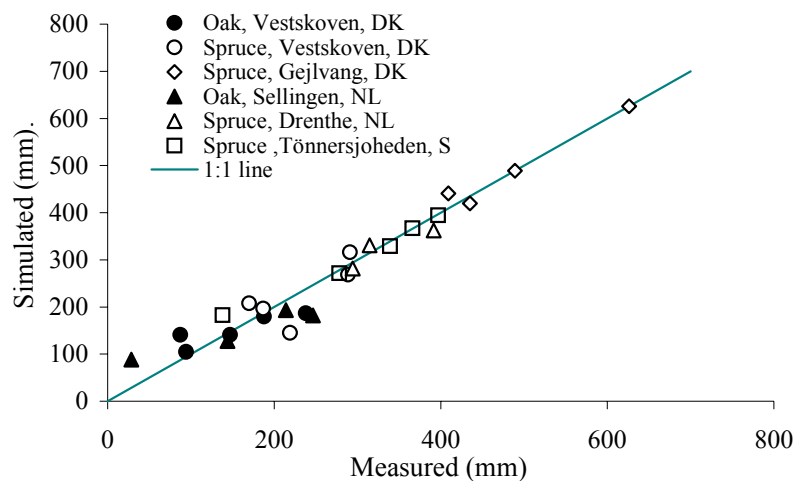


Figure 3.1. Measured and simulated yearly interception fluxes (mm) for 2002.

3.2. Simulated soil water contents

The model simulated measured soil water contents quite well in most stands. Examples of the simulated and the measured soil water content are shown for the 18-yr old oak stand at Sellingen and the 9-yr old oak stand at Vestskoven, the 33-yr old spruce stand at Vestskoven, the 42-yr old spruce stand at Gejlvang and the 76-yr old spruce stand at Tönnersjöheden (Figure 3.2). At the 18-yr old oak stand at Sellingen (NL), the simulated water contents at 20 cm depth were generally within the range of measured values at the 3 measurement points within the plot. However, extremely high water contents ($0.42 \text{ cm}^3 \text{ cm}^{-3}$) occurring in autumn and winter 2001/2002 were underestimated ($0.36 \text{ cm}^3 \text{ cm}^{-3}$), indicating that the simulated drainage fluxes are too high. On the other hand, in summer, simulated water contents at 20 cm depth tended to be slightly ($0.05 \text{ cm}^3 \text{ cm}^{-3}$) higher than measured values. Simulated water contents at the 9-yr old oak stand at Vestskoven were close to measured values throughout the year. However, measurements in summer are relatively sparse making it difficult to compare the simulated results with the actual situation in the summer period.

In all the spruce stands, the measured water contents were generally close to measured values. The best results were obtained for the site at Gejlvang with the exception of spring 2001, where the model underestimated the soil water contents with up to $0.07 \text{ cm}^3 \text{ cm}^{-3}$. At Vestskoven, simulated water contents tended to be lower than measured values in winter 2000-2001, whereas water contents were slightly overestimated in winter 2002. At Tönnersjöheden the simulated seasonal variation in water contents was much lower than at the Dutch and Danish sites. In winter, measured and simulated water contents fluctuated between 0.25-0.30. This pattern was simulated by the model although sometimes a slight shift between measured and simulated peaks occurred, which may be due to uncertainties in the prediction of snow melt events or effects of freezing and thawing of the soil, which is not included in the model. In summer 2002, two dry episodes occurred at Tönnersjöheden that led to a drop in the simulated water contents. During the first dry episode, TDR measurements were absent, but during the second dry episode simulated water contents were close to measured values.

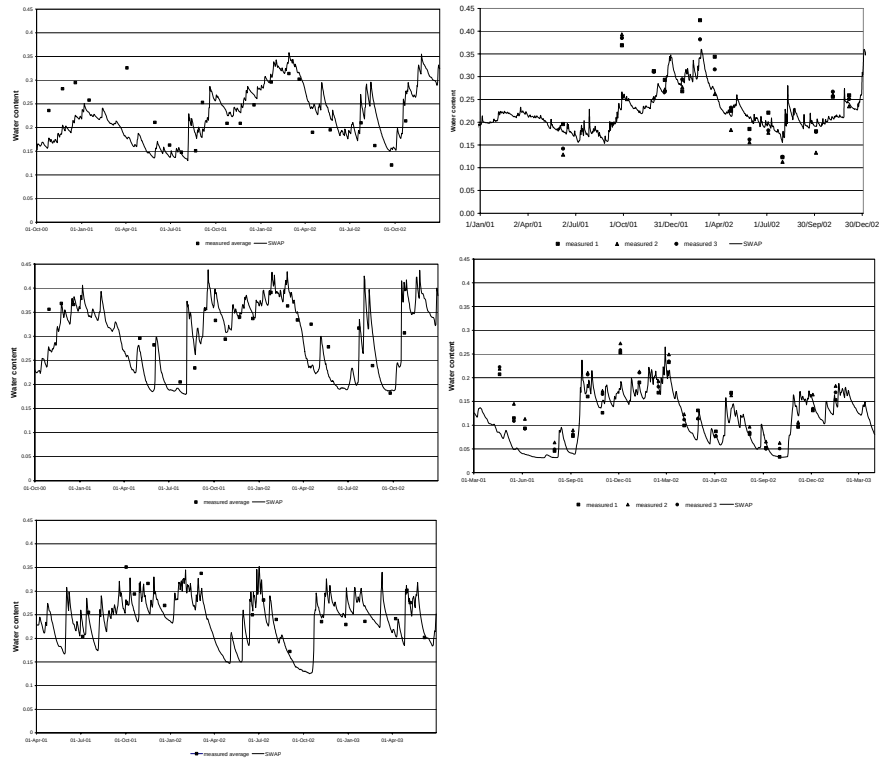


Figure 3.2. Measured and simulated water content at 20 cm below surface for (top left) the 33-yr old spruce stand at Vestskoven, (top right) the 18-yr old oak stand at Sellingen, (middle left) the 9-yr old oak stand at Vestskoven, (middle right) the 42-yr old spruce stand at Gejlvang and (bottom left) the 73-yr old spruce stand at Tönnersjöheden.

3.3. Chloride balances

Chloride input ranged from approximately $17 \text{ kg ha}^{-1} \text{ yr}^{-1}$ at the youngest oak stand at Vestskoven to more than $120 \text{ kg ha}^{-1} \text{ yr}^{-1}$ at the oldest spruce stand at Gejlvang. Budgets ranged from -30 to $23 \text{ kg ha}^{-1} \text{ yr}^{-1}$ (Figure 3.3). One third of the stands had a negative budget (losing more Cl than what comes in). At the remaining stands, the Cl leaching flux was lower than the throughfall flux, indicating that the hydrological model tended to underestimate the leaching fluxes. This is confirmed by the mean ratio of $\text{Cl}_{\text{out}}/\text{Cl}_{\text{in}}$ which was 0.94.

At the oak chronosequences the budgets at 90 cm depth ranged between -11.1 to $9.1 \text{ kg ha}^{-1} \text{ yr}^{-1}$. At most of the stands, the Cl output was within 25% of the Cl input, except for the two youngest oak stands at Vestskoven where chloride output was considerably higher than the input. The median ratio of $\text{Cl}_{\text{out}}/\text{Cl}_{\text{in}}$ was 1.16 for the

Vestskoven oak chronosequences. The output fluxes tended to be higher than input fluxes at the young stands and the opposite at the older stands. At the Dutch oak stand at Sellingen, the median ratio of Cl_{out}/Cl_{in} was 0.99. At the 4 and the 11 years old stand the Cl leaching was within 3% of the Cl throughfall fluxes. At the other two stands, a deviation of approximately 22% was found.

Deviations in the Cl budgets were generally somewhat larger for the spruce stands and ranged from -30.3 to $23.3 \text{ kg ha}^{-1} \text{ yr}^{-1}$. In the Netherlands and Sweden the median Cl ratio was approximately 1.1. Considerable deviations were found at the older spruce stands at Drenthe due to uncertainties in throughfall and leaching fluxes due to drought (van der Salm et al. 2005). In Sweden, Cl output fluxes were substantial higher than input fluxes for the youngest and the oldest stands. This is caused by rather high Cl concentrations in January 2002. When the period April 2001 to April 2003 was considered the Cl output was about $20 \text{ kg ha}^{-1} \text{ yr}^{-1}$ lower at both sites. At the Danish spruce stands, Cl output fluxes were consistently higher than input fluxes in the young sites (up to 14 years old), leading to a median Cl ratio of 0.8.

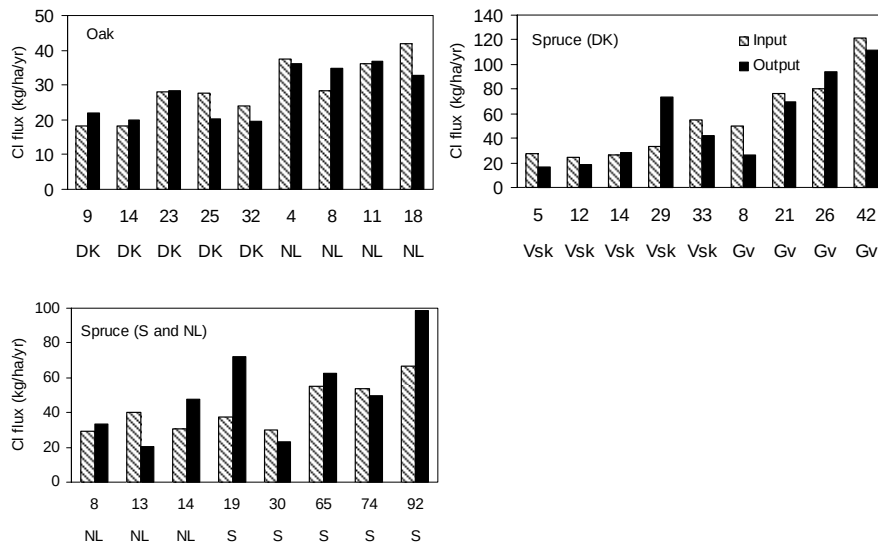


Figure 3.3. Chloride input and output fluxes for 2002 for the six chronosequences. *Vsk* = Vestskoven, *DK* and *Gv* = Gejlvang, *DK*.

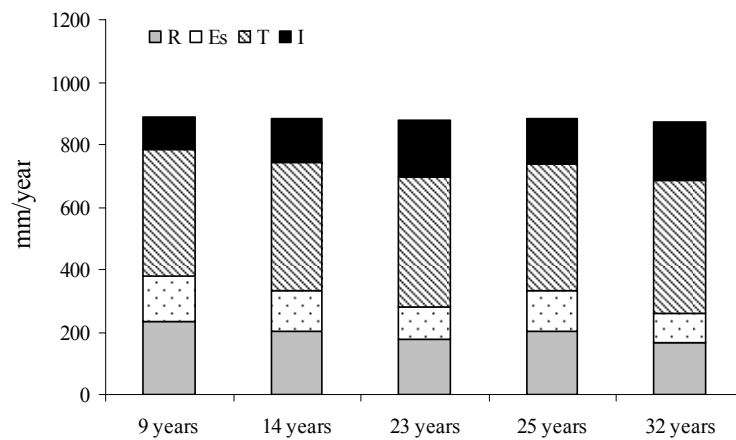
3.4. Water balances

3.4.1. Oak stands

Water balances for the Dutch and Danish oak stands were quite comparable (Figure 3.4), despite differences in soil type, drainage and climate. The Danish oak stands

received almost 900 mm of precipitation in 2002, whereas the Dutch site received a somewhat higher precipitation (1033 mm). About 10-20% (100-200 mm) of the precipitation is lost by interception (Figure 3.4). The largest amount of water is lost by transpiration (45-50%). Calculated transpiration fluxes amounted to approximately 400 mm in Denmark and 450 mm in the Netherlands. Soil evaporation fluxes ranged between 100 and 150 mm. Water recharge by drainage and leaching ranged from 200 mm in Denmark to 300 mm in the Netherlands.

a)



b)

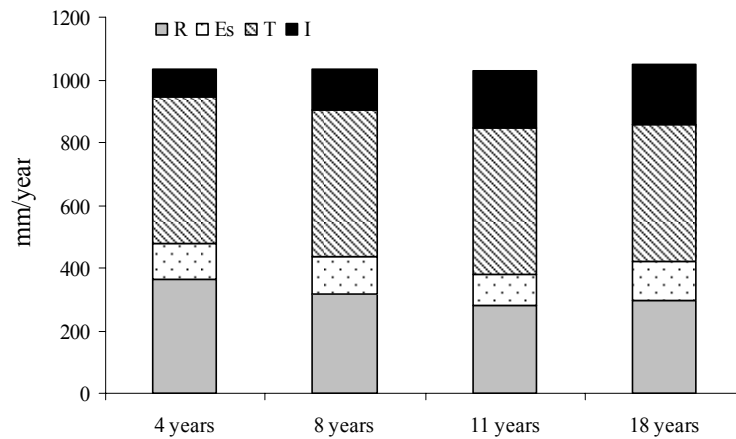


Figure 3.4. Water balances for the oak chronosequences at a) Vestskoven and b) Sellingen (R= water recharge, E_s = soil evaporation, T= transpiration, I= interception).

3.4.2. Spruce stands

Water balances for the four spruce stands differed considerably, mostly due to differences in climate and density of the forests (Figure 3.5). The Swedish spruce stands and the Danish spruce stands at Gejlvang received more precipitation (approximately 1100-1200 mm) than the Dutch site and the Danish site at Vestskoven (approximately 900 mm). Interception losses ranged from less than 150 mm in the youngest stand at Vestskoven to more than 600 mm in the 21-yr old spruce stand at Gejlvang. Interception accounted for 15-50% of the total water loss in the spruce stands. Losses by soil evaporation were generally low and ranged between 20 and 70 mm. Soil evaporation losses are considerably lower than in the oak stands due to the higher soil cover resulting in a lower amount of radiation reaching the forest floor. Transpiration fluxes ranged between 300 mm in the relative dry Dutch spruce stands to 450 mm in the wetter Swedish and Danish sites. Water recharge ranged from less than 50 mm in the oldest Dutch spruce stand to more than 300 mm at Gejlvang (DK) and Tönnersjöheden (S).

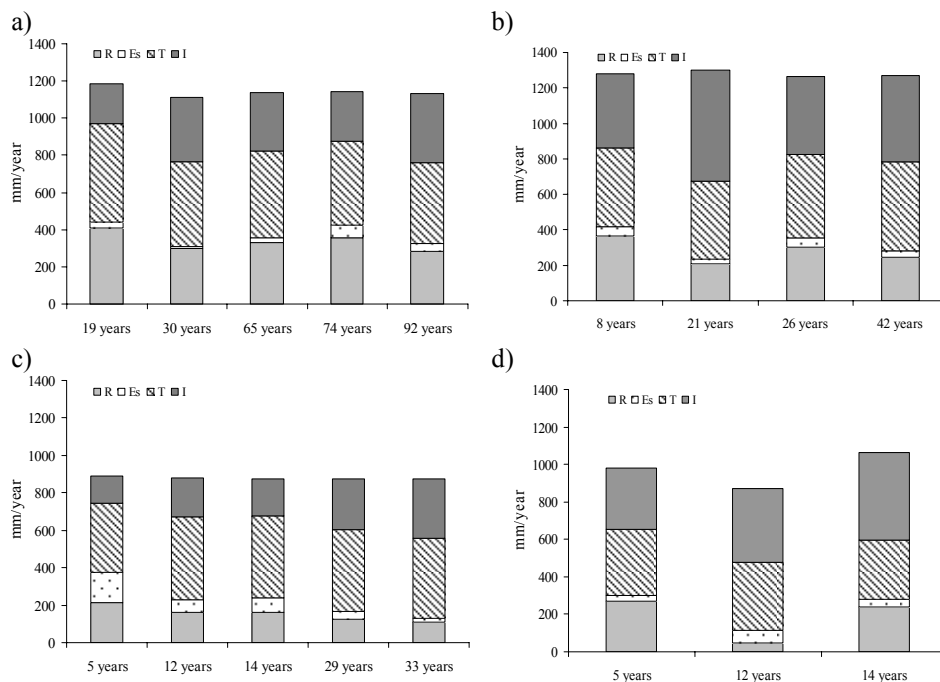


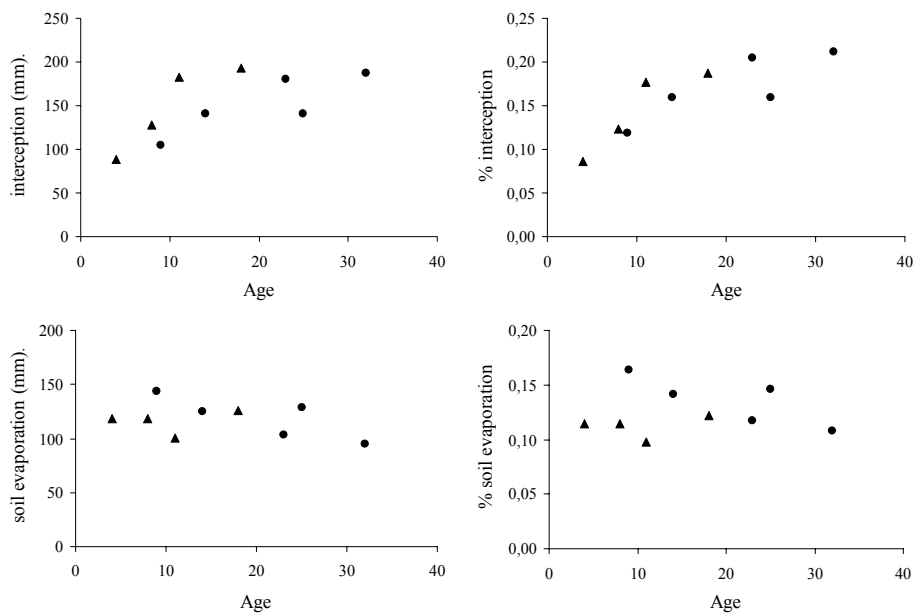
Figure 3.5. Water balances for the spruce chronosequences at a) Tönnersjöheden, b) Gejlvang, c) Vestskoven and d) Drenthe (R= water recharge, Es= soil evaporation, T= transpiration, I= interception).

3.5. Changes in water balances with age

3.5.1. Oak stands

The hydrological fluxes were in the same order of magnitude at the oak chronosequences in Denmark and the Netherlands. The change in fluxes with age of the trees showed a rather coherent pattern (Figure 3.6). Interception losses increased from 90 mm in the 4-yr old stand in Sellinger to approximately 200 mm at an age of 15-20 years. The strongest increase was found in the first 15 years and leveled off afterwards. Losses by interception were less than 10% at the youngest stand and increased to approximately 20% in the oldest stands.

Soil evaporation was more or less constant in the Dutch stands (120 mm, 10% of the rainfall). In the Danish sites a slight decline was found from 145 to 95 mm (15-10%). These differences are caused by differences in management. At the Dutch sites management is absent and a dense herb layer is present, limiting soil evaporation. At the Danish sites weed control is more intensive during the first years after afforestation leading to a lower soil cover.



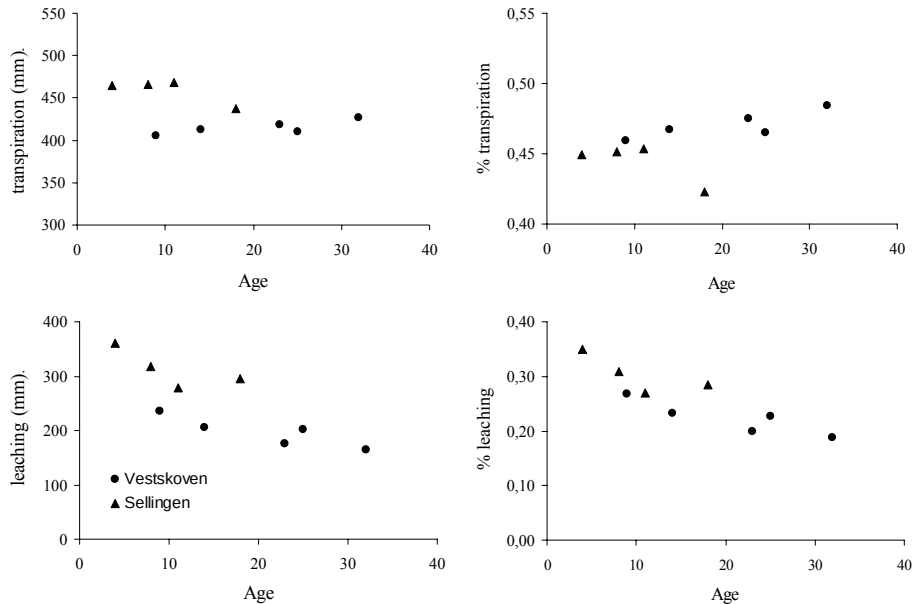


Figure 3.6. Absolute hydrological fluxes (interception, soil evaporation, transpiration and leaching) (mm) and relative hydrological fluxes (% of precipitation) in the oak stands in 2002 as a function of age.

Transpiration was almost constant at the Dutch sites and showed a slight increase with age at the Danish sites. Leaching clearly decreased with age from almost 400 mm in the youngest Dutch site to less than 200 mm in the older Danish sites. At the Danish sites, leaching fluxes were lower due to the lower precipitation and the decline was slightly less (from 240 mm to 170 mm). A more coherent picture of the changes in leaching with age can be obtained by expressing the leaching flux as a percentage of the precipitation. Leaching decreased from 35% in the 4-yr old oak stand to 19% in the 30-yr old stand. The fastest decline is found in the first 15-20 year and it levels off after canopy closure. Linear regression showed that the average decline is 6 mm yr^{-1} or $0.5\% \text{ yr}^{-1}$ (Table 3.7).

3.5.2. Spruce stands

The variation in hydrological fluxes between the various spruce stands was much larger than for the oak stands, due to more pronounced differences in climate, age and planting density. Interception increased with age in the first 40 years. The Swedish sites showed that interception losses remain at a fairly constant level with a further increase in age (Figure 3.7). The fraction of precipitation lost by interception at the Vestsboven chronosequence, the two oldest plots of the Gejlvang chronosequence and the youngest plots of the Tönnersjöheden chronosequences,

were quite similar and increased from less than 20% at the 8-yr old stand to approximately 40% 40 years after afforestation. The interception losses at the Dutch chronosequence and the two youngest plots of the Gejlvang chronosequence also increased with age but losses were much higher and increased from 34% at the 8-yr old stand to 53% at the 20-yr old stand in Gejlvang. The high losses in the two youngest stands at Gejlvang can be explained by the high stem number (5800 stems/ha) compared to the other sites. The stem number and also the height of the Dutch chronosequence are in the same order of magnitude as most of the Vestskoven stands.

Soil evaporation generally decreased in the first 40 years after afforestation from more than 75 mm to less than 20 mm. However, differences between the individual stands were substantial. For example, simulated soil evaporation varied from 160 mm at the 8-yr old stand in Vestskoven to 28 mm at the 8-yr old stand in the Netherlands.

Table 3.7. Change in water recharge as a function of age.

Site	Species	Precipitation (mm)	Leaching unit	Equation	R ² _{adj}
NL+DK	oak	900-1000	(mm)	345 – 6 Age	0.66
			%	0.34 – 4.9 10 ⁻³ Age	0.75
S	spruce	1100	(mm)	384 – 0.9 Age	0.29
			(%)	0.34 – 0.8 10 ⁻³ Age	0.29
Vestskoven, DK	spruce	900	(mm)	213 – 3.2 Age	0.91
			(%)	0.24 – 3.2 10 ⁻³ Age	0.91
Gejlvang, DK	spruce	1200	(mm)	350 – 2.9 Age	0.35
			(%)	0.29 – 2.4 10 ⁻³ Age	0.35
NL	spruce	1000	(mm)	324 -13.0 Age	0.27
			(%)	0.34- 1.3 10 ⁻² Age	0.27

Changes in transpiration with age differed somewhat for the four chronosequences. At the Dutch chronosequence, a decline in transpiration was found, probably due to drought stress caused by the high interception losses. At the Danish chronosequence at Vestskoven, transpiration was almost constant (440 mm), whereas transpiration increased from 440 to 500 mm at the Danish chronosequence at Gejlvang. At the Swedish chronosequence, a decline was found from 520 mm at the 19-yr old stand to 430 mm at the 92-yr old stand.

Leaching decreased with age at all the chronosequences (Figure 3.7, Table 3.7). The strongest decline was found at the Dutch chronosequence and at the Danish chronosequence at Vestskoven where leaching decreased with respectively 13.0 and 3.2 mm yr⁻¹. The decline in leaching flux was slightly less (2.9 mm yr⁻¹) at the other Danish chronosequence (Gejlvang) as the site is wetter and less fertile. The lowest

decline in leaching rate was found at the mature forest stands in Sweden, where leaching declined with 0.9 mm yr^{-1} .

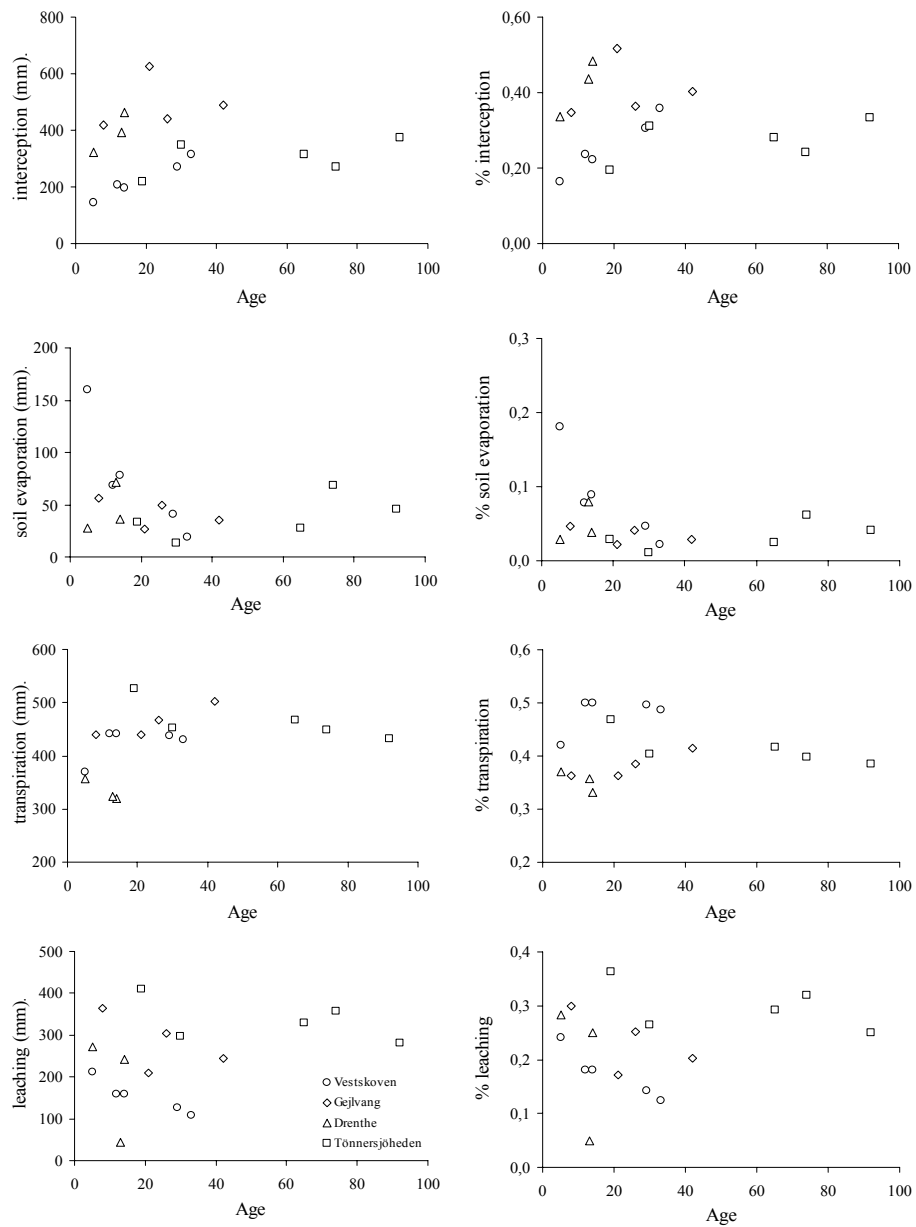


Figure 3.7. Absolute hydrological fluxes (mm) and relative hydrological fluxes (% of precipitation) in the spruce stands in 2002 as a function of age.

4. DISCUSSION

4.1. Validity of the simulated fluxes

The model was able to simulate measured throughfall fluxes and soil water contents quite satisfactorily in the different forest stands. However, the model was only validated for a period of one to two years. Chloride budgets were constructed to have an additional possibility for validation. Median Cl leaching fluxes were within 6% of the Cl input by throughfall. However, at two thirds of the stands the Cl output flux was lower than Cl input flux. At most stands, the deviations in the Cl budgets were due to uncertainties in the measured concentrations in throughfall and soil solution or caused by changes in the amount of water storage in the soil profile during the considered period. At the Danish spruce stands, however, Cl output fluxes were consistently underestimated in the young stands (up to 14 years old), suggesting an underestimation of the water recharge at the considered stands.

Another possibility to test the validity of the obtained results is to compare them with literature data on water recharge from various European forest stands published between 1987 and 2000 (van der Salm et al. 2006). These data originated from 34 different sites in north-western Europe, including 6 oak and 7 spruce sites. In general, leaching fluxes obtained in our study are somewhat lower compared to the literature data (Figure 3.8).

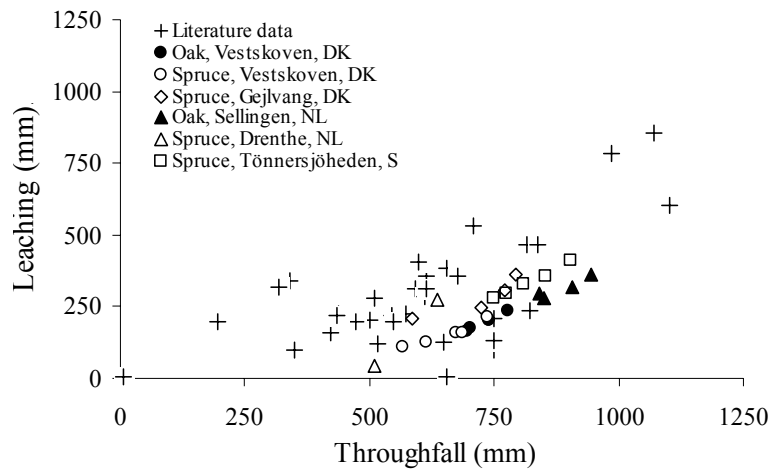


Figure 3.8. Yearly leaching fluxes (mm) for 34 European stands (literature data) compared to the data simulated for the AFFOREST chronosequences.

These lower fluxes are mainly caused by higher simulated transpiration fluxes. For example, simulated transpiration in the oak stands in Denmark and the Netherlands ranged from 400 to 460 mm. Literature data for oak in the Netherlands and Denmark indicated values between 260 and 300 mm (Bouten et al. 1992; Dolman 1988; Hendriks et al. 1990; Ladekarl 1998; van Grinsven et al. 1987). Transpiration fluxes

for spruce in the studied area are relatively scarce. Bouten & Jansson (1995) presented values for Sollingen in Germany (323 mm), Boyle et al. (2000) found a value of 167 mm in Ireland. For Klosterhede in Denmark, transpiration was around 300 mm (Beier 1998), whereas intensive measurements in Norunda (Sweden) led to values between 181 and 243 mm during the growing season (Grelle et al. 1997; Jansson et al. 1999). All these values are considerably lower than values obtained for the chronosequences in Denmark, Sweden and the Netherlands, which ranged between 300 and 500 mm. These higher transpiration fluxes may partly be explained by the fact that the studied chronosequences are often located on fine textured soils with a good water supply (Sellingen, Vestskoven) or in high precipitation areas (Tönnersjöheden, Gejlvang).

4.2. Validity of the simulated changes in fluxes with age

Literature data indicated a clear increase in water recharge with an increase in forest area in catchments (Bosch & Hewlett 1982; Blackie 1993; Calder 1990). A statistical analysis of an international database on afforestation/deforestation experiments showed that 100% deforestation resulted in a change in water recharge of 330 mm in coniferous forests and 200 mm in deciduous forests (Sahin & Hall 1996). The data found in the chronosequences correspond quite well with these general figures. In the oak chronosequences, leaching decreased from almost 400 mm in the youngest Dutch site to less than 200 mm in the older Danish sites. In the spruce stands, the observed decline in leaching fluxes ranged between 100-230 mm. This reduction seems to be considerably lower than the data presented by Sahin & Hall (1996). However, even in the youngest stands in the chronosequence, the water recharge is strongly reduced compared to a deforested situation. For example, interception losses in the youngest stands accounted for a water loss of 150 mm. Data for the Netherlands also indicated that leaching from the 8-yr old spruce stand was 100-200 mm lower when compared to agricultural use (van der Salm et al. 2005b). When these initial losses are accounted for, the total reduction in water recharge is 200-400 mm, which is in the same order as the literature data.

The reduction in water recharge upon afforestation is mainly due to an increase in interception evaporation and transpiration. Both interception evaporation and transpiration increase with LAI (Hibbert 1967; Rudakov 1973). Reported interception losses range from 15-25% for deciduous forests and from 20-40% in coniferous forest (Hibbert 1967). These values are comparable with the data in the chronosequences, where interception decreased from 9 to 20% at the oak sites and from 16 to 52% at the spruce sites. Under comparable circumstances, the increase in interception losses with age should be faster in coniferous forest compared to oak (Aussenac & Boulangeat 1980). Similar results are found at the studied chronosequences. In the oak stands the interception increases with 4-7% in 10 years, whereas in the spruce stands the increase ranged from 7-13% in 10 years.

Transpiration is reported to increase with age by approximately 100 mm in 10 years in spruce and by approximately 50 mm in oak stands (Molchanov 1960; Aussenac 1970; Murakami et al. 2000) due to an increase in LAI. In the examined chronosequences the increase in transpiration is generally less than reported in

literature. At the oak chronosequence at Sellingen, the transpiration rates remain stable and at the Vestskoven stand the increase is only 10 mm/10 year. At the spruce chronosequences in Denmark, an increase of 20 mm was found in 10 years. In the Dutch and Swedish spruce chronosequences, no increase in transpiration rate was found. The low or negligible increases in the transpiration at the chronosequences may be (partly) explained by the limited changes in LAI compared to the forest stands mentioned in literature. However, CI budgets indicated that the transpiration fluxes tended to be somewhat overestimated in the young (spruce) stands. If the CI budgets are correct this may also explain the limited changes in transpiration fluxes between the young and the old stands. Molchanov (1960) further reported a decline in transpiration in coniferous forest at an age of 40 years or more. These data are affirmed by the Tönnersjöheden chronosequence where transpiration declined by 35 mm between an age of 65 and 92 year.

5. CONCLUSIONS

Changes in hydrological fluxes upon afforestation were studied in six chronosequences in Sweden, Denmark and the Netherlands. Changes in interception evaporation were investigated by measuring rainfall and throughfall fluxes in the various forest stands. Changes in water recharge (leaching) were modelled using the soil hydrological model SWAP. The model was validated using measured soil water contents. The calculated fluxes were compared to CI budgets for the various stands.

Results showed that the model was able to simulate throughfall fluxes, soil water contents and ground water levels quite well in the different forest stands. Median CI leaching fluxes were within 6% of the chloride input by throughfall. At some sites the CI budgets deviated substantially from zero (-30 to 23 kg ha⁻¹ yr⁻¹). This is not surprising as the monitoring period is rather short and changes in soil water content and errors in individual measurements of CI concentrations may substantially influence the budgets. Taking these uncertainties into account the results are acceptable for most of the sites. Exceptions are for the youngest spruce stands in Denmark (< 14 year old), where CI output fluxes and thus water recharge are systematically underestimated.

Afforestation has a clear influence on the water recharge of the considered sites. Water recharge is generally lower under spruce compared to oak. In the spruce stands, 5–30% of the incoming precipitation leads to water recharge to groundwater and surface water. In the oak stands, 20–35% of the precipitation is lost as water recharge. In general, water recharge declined with increasing stand age. In the oak stands, leaching decreased from 35 to 20% of the precipitation in the first 30 years. In the spruce stands, the water recharge differed considerably for the four chronosequences that were investigated. In general, the decline in water recharge in the spruce stands was approximately 100–150 mm (10–20%). The decline in water recharge is mainly caused by an increase in interception evaporation. In the oak stands, interception losses increased by more than 100 mm (from 10% of the precipitation in the youngest stands to 20% at an age of 30 years). In the spruce stands, interception evaporation increased with 100 to 200 mm and interception was responsible for 20 to 40% of the water losses. In both the oak and spruce stands,

losses by soil evaporation slightly declined. Transpiration slightly increased in the oak stands and transpiration remained fairly stable in the spruce stands.

The results found in this study support the general picture of effects of afforestation as based on literature from deforestation studies. Upon afforestation a decline in water recharge of 200-400 mm can be expected. This decline is strongly determined by the increase in interception evaporation, which is larger under spruce compared to oak. Literature data also stress the impact of increasing transpiration in the period from afforestation to canopy closure. In our study, the increase in LAI and the associated increase in transpiration was very limited (10-20 mm/10 years) compared to literature data (50-100 mm/10 years).

The above mentioned results show that afforestation leads to a reduction in water recharge compared to agricultural use. This reduction is mainly due to an increase in interception evaporation. The strongest reduction is found when sites are afforested with dense spruce forests. The smallest impact is found in open deciduous forest, which has lower interception evaporation.

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