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Modeling the Impact of Canopy Structure on the Spatial Variability of Net Forest Precipitation and Interception Loss in Scots Pine Stands

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Abstract: The aim of this study was to identify the most significant stand parameters affecting net forest precipitation and interception loss in Scots pine stands and to develop multiple linear regression models (MLR) that can be used for practical purposes to predict net forest precipitation and interception rates in northern Germany using forest inventory data and gross precipitation. In the model, the forest canopy is characterized by four parameters: mean tree height, diameter at breast height, number of stems and canopy cover fraction. The meteorological input is only annual gross precipitation.

Keywords: Rainfall-interception, *Pinus sylvestris*, multiple linear regressions, Northern Germany lowlands.

INTRODUCTION

To ensure the groundwater resources and the stability of forest under changing climate conditions, the water budget of forests is an essential topic today [1]. The interception rate is a major factor in the water balance [2, 3], because the annual evapotranspiration must normally be fewer than the annual rainfall [4]. Regressions of calculated seepage flow below the rooting zone and the amount of throughfall have been found to be remarkably constant [5]. A simple method to predict the amount of seepage water is the use of regression models between annual gross rainfall and net precipitation on the one hand and net precipitation and seepage flow on the other hand. Therefore the estimation of interception rates is a prerequisite for modeling the amount of seepage flow.

Large variation in pine interception has been observed in several studies [6-14]. In general, the amount of water that is intercepted has been found strongly depending on both climatic conditions and vegetation type and structure [15, 16]. Several factors could explain the amount of interception on different scales. On a large scale, interception depends above all on climate factors [17] such as gross precipitation, rainfall intensity and duration [18], wind velocity [19], available evaporative energy and fog incidence [20]. On a regional scale, a major control of the interception loss is the vegetation type and tree species [13, 14]. Within tree species the interception loss is influenced by the canopy structure [21-23], stand density [24-26] and other stand parameters, determining the canopy's capacity to store water temporarily. But the attempts from Peck & Mayer [13] to systematize the interception in forest stands in dependence of stand parameters only show no functional dependencies of general validity. However, comparisons among different studies, often for the same tree species, were difficult because of the more or less different climatic conditions.

To predict the rainfall interception according to the climatic conditions and the vegetations characteristics many models have been developed empirically, physically or stochastically [15]. The models of RUTTER *et al*. [27] and GASH [28] described the process of rainfall interception satisfactorily and were integrated in revised or adapted versions in many simulation models for evaporation, soil water and stream flow (e.g. [29]). Both models however, require detailed input data, which limit application in general. Models like the RUTTER model must be checked with site specific throughfall data or in extreme cases even be calibrated, because the canopy drainage function involves empirical parameters that sometimes need to be optimized. A simplification of the RUTTER model especially for pine forests was developed by Mulder [2], but the data requirement is still higher than for the GASH model [30]. The interception model from Anders *et al*. [31] is a further development of existing approaches for process orientated modeling of interception, but this model also needs climatic information in daily resolution. Therefore there is a need for simple but effective models for the prediction of rainfall interception and net precipitation under a full range of management conditions for Scots pine forests in northern Germany. These models should only require easily-available forest inventory data and meteorological parameters, like annual sum of gross precipitation. Therefore this study has two objectives:

(i) to point out the relationships between the net forest precipitation and interception loss and conventional forestry parameters such as stand density, tree height, and diameter at breast height for Scots pine stands.

(ii) to develop a spatial modeling approach for predicting net forest precipitation using only stand and climatic variables.

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MATERIALS AND METHODOLOGY

Terms and Definitions

Before the description of data compilation and model development, a short definition of terms to be used is appropriate. The terms when partitioning of gross precipitation into throughfall and stemflow are defined as described in Fig. (**1**).

The net forest precipitation is defined here as the amount of rainfall transmitted below the canopy, originating from either dripping leaves or branches or from free throughfall. The amount of interception by the canopy including leaves, branches and stems, could be estimated by the following water balance equation:

$$I = P_g - (TF + SF) \quad (1)$$

where I, Pg, TF and SF are interception, gross precipitation, throughfall and stemflow, respectively. Stemflow in pine stands generally represents a minimal proportion of gross precipitation [10, 32, 33], so we used the simplified equation (2) for every dataset when data of stemflow measurements are missing.

$$I = P_g - TF \quad (2)$$

However this simplified assumption could lead to uncertainties in very young stands with higher amounts of stemflow [34, 35].

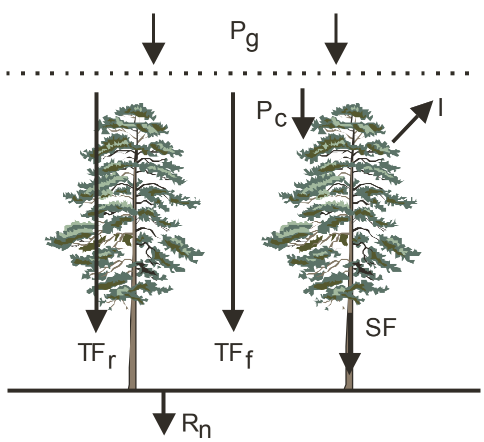

Fig. (1). Partitioning of water in a forest stand, acc. to Levia & Frost [36]. P_g is incident gross precipitation, P_c is precipitation that reaches the crown, I is interception, SF is stemflow, TF_f is free throughfall, TF_r is release throughfall, R_n is net precipitation.

Data Compilation

Building on individual published investigations we assembled a database that includes information on field precipitation and canopy throughfall in Scots pine stands in the northern Germany lowlands. In the database we compiled published data from journals, book chapters and reports. Fig. (**2**) shows the 78 forest stands throughout the study area and the mean annual precipitation. For each stand we collected the different climatic and stand variables listed in Table **1**. A few papers contained suitable information of the stand structure. In some cases supplementary informations were obtained from additional papers about the investigated stand. When the data of the stand basal area (BA) was missing, it is calculated using the diameter at breast height and the number of trees in the stand. If there was only information about the age and the stand height we used the Foresttools2 from Nagel [37] to estimate the diameter at breast height for the stands. If basal area and diameter at breast height were available we calculated the number of stems from these two stand parameters. Precipitation data for collection periods of less than one year were not included in the database. For more detailed information about the variables and data distribution see Table **2**.

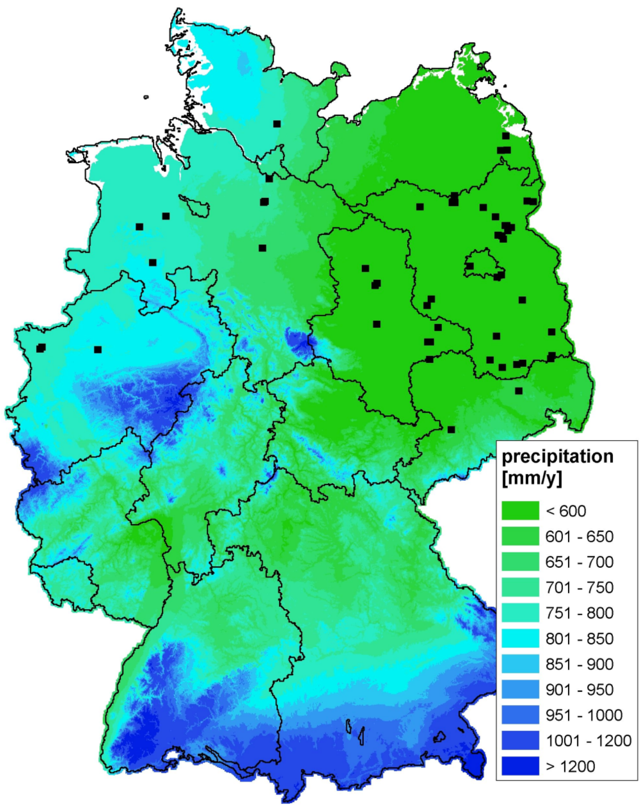

Fig. (2). Map of Germany showing locations of the 78 Scots pine stands in northern Germany lowlands. Precipitation data after: Hijmans *et al*. [38].

Statistics

Basic descriptive statistics, the arithmetic means (m_a), medians (m_m), standard deviations (sd), minimal (min) and maximal (max) values were calculated to describe the variability in interception data over the whole collection period for each stand and year. Also the coefficient of variation was estimated from m_a and sd and expressed as %. To identify the most important stand variables affecting interception on stand and tree scale we applied correlation (Spearman) analysis to the restricted dataset. Spearman correlation coefficients (r_{Spear}) were used because of non-normal distribution [61]. In the subsequent chapters the significant correlations are given at $a = 0.05^{*}$ or $a = 0.01^{**}$, respectively. Multiple linear regression (MLR) was then used to develop the models for predicting interception loss

Table 1. General Description of the 78 Scots Pine Stands Included in this Study. LAT: Latitude; LONG: Longitude; Pg: Gross Precipitation; Rn: Net Precipitation; AGE: Mean Stand Age; STE: Number of Trees Per Hectare; DBH: Diameter at Breast Height; H: Mean Tree Height; BA: Basal Area

NUM	Sitename	LAT dec (°)	LONG dec (°)	Observation Period	Pg (mm)	Rn (mm)	Stand Characteristics					Source
							AGE y	STE n ha^{-1}	DBH cm	H m	BA m²/ha	
1	Antlan	53.76	13.89	1988	520	352	44	n.d.	n.d.	n.d.	n.d.	[39]
2	Rothmühl	53.62	13.90	1988	434	242	42	n.d.	n.d.	n.d.	n.d.	[39]
3	Rothmühl	53.62	13.80	1988	456	303	36	n.d.	n.d.	n.d.	n.d.	[39]
4	Rothmühl	53.62	13.79	1988	450	292	53	n.d.	n.d.	n.d.	n.d.	[39]
5	Bucheheide	53.07	13.46	1987-1988	563	350	57	n.d.	n.d.	n.d.	n.d.	[39]
6	Menz	53.13	12.99	1986-1988	620	438	66	n.d.	n.d.	n.d.	n.d.	[39]
7	Menz	53.13	13.00	1986-1988	620	447	65	n.d.	n.d.	n.d.	n.d.	[39]
8	Menz	53.13	12.97	1986-1988	620	334	30	n.d.	n.d.	n.d.	n.d.	[39]
9	Menz	53.13	12.96	1986-1988	606	385	43	n.d.	n.d.	n.d.	n.d.	[39]
10	Schwedt	53.11	14.18	1986-1987	594	416	45	n.d.	n.d.	n.d.	n.d.	[39]
11	Schwedt	53.10	14.28	1986	473	335	39	n.d.	n.d.	n.d.	n.d.	[39]
12	Chorin	52.88	13.83	1986-1988	717	461	106	n.d.	n.d.	n.d.	n.d.	[39]
13	Chorin	52.86	13.90	1986-1988	723	485	106	n.d.	n.d.	n.d.	n.d.	[39]
14	Finowthal	52.79	13.68	1986-1988	660	469	66	n.d.	n.d.	n.d.	n.d.	[39]
15	Eberswalde	52.78	13.74	1986-1988	711	511	108	n.d.	n.d.	n.d.	n.d.	[39]
16	Colbitz	51.96	11.68	1986-1988	601	373	42	n.d.	n.d.	n.d.	n.d.	[39]
17	Colbitz	52.34	11.67	1986-1988	607	367	55	n.d.	n.d.	n.d.	n.d.	[39]
18	Dolle	52.36	11.70	1986-1988	616	356	51	n.d.	n.d.	n.d.	n.d.	[39]
19	Schmerwitz	52.13	12.49	1988	611	446	49	n.d.	n.d.	n.d.	n.d.	[39]
20	Wittenberg	51.91	12.65	1986-1988	654	461	73	n.d.	n.d.	n.d.	n.d.	[39]
21	Radis	51.77	12.48	1986-1988	659	431	43	n.d.	n.d.	n.d.	n.d.	[39]
22	Radis	51.77	12.50	1986-1988	673	412	55	n.d.	n.d.	n.d.	n.d.	[39]
23	Spremberg	51.55	14.41	1986-1987	657	440	64	n.d.	n.d.	n.d.	n.d.	[39]
24	Spremberg	51.58	14.43	1986-1998	660	457	45	n.d.	n.d.	n.d.	n.d.	[39]
25	Fahlenberg	52.40	13.70	1997-1998	619	392	31	4300	n.d.	n.d.	n.d.	[40]
26	Fahlenberg	52.40	13.70	1997-1998	619	449	31	2300	n.d.	n.d.	n.d.	[40]
27	Fahlenberg	52.40	13.70	1997-1998	619	476	31	1000	n.d.	n.d.	n.d.	[40]
28	Fahlenberg	52.40	13.70	1997-1998	619	380	31	6300	n.d.	n.d.	n.d.	[40]
29	Dübener Heide	51.77	12.52	1993	811	645	n.d.	n.d.	n.d.	n.d.	n.d.	[41]
30	Dübener Heide	51.77	12.52	1993	884	586	n.d.	n.d.	n.d.	n.d.	n.d.	[41]
31	Dübener Heide	51.77	12.52	1993	903	549	n.d.	n.d.	n.d.	n.d.	n.d.	[41]
32	Dübener Heide	51.77	12.52	1993	962	672	n.d.	n.d.	n.d.	n.d.	n.d.	[41]
33	Dübener Heide	51.77	12.52	1993	856	592	n.d.	n.d.	n.d.	n.d.	n.d.	[41]
34	Dübener Heide	51.77	12.52	1993	836	573	n.d.	n.d.	n.d.	n.d.	n.d.	[41]
35	Rösa	51.60	12.50	1994-1995	708	525	61	935	20.7	16	34	[42, 43]
36	Taura	50.90	12.80	1994-1995	842	602	45	853	20.6	18	28	[42, 43]
37	Neuglobsow	53.20	13.00	1994-1995	738	507	65	1043	21	20.1	36	[42, 43]
38	Natteheide	53.10	12.43	1996/97	448	316	72	722	24.4	21.9	33.8[a]	[44, 45]

(Table 1 continued)

NUM	Sitename	LAT dec (°)	LONG dec (°)	Observation Period	Pg (mm)	Rn (mm)	Stand Characteristics					Source
							AGE y	STE n ha^{-1}	DBH cm	H m	BA m²/ha	
39	Beerenbusch	53.14	12.97	1996/97	471	326	67	594	29.6	25.7	33.8[a]	[44, 45]
40	Weitzgrund	52.19	12.56	1996/97	456	327	87	725	24.7	21.1	34.7[a]	[44, 45]
41	Neusorgefeld	51.80	13.57	1996/97	550	355	75	656	27.2	24	34.2[a]	[44, 45]
42	Schwenow	52.14	14.01	1996/97	540	389	78	504	29.4	24.4	34.2[a]	[44, 45]
43	Britz	52.88	13.80	1992-99	633	377	27	3001	10.9	12.8	28	[22]
44	Britz	52.88	13.80	1995	658	481	77	720	n.d..	n.d.	n.d.	[46-48]
45	Kienhorst 95	52.97	13.65	1995	660	441	70	916	22.7	21.1	37	[46-48]
46	Kienhorst	52.97	13.65	1996/97	514	397	90	371	33.7[b]	25.5	33[a]	[44, 52]
47	Lichterfelde	52.51	11.52	1995	695	494	81	770	20.2	18	24.6	[46-48]
48	Kahlenberg	52.75	13.76	n.d.	600	408	84	670	25.3[b]	27.4	33.8[a]	[49]
49	Eberswalde	52.83	13.84	1996-1999	532	389	95	369	33.5	23.1	32.5[a]	[50]
50	Schipkau	51.51	13.87	1996-1998	723	379	22	11899	n.d.	n.d.	n.d.	[51]
51	Plessa	51.49	13.64	1996-1998	709	463	62	1003	n.d.	n.d.	n.d.	[51]
52	Bärenbrück	51.81	14.45	1996-1998	851	390	16	7375	n.d.	n.d.	n.d.	[51]
53	Meuro	51.52	13.96	1996-1998	754	346	20	12840	n.d.	n.d.	n.d.	[51]
54	Domsdorf	51.57	13.45	1996-1998	662	409	34	3247	n.d.	n.d.	n.d.	[51]
55	Köpenicker W.	52.38	13.63	1996/97	465	353	90	572	25.2[b]	17.3	29.2[a]	[44, 52]
56	Grunewald J. 63	52.50	13.20	1987-1988	620	455	40	n.d.	14	15	n.d.	[53]
57	Grunewald J. 63	52.50	13.20	1996/97	436	363	50	980	20.2[b]	19.1	31.4[a]	[44, 52]
58	Grunewald J. 91	52.50	13.20	1987-1997	543	432	140	208	34.1[b]	22.9	25.5[a]	[52, 54, 55]
59	Holdorf	52.56	8.09	1996-1999	690	477	50	1000	22.5	15	39.8[a]	[56]
60	Holdorf	52.56	8.09	2002	754	495	60	600	22.5	15	23.9[a]	[12]
61	Sandkrug	53.02	8.29	1996-1999	713	497	52	900	22.5	17	35.8[a]	[56]
62	Sandkrug	53.02	8.29	2002	758	490	65	650	22.5	17	25.8[a]	[12]
63	Xanten	51.67	6.35	1982/1983	810	566	55	410	22.5	30	29[a]	[57]
64	Haard 1	51.69	7.26	1981/1983	854	559	82	578	25.7	17.4	30[a]	[57]
65	Lüneburger H.	53.18	9.90	1980-1985	804	618	100	338	22.4	29.3	22.8[a]	[58]
66	Harburg	53.40	9.97	1982-1983	688	408	60	n.d.	n.d.	n.d.	n.d.	[59]
67	Sellhorn	53.17	9.88	1982	782	582	106	n.d.	n.d.	n.d.	n.d.	[60]
68	Segeberg	53.94	10.10	1973/1977	692	460	31	1737	15.5	14	33[a]	[20]
69	Kleve	51.69	6.38	1996/97	601	454	62	516	27.9	20	31.3[a]	[44, 52]
70	Laußnitz	51.25	13.88	1996/97	711	460	90	669	n.d.	n.d.	n.d.	[44, 52]
71	Augustend. A1	52.91	7.86	2002	825	440	15	4125	8.1[b]	7	21[a]	[12]
72	Augustend. A2	52.91	7.86	2002	825	418	28	3100	10.2[b]	11	25.1[a]	[12]
73	Augustend. A3	52.91	7.86	2002	825	616	29	2400	12.2[b]	14	28.1[a]	[12]
74	Augustend. W2	52.91	7.86	2002	825	571	60	550	27[b]	20	31.6[a]	[12]
75	Augustend. W1	52.91	7.86	2002	825	590	60	533	27.5[b]	20	31.6[a]	[12]
76	Augustend. A4	52.91	7.86	2002	825	611	123	220	39.7[b]	21	27.2[a]	[12]
77	August. BDF	52.91	7.86	1996/97	630	479	60	652	24.3[b]	17.9	30.3[a]	[44, 52]
78	Meißendorf	52.72	9.86	1996-1999	692	456	62	900	27.5	20	53.5	[56]

n.d.: not determined; a: estimated from number of trees and diameter at breast height; b: estimated with Foresttools2 [37].

Table 2. List of variables, their Abbreviations and Range for the Stands Used in this Study. Declaration: m_a: Arithmetic Mean, m_m: Median, min: Minimum, max: Maximum

Variable	Unit	m_a	m_m	min	max	n
gross precipitation [Pg]	mm	665	646	399	1002	161
net forest precipitation [Rn]	mm	447	440	242	737	161
interception [I] (=Pg-Rn)	mm	218	211	59	524.7	161
interception [I_P]	%	32	31	15	59	161
tree age [AGE]	a	65	60	15	140	155
number of stems [N]	$n \cdot ha^{-1}$	2048	900	208	12840	93
tree height [H]	m	20	20	7	30	69
diameter at breast height [DBH]	cm	25	23	8.1	40	70
stand basal area [BA]	m²	31	31	21	53	67

and net forest precipitation. Our underlying principle was to develop predictive models that could not only offer accurate (high $_{adj}R^2$ values) and exact (low standard error of the estimate) estimates of interception for specific stand and weather conditions, but that would also use predictive variables that were easily and widely available. This would enable the models to be easily applied to other sites.

Derivation of the Regression Model

Based on the assembled database it is possible to develop a multivariate linear regression (MLR) model. However, without any functional biological or physical explanation in such a model, the transfer of model results and model formulation to other regions and stands will be restricted. So our model formulation is somewhat different from a common MLR model. At various hydrological models the modeling of interception will be carried out in two steps mostly comparable to the RUTTER model. In a first step the fraction of precipitation that reaches the crown (P_c) is calculated as:

$$P_c = P_g \cdot (1 - f_{TFf}) \tag{3}$$

where Pg is the gross precipitation, and f_{TFf} is the fraction of the precipitation that directly reaches the soil surface. In a second step the actual interception is calculated, depending on the energy supply and the water, which is stored in the canopy. Simplified we can say that the canopy storage capacity and the canopy cover fraction are responsible for differences in throughfall and interception loss under comparable climatic condition. Therefore the model formulation is based on the assumption that there is a relationship between the needle mass of a specific tree and the canopy water storage capacity [62]. In practice it is almost not possible to measure net precipitation or interception at the tree level from field experiments. In contrast, in forest models, the stand parameters are usually determined at the tree level (e.g. BWIN or SILVA: [63, 64]). Therefore, to make this model also applicable to forest growth models, the part of the literature data that contained information about the number of trees, the net precipitation and the interception stand level values were simply divided by the number of trees.

The relationships between the needle mass and the parameters of a single tree are generally assumed to have the allometric form [65]:

$$y = b_0 \cdot x^{b_1} \tag{4}$$

where y stands for aboveground biomass, like the needle mass (nm), and x is a variable for stand parameters such as diameter at breast height (DBH) or tree height (H). This allometric function has been shown to predict foliage biomass by many studies [66-71]. In many cases these two variables are often combined to a single variable (BHD²H). However the relationship between DBH or H and tree foliage biomass may sometimes be more complex. Another allometric model after Crow [68] is more flexible then the BHD²H.

$$nm = b_0 \cdot BHD^{b1} \cdot H^{b2} \tag{5}$$

After a logarithmic transformation of this equation, it could be used in a multiple linear regression analysis:

$$\ln nm = \ln b_0 + b_1 \cdot \ln(BHD) + b_2 \cdot \ln(H) \tag{6}$$

Based on the assumption that there are approximately linear relationships between the open field precipitation and interception [8] on the one hand and between the crown cover fraction and the interception [31] on the other hand, we formulated the following models for net forest precipitation and interception loss.

$$\begin{aligned} \ln R_n = \ln b_0 + b_1 \cdot \ln(BHD) + b_2 \cdot \ln(H) \\ + b_3 \cdot \ln(CF) + b_4 \cdot \ln(P_g) + e \end{aligned} \tag{7}$$

where R_n is the net forest precipitation, DBH the diameter at breast height, H the tree height, CF the crown cover fraction and Pg the gross precipitation.

The intercepted precipitation (I) can be expressed as an own model in the same way:

$$\begin{aligned} \ln I = \ln b_0 + b_1 \cdot \ln(BHD) + b_2 \cdot \ln(H) \\ + b_3 \cdot \ln(CF) + b_4 \cdot \ln(P_g) + e \end{aligned} \tag{8}$$

or as the difference between gross precipitation and net forest precipitation from equation 2.

The upscaling from single tree to stand level will be done by the amount of trees in the stand. For the model parameterisation there is a need of information about the crown cover fraction (CF) for the different stands in this study. The CF is:

$$CF = \frac{CA}{SA} \qquad [\mathrm{m}^2 \cdot \mathrm{m}^{-2}] \tag{9}$$

where CA is the crown area and SA is the area of the stand.

The CA for the stand was calculated from the maximum crown radius (Cr) in meters and the number of trees (N) in the stands:

$$CA = \pi \cdot Cr^2 \cdot N \quad [\mathrm{m}^2] \tag{10}$$

Pretzsch *et al.* [64] provided a relationship between the crown radius and tree height (H) and diameter at breast height (DBH). Using their parameters we get the following function for the estimation of the crown radius for a single tree:

$$C_r = \exp\left(\begin{matrix} -0.5515 + 0.6468 \cdot \ln(DBH) \\ -0.0062 \cdot H + 0.1904 \cdot \ln\left(\dfrac{H}{DBH}\right) \end{matrix}\right) [\mathrm{m}] \tag{11}$$

RESULTS AND DISCUSSION

Variability and Correlations

There was considerable variation in measured interception loss between the stands from the literature. The coefficient of variation calculated across all stands and years was 35.7%. The frequency distribution of the interception loss in percent of gross precipitation is comparable to an curve of normal distribution (see Fig. **3**). The lowest interception loss in one year (59 mm) was found in the oldest stand (140 years) and the highest (525 mm) in a 16-year-old stand. These observations indicate that under comparable climatic conditions, the stand properties were very important in determining interception at any particular site.

Using the dataset, interception was significantly ($p < 0.05$) correlated with most of the variables which were included in this study (Tables **2** and **3**). No significant correlations were only found between interception and basal area on stand level and interception and gross precipitation on single tree level. On stand level the interception loss shows a very strong positive correlation to the number of trees in the stand. This effect of thinning is often described in the literature [24, 72-74]. The strong negative correlation between the volumetric variables (H and DBH) and the interception loss on stand level is not of a plausible functional explanation. It could be the result from an correlation between the volumetric variables and the number of stems in a stand. The correlation analysis for the single tree level showed the strongest correlation with the number of stems in the stand and the crown cover fraction. These were parameters known to describe the free throughfall (TF_f). Parameters which describe canopy biomass (DBH, H or AGE) and therefore the storage capacity of a tree, showed also very strong correlations with the interception loss. This positive correlation indicates that the approach to model the interception and the net precipitation from single tree level is functionally justified.

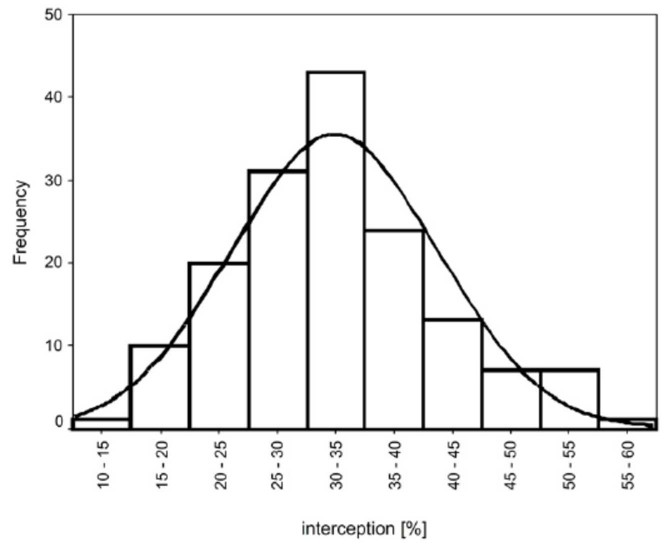

Fig. (3). Frequency distribution of annual interception rates of 78 stands in northern Germany lowlands. Note that one stand could have many years with throughfall measurements.

Interception and Net Precipitation Models

The simple correlations discussed above indicated the most important factors, explaining interception individually. Indeed, simple regression models could have been used to predict interception and net precipitation adequately, for

Table 3. Spearman Correlation Coefficients Between Interception Loss and Gross Precipitation and Various Stand Characteristics on Stand and Single Tree Level

Variable	Unit	Stand Level		Single Tree Level	
		r_{Spear}	n	r_{Spear}	n
precipitation (P)	mm	0.638**	161	$0.039^{n.s.}$	93
age (AGE)	y	-0.441**	155	0.828**	93
stem number (N)	$n \cdot ha^{-1}$	0.632**	93	-0.904**	93
basal area (BA)	$m^2 \cdot ha^{-1}$	$0.166^{n.s.}$	67	-0.469**	67
diameter at breast height (DBH)	cm	-0.489**	69	0.565**	67
height (H)	m	-0.449**	69	0.605**	67
crown cover fraction (CF)	$m^2 \cdot m^{-2}$	0.550**	67	-0.805**	67

Table 4. Selected Multiple Regression Models for Estimating Annual Interception Loss and Net Forest Precipitation for a Single Tree

Model No.	n	Constant	x Variable Coefficients					p	$_{adj}R^2$
lnI			**lnP_g**	**lnDBH**	**lnH**	**lnDBH²H**	**lnCF**		
1	67	-13.126	1.294	1.034	-	-	-0.648	0.000	0.902
lnR_n			**lnP_g**	**lnDBH**	**lnH**	**lnDBH²H**	**lnCF**		
2	67	-10.419	0.926	0.988	0.208	-	-1.083	0.000	0.990
3	67	-10.110	0.934	1.064	-	-	-1.130	0.000	0.988
4	67	-10.407	0.894	-	-	0.424	-1.057	0.000	0.987

Declaration: ln: natural logarithms; I: interception; Rn: net forest precipitation; Pg: gross precipitation; DBH: diameter at breast height; H: height; CF: crown cover fraction.

example with the stand age. But to obtain a higher degree of explanation the effects of several variables need to be included. We used a regression analysis to explore the formulated models in equation 7 and 8. Naturally the models and the individual variables had to be statistically significant ($p < 0.05$), but also had to have a high adjusted-degree of explanation ($_{adj}R^2$) value and randomness in the residual. The models that agree with these criteria are presented in Table **4**.

For the direct interception loss of a single tree, the model with the highest $_{adj}R^2$ and the lowest standard error of the estimate was model 1, using the variables gross precipitation, diameter at breast height and the crown cover fraction. The tree height was excluded when developing this model, because its relationships were not significant. The interception values predicted with model 1 are plotted *vs* the measured values in Fig. (**4**).

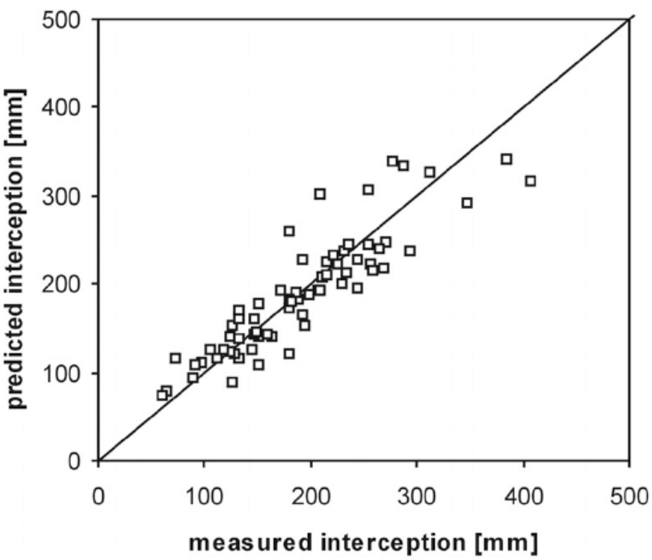

Fig. (4). Relationship between predicted and measured interception loss using gross precipitation and stand parameters (model 1, Table **4**).

The model 2 had the highest $_{adj}R^2$ values and the lowest standard error for estimating the net precipitation in the stand. Beside the gross precipitation the model is using diameter at breast height, tree height and the crown cover fraction. However there was only a little reduction in the $_{adj}R^2$ value when tree height was excluded from the

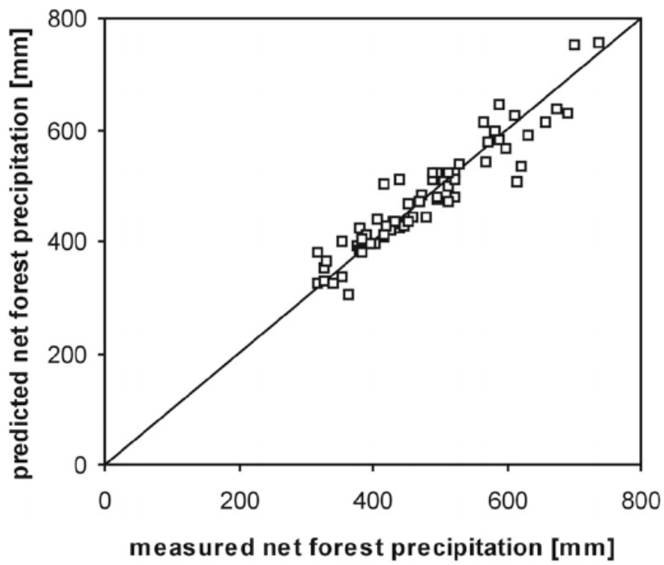

Fig. (5). Relationship between predicted and measured net forest precipitation using gross precipitation and stand parameters (model 2, Table **4**).

regression model. The amount of net precipitation estimated with model 2 is plotted against the measured values for net precipitation in Fig (**5**). There is also no systematic deviation between modeled and measured data. However, it should be taken into account, that even small changes in the breast height diameter have considerable impact on the modeling results. But also the quality of the developed models dependents on the quality of the forest inventory data, which were used for the model parameterisation. Measurements over a sufficiently long period in one stand automatically suffer the timeliness of the recorded inventory data. There are also uncertainties in the data of tree height. Often it is not safe whether the published data describes the mean tree height for a stand or the top height, for example. Other uncertainties may arise from the transformation of the allometric functions, since they could lead to a slide distortion of the values [75, 76]. Finally special climatic conditions (wind speed, available evaporative energy, fog incidence etc.) could lead to errors in predicting net throughfall interception.

In all models the diameter at breast height and the crown cover fraction were selected with the best fit. This is particularly helpful since the DBH is easily and rapidly

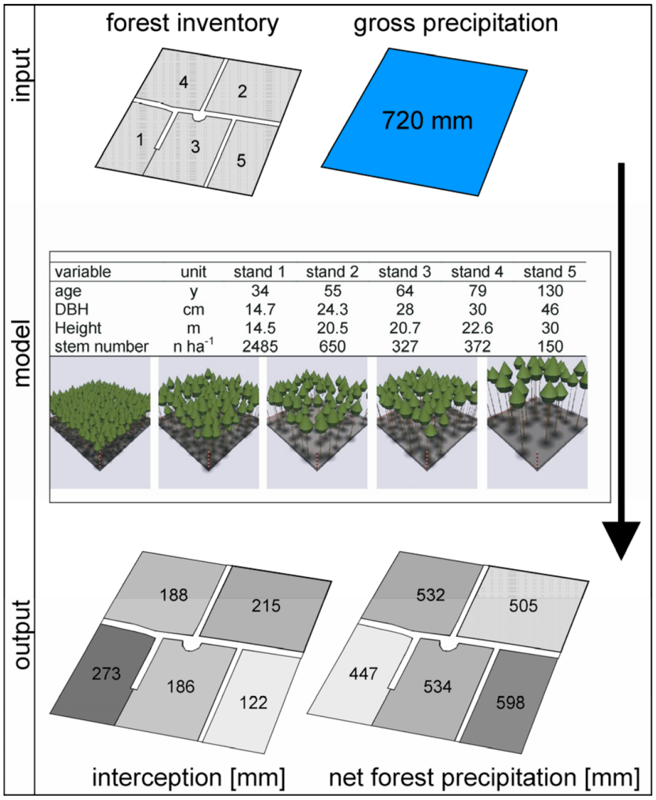

Fig. (6). Use of models for regionalization of net forest precipitation and interception with forest inventory data.

measured in the field and the crown cover fraction could be estimated with equation 11 from DBH and H. With such data requirements the net forest precipitation into the stands can be estimated based on digital forest inventory maps and regionalized gross precipitation maps. For example, a spatial model application is shown in Fig. (**6**). By incorporating the models into spatially explicit forest simulation models, the effects of growing trees on net forest precipitation could be dynamically modeled and the results could be scaled up to the landscape level.

CONCLUSIONS

For practical application, the data requirements of the developed models constitute an advantage. The attempt to create models requiring only stand characteristics that are routinely measured and easily available climate data (gross precipitation) has been successful. Number of stems, diameter at breast height and the crown cover fraction were the most important stand characteristic explaining the interception. The model was based on data from stands with very different stand parameters and therefore may be reliable when applied to stands with other stand parameters. Under the assumption that the climatic conditions in the investigated area are relative similar, the gross precipitation is taking into account as a predictive variable in the model. As with all regression models, applicability is restricted to climatic conditions represented by the basic data set. Hence, before the application of the models to other regions than the northern Germany lowlands, it should first carefully be tested.

ACKNOWLEDGMENTS

The study was supported by BMBF within the frames of joint project “Decision Support System - Forest and Climate Change” (DSS-WuK).

REFERENCES

[1] Jansen M, Döring C, Ahrends B, *et al*. Anpassungsstrategien für eine nachhaltige Waldbewirtschaftung unter sich wandelnden Klimabedingungen - Entwicklung eines Entscheidungsunterstützungssystems Wald und Klimawandel (DSS-WuK). Forstarchiv 2008; 79: 131-42.

[2] Mulder JPM. A simulation of rainfall interception in a pine forest. PhD., Groningen, Rijksuniv 1983; p. 109.

[3] Müller J, Anders S. Vergleichende Untersuchungen zum Stoff- und Wasserhaushalt von Laub- und Nadelwaldökosystemen im nordostdeutschen Tiefland. Beiträge für Forstwirtschaft und Landschaftsökologie 1996; 30(1): 29-30.

[4] Rutter AJ, Kershaw KA, Robins PC, Morton AJ. A predictive model of rainfall interception in forests. I. Derivation of the model from observations in a plantation of Corsican pine. Agric Meteorol 1972; 9: 367-84.

[5] Borken W, Matzner E. Nitrate leaching in forest soils: an analysis of longterm monitoring sites in Germany. J Plant Nutr Soil Sci 2004; 167(3): 277-83.

[6] Brechtel HM. Ein methodischer Beitrag zur Quantifizierung des Einflusses von Waldbeständen verschiedener Baumarten und Altersklassen auf die Grundwasserneubildung in der Rhein-Main-Ebene. Z. der Deutschen Geolog. Gesellschaft Hannover 1973; 124: 593-605.

[7] Crockford RH, Richardson DP. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. Hydrol Process 2000; 14: 2903-30.

[8] Iida S, Tanaka T, Sugita M. Changes of interception process due to the succession from Japanese red pine to evergreen oak. J Contam Hydrol 2005; 315: 154-66.

[9] Jenssen M. Wirkung der Kronendächer auf Interzeptionsverdunstung und Niederschlagsverteilung in Kiefern- und Buchenbeständen des nordostdeutschen Tieflandes. In: Anders, S. Ökologie und Vegetation der Wälder Nordostdeutschlands. Einfluß von Niederschlagsarmut und erhöhtem Stickstoffeintrag auf Kiefern-, Eichen- und Buchen-Wald- und Forstökosysteme des nordostdeutschen Tieflandes. Oberwinter: Dr. Kessel 2002; pp. 93-9.

[10] Kittredge J, Loughead HJ, Mazurak A. Interception and stemflow in a pine plantation. J Forest 1941; 39(6): 505-22.

[11] Lawson ER. Throughfall and stemflow in a pine-hardwood stand in the Quachita Mountains of Arkansas. Water Resour Res 1967; 3: 731-5.

[12] Mohr K, Meesenburg H, Horvath B, Meiwes KJ, Schaaf S, Dämmgen U. Bestimmung von Ammoniak-Einträgen aus der Luft und deren Wirkungen auf Waldökosysteme (ANSWER-Projekt). Landbauforschung Völkenrode, Sonderheft, 279. Braunschweig: Bundesforschungsanstalt für Landwirtschaft (FAL) 2005; p. 113.

[13] Peck A, Mayer H. Einfluß von Bestandesparametern auf die Verdunstung von Wäldern. Forstw Cbl 1996; 115: 1-9.

[14] Zinke PJ. Forest interception studies in the United States. In: Supper, W.E. & H.W. Lull: forest hydrology: proceedings of a national science foundation advanced science seminar. Oxford: Pergamon Press 1967; pp. 137-61.

[15] Liu S. A new model for the prediction of rainfall interception in forest canopies. Ecol Modell 1997; 99: 151-9.

[16] Muzylo A, Llorens P, Domingo F. Variability of interception canopy parameters with the event weather conditions and its effect on rainfall interception modelling. Geophys Res Abstr 2008; 10: EGU2008-A-07260.

[17] Loustau D, Berbigier P, Granier A. Interception loss, throughfall and stemflow in a maritime pine stand. II. An application of Gash's analytical model of interception. J Hydrol 1992; 138: 469-85.

[18] DVWK. Ermittlung des Interzeptionsverlustes in Waldbeständen bei Regen. Merkblätter zur Wasserwirtschaft, 211. Hamburg u. Berlin. Paul Parey 1986; p. 11.

[19] Weihe J. Die Ermittlung des Regenverlustes durch die Interzeption des Waldes. Beiträge zur Hydrologie – Kirchzarten, Sonderheft 1982; 4: 49-59.

[20] Balázs A. Ein kausalanalytischer Beitrag zur Quantifizierung des Bestandes- und Nettoniederschlages von Waldbeständen. Nippes. Kirchzarten: Verl. Beitr. zur Hydrologie 1983; p. 180.

[21] Herbst M, Thamm F. Interzeptionsverlust eines norddeutschen Buchenwaldes - eine Anwendung des Interzeptionsmodells von Gash. Z. Kulturtechn. Landentw 1994; 35: 311-9.

[22] Müller J. 30 Jahre forsthydrologische Forschung auf der Großlysimeteranlage in Britz - Zielstellung und Ergebnisse. 11. Gruppensteiner Lysimetertagung. Höhere Bundeslehr-und Forschungsanstalt für Landwirtschaft, Irdning. Raumberg-Gumpenstein. 5 und 6. April 2005; pp. 9-32.

[23] Pypker TG, Bond BJ, Link TE, Marks D, Unsworth MH. The importance of canopy structure in controlling the interception loss of rainfall: examples from a young and an old-growth Douglas-fir forest. Agric For Meteorol 2005; 130: 113-29.

[24] Aboal JR, Jiménez MS, Morales D, Gil P. Effects of thinning on throughfall in Canary Islands pine forest - the role of fog. J Hydrol 2000; 238: 218-30.

[25] Fleischbein K, Wilcke W, Goller R, *et al*. Rainfall interception in a lower montane forest in Ecuador: effects of canopy properties. Hydrol Process 2005; 19: 1355-71.

[26] Van Dijk AIJM, Bruijnzeel LA. Modeling rainfall interception by vegetation of variable density using an adapted analytical model. Part 1. Model description. J Hydrol 2001; 247: 230-8.

[27] Rutter AJ, Kershaw KA, Robins PC, Morton AJ. A predictive model of rainfall interception in forests. I. Derivation of the model from observations in a plantation of corsican pine. Agric Meteorol 1972; 9: 367-84.

[28] Gash JHC. An analytical model of rainfall interception by forests. QJR Meteorol Soc 1979; 105: 43-55.

[29] Federer CA, Vörösmarty C, Feketa B. Sensitivity of annual evaporation to soil and root properties in two models of contrasting complexity. J Hydrometeorol 2003; 4: 1276-90.

[30] Lankreijer HJM, Hendriks MJ, Klaassen W. A comparision of models simulating rainfall interception of forests. Agric For Meteorol 1993; 64: 187-99.

[31] Anders S, Beck W, Bolte A, *et al*. Ökologie und Vegetation der Wälder Nordostdeutschlands. Oberwinter: Dr. Kessel. 2002; pp. 283.

[32] Gash JHC, Stewart JWB. The evaporation from Thetford Forest during 1975. J Hydrol 1977; 35(3/4): 385-96.

[33] Silva IC, Rodríguez HG. Interception loss, throughfall and stem flow chemistry in pine and oak forests in north-eastern Mexico. Tree Physiol 2001; 21: 1009-13.

[34] Loustau D, Berbigier P, Granier A, Moussa FEH. Interception loss, throughfall and stemflow in a maritime pine stand. I. Variablility of throughfall and stemflow beneath the pine canopy. J Hydrol 1992; 138: 449-67.

[35] Mitscherlich G. Wald, Wachstum und Umwelt, I & II. Frankfurt a.M.: Sauerländer Verlag 1981; pp. 144-402.

[36] Levia DFJ, Frost EE. Variability of throughfall volume and solute inputs in wooded ecosystems. Prog in Phys Geogr 2006; 30(5): 605-32.

[37] Nagel J. ForestTools2: Forstliche Software-Sammlung. Selbstverlag J. Nagel 2007. Available from: http://wwwuser.gwdg.de/~jnagel/cdft.html.

[38] Hijmans RJ, Camerion SE, Parra JL, Jones PG, Jarvis A. Very high resolution interpolated climate surfaces for global land areas. Available from: http:// www. worldclim. org. Int J Climatol 2005; 25: 1965-78.

[39] Simon KH, Westendorff K. Stoffeinträge mit dem Niederschlag in Kiefernbestände des nordostdeutschen Tieflandes in den Jahren 1985-1989. Beitr. Forstwirtschaft 1991; 25(4): 177-80.

[40] Einert P. Depositionsuntersuchungen im Rahmen des Forschungsprogramms: "Langfristige waldbauliche Untersuchungen in Kiefernbeständen der Berliner Forsten". Beitr. Forstwirtsch. u. Landsch.ökol 2000; 34(3): 109-12.

[41] Niehus B, Brüggemann L. Untersuchungen zur Deposition luftgetragener Stoffe in der Dübener Heide. Beitr. Forstwirtsch. u. Landsch.ökol 1995; 29 (4): 160-3.

[42] Weisdorfer M, Schaaf W, Blechschmidt R, Schütze J, Hüttl RF. Soil chemical response to drastic reductions in deposition and its effects on the element budgets of three Scots pine ecosystems. In: Hüttl, R.F. & K. Bellmann: changes of atmospheric chemistry and effects on forest ecosystems. A roof experiment without roof. Nutrients in Ecosystems, 3. Dordrecht / Boston / London: Kluwer Academic 1998; pp. 187-225.

[43] Hüttl RF, Bellmann K. Site and stand description. In: Hüttl, R.F. & Bellmann K. Changes of atmospheric chemistry and effects on forest ecosystems. A roof experiment without roof. Nutrients in ecosystems, 3. Dordrecht / Boston / London: Kluwer Academic 1998; pp. 17-20.

[44] Gehrmann J, Andreae H, Fischer U, Lux W, Spranger T. Luftqualität und atmosphärische Stoffeinträge an Level II - Dauerbeobachtungsflächen in Deutschland. Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft (BMVEL) 2001; p. 94.

[45] Kallweit R. Kalkulation von Vorräten und Umsätzen oberirdischer Biomassekompartimente und Nährstoffmengen der Kiefernbestände an Level-II-Flächen Brandenburgs. Beitr Forstwirtsch Landsch Ökol 2001; 35(1): 37-44.

[46] Bolte A. Die Bodenvegetation in Kiefernökosystemen - eine Steuergröße für den Wasser- und Stoffhaushalt. Mitteilungen der Bundesforschungsanstalt für Forst- und Holzwirtschaft 1996; 185: 97-111.

[47] Müller J. Beziehung zwischen Vegetationsstrukturen und Wasserhaushalt in Kiefern- Buchenökosystemen. Mitteilungen der Bundesforschungsanstalt für Forst- und Holzwirtschaft 1996; 185: 112-28.

[48] Anders S, Beck W, Bolte A, *et al*. Waldökosystemforschung Eberswalde - Einfluß von Niederschlagsarmut und erhöhtem Stickstoffeintrag auf Kiefern-, Eichen- und Buchen-Wald- und Forstökosysteme des nordostdeutschen Tieflandes. Eberswalde 1999; p. 247.

[49] Anders S. Angespannter Wasserhaushalt und zweischichtige Kiefern-Buchen-Mischbestände - ist dies das Aus für ein bewährtes waldbauliches Modell? In: Brandenburgischer Forstverein: Klimawandel - Wie soll der Wald der Zukunft aussehen? Tagungsbericht des Brandenburgischen Forstvereins e.V. zur Jahrestagung vom 26. Mai 2004 in Eberswalde. Eberswalde 2004; pp. 67-86.

[50] Müller J. Ermittlung von Kennwerten des Wasserhaushaltes in Kiefern- und Buchenbeständen des nordostdeutschen Tieflands. Beiträge für Forstwirtschaft und Landschaftsökologie 2001; 35(1): 14-8.

[51] Scherzer J. Der Wasserhaushalt von Kiefernforsten auf Kippböden der Niederlausitz. Cottbuser Schriften zu Bodenschutz und Rekultivierung, 16. Cottbus: Brandenburgische Techn. Univ. 2001; 136.

[52] BMELF. Dauerbeobachtungsflächen zur Umweltkontrolle im Wald Level II - Erste Ergebnisse. Bonn: BMELF 1997; p. 148.

[53] Marschner B. Elementumsätze in einem Kiefernforstökosystem auf Rostbraunerde unter dem Einfluß einer Kalkung - Düngung. Berichte des Forschungszentrums Waldökosysteme der Universität Göttingen: Reihe A, 60. Göttingen 1990; p. 192.

[54] Dohlen M, Marschner B, Darius F. Langfristige Entwicklung von Stoffkonzentrationen in der Bodenlösung aus einer podsolierten Braunerde unter einem Kiefern-Eichen-Mischbestand. Mitteilungen der Deutschen Bodenkundlichen Gesellschaft 2001; 96: 173-4.

[55] Kratz W. Untersuchungen zur oberirdischen Streuproduktion in Berliner Stadtwäldern. Verhandlungen der Gesellschaft für Ökologie 1999; 24: 423-30.

[56] Mohr K. Stoffimmissionen in Nordwestdeutschland - Untersuchungen zu den ökologischen Auswirkungen auf Kiefernforsten und Möglichkeiten der Bioindikation. Dissertation vom Fachbereich Biologie, Geo- und Umweltwissenschaften der Carl von Ossietzky Universität: Oldenburg 2001; p. 182.

[57] Block J, Bartels U. Ergebnisse der Schadstoffdepositionsmessungen in Waldökosystemen in den Meßjahren 1981/82 und 1982/83. Forschung und Beratung, Reihe C. Düsseldorf 1985; p. 296.

[58] Bredemeier M. Stoffbilanzen, interne Protonenproduktion und Gesamtsäurebelastung des Bodens in verschiedenen Waldökosystemen Norddeutschlands. Berichte des Forschungszentrums Waldökosysteme/Waldsterben, Reihe A. Göttingen 1987; p. 192.

[59] Ulrich B, Rastin N. Erfassung der Einträge und des Verbleibs von Luftverunreinigungen in den Wäldern der Landesforstverwaltung Hamburg. In: Rastin, N. & B. Ulrich: Bodenzustand und Depositionsbelastung von Waldökosystemen im Forstamt Ham-

burg. Berichte des Forschungszentrums Waldökosysteme/Waldsterben, 10. Göttingen 1985; pp. 92-176.
[60] Meesenburg H, Meiwes KJ, Schultz-Sternberg R. Entwicklung der atmogenen Stoffeinträge in niedersächsische Waldbestände. Forst und Holz 1994; 49(9): 236-8.
[61] Myers JL, Well AD. Research design and statistical analysis. Erlbaum 2003; p. 760.
[62] Rutter AJ, Morton AJ. A predictive model of rainfall interception in forest. III. Sensitivity of the model to stand parameters and meteorological variables. J Appl Ecol 1977; 14: 567-88.
[63] Nagel J, Albert M, Schmidt M. Das waldbauliches Prognose- und Entscheidungsmodell BWINPro 6.1. Forst und Holz 2002; 57: 486-93.
[64] Pretzsch H, Biber P, Durský J. The single tree-based stand simulator SILVA: construction, application and evaluation. For Ecol Manage 2002; 162: 3-21.
[65] Fehrmann L, Kleinn C. General considerations about the use of allometric equations for biomass estimation on the example of Norway spruce in central Europe. For Ecol Manage 2006; 236: 412-21.
[66] Bartelink HH. Allometric relationships for biomass and leaf area of beech (*Fagus sylvatica L.*). Ann Sci For 1997; 54: 39-50.
[67] Burton AJ, Pregitzer KS, Reed DD. Leaf area and foliar biomass relationships in northern hardwood forests located along an 800 km acid deposition gradient. For Sci 1991; 37: 1041-59.
[68] Crow TR. A guide to using regression equations for estimation tree biomass. North J Appl For 1988; 5: 15-22.
[69] Pastor J, Aber JD, Melillo JM. Biomass prediction using generalized allometric regressions for some Northeast tree species. For Ecol Manage 1984; 7: 265-74.
[70] Reiners WA. Structure and energetics of tree Minnesota forests. Ecol Monogr 1972; 42: 71-94.
[71] Tobin B, Black K, Osborne B, Reidy B, Bolger T, Nieuwenhuis M. Assessment of allometric algorithms for estimating leaf biomass, leaf area index and litter fall in different-aged Sitka spruce forests. Forestry 2006; 79(4): 453-65.
[72] Aussenac G, Granier A. Effects of thinning on water stress and growth in Douglas-fir. Can J For Res 1988; 18: 100-5.
[73] Stogsdill WR, Wittwer RF, Hennessey TC, Dougherty PM. Relationship between throughfall and stand density in a Pinus taeda plantation. For Ecol Manage 1989; 29(1-2): 105-13.
[74] Veracion VP, López ACB. Rainfall inteception in a thinned Benguet pine forest stand. Sylvatrop 1976; 1(2): 128-34.
[75] Korsmo H. Weight equations for determining biomass fractions of young hardwoods from natural regenerated stands. Scand J For Res 1995; 10: 333-46.
[76] Satoo T, Madgwick HAI. Forest Biomass. Forestry Sciences, 6. Nijhoff/ Junk. Haque 1982; 6: 152.

Received: October 9, 2009 Revised: October 26, 2009 Accepted: October 26, 2009

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