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Original article

Estimation of crown radii and crown projection area from stem size and tree position

Rüdiger GROTE*

Chair for Forest Yield Science, Department of Ecology and Landscape Management, TU Munich, Am Hochanger 13, 85354 Freising, Germany

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Abstract – This paper describes a method for crown radii estimation in different cardinal directions using tree diameter, height, crown length, and stem position within the stand as independent variables. The approach can serve for the initialisation of crown dimensions if measured crown radii are not available in order to address various research questions. Test calculations are carried out with 4 pure spruce (*Picea abies* L. Karst), 5 beech (*Fagus sylvatica* L.), and 6 mixed stands with both species. Simulated tree radii, crown projection area and canopy cover are compared with measurements and simple estimation procedures based on logarithmic and linear equations. In beech stands and dense spruce stands the estimates with the new approach are similar or superior to those obtained with the other methods. However, in sparse plots or in stands, which have experienced a recent thinning crown size of trees is overestimated.

crown projection area / crown radii / *Fagus sylvatica* / mixed forests / *Picea abies*

Résumé – Estimation des rayons et de la zone de projection de la couronne en utilisant les dimensions de la tige et la position de l'arbre. Cet article introduit une méthode mathématique qui permet une estimation du rayon, en utilisant seulement les dimensions de la tige de la couronne et la position de l'arbre. Cette méthode permet d'initialiser les dimensions de la couronne dans le cas où on ne connaît pas les rayons pour ainsi traiter de différentes questions scientifiques. La méthode est testée sur de nombreux peuplements d' épicéas (*Picea abies*) et de hêtres (*Fagus sylvatica*), non seulement constitués d'une seule essence mais aussi de forêts mixtes, dans le sud de l'Allemagne. Les simulations du rayon des couronnes, de la surface de projection d'une couronne et du degré de couverture sont comparées avec des mesures et d'autres estimations basées sur des équations linéaires ou logarithmiques. Les résultats montrent que la nouvelle méthode est appropriée pour la représentation des rayons des couronnes de hêtres et pour des peuplements denses d'épicéa. En revanche le rayon et la surface de la couronne d'arbres ayant poussé dans des lieux clairsemés ou ayant subi une éclaircie sont surestimés.

projection des couronnes / rayons des couronnes / *Fagus sylvatica* / forêts mixtes / *Picea abies*

1. INTRODUCTION

Many ecological and economic problems in forestry today (e.g. continuous cover forestry, wood production and quality) are approached using crown dimensional measures. For example, individual tree competition indices are derived from crown area estimates [6, 38] because crown dimension is a result of past competition as well as an indicator of the current growth potential [27]. Thus, crown dimensional measures are also used in more sophisticated single-tree models – particularly when forest growth in uneven-aged or mixed species stands is addressed [40]. Furthermore, crown size and canopy cover determine the probability of successful natural regeneration by its influence on the pattern of shade, light, and rainfall on the ground [49]. In general, many approaches of modelling light distribution (e.g. [48]), water balance (e.g. [2, 37]), tree growth (e.g. [7, 41]), and tree physiology (e.g. [50]) depend on information about crown dimensions of individual trees. Possibly, considering a more realistic crown shape will become increasingly important also for stem quality simulation, because branch dimension is one of the most important determinants [30].

Despite its importance crown extension remains difficult to determine. It can only be measured by optical methods from below [44] or from above [1], which both are subjected to a likely underestimation of crown width due to a limited visibility of crowns. The crown projection area can be estimated from stem dimensions [15, 52], but has to be thoroughly parameterised for specific stand conditions [18], which in most cases involves again a large number of direct measurements. Finally, canopy cover can not be assumed to be the sum of tree crown projection areas, because overlapping is a common phenomenon particularly in dense, uneven-aged, and mixed stands.

The difficult measurements and the sensitivity of crown dimension on management makes it desirable to develop estimation procedures based on variables that are easier to measure

* Corresponding author: ruediger.grote@imk.fzk.de

Table I. Site description of the stands used for evaluation.

Location	Plot no.	Reference year	Year of last thinning	Age		Plot size (m^2)	Average height (m)		Average diameter (cm)		Stand density (trees/ha)		Basal area (m^2/ha)	Area thinned* (m^2/ha)
				Spruce	Beech		Spruce	Beech	Spruce	Beech	Spruce	Beech		
Eurach	1	1999	1996	47		1178	13.89		14.93		1477		25.9	0
	2			47		1087	9.85		11.07		1638		15.8	2.9
	3			47		1140	13.51		13.67		1316		19.3	6.5
	4			47		1197	13.79		16.51		902		19.3	4.1
Starnberg	1	1993	1986		66	1520		16.51		17.58		623	15.1	3.8
	2				66	1314		20.64		23.43		731	31.5	0.1
	3				66	1423		16.38		16.75		485	10.7	4.6
	4				66	1572		18.24		20.8		560	19.0	3.8
	5				66	1623		19.69		19.68		327	9.9	4
Freising	1	1994	unknown	44	51	4285	23.51	22.28	24.66	19.28	558	352	36.9	
	2			77	97	5301	38.9	30.74	32.74	44.66	562	63	57.2	
	3			95	120	3071	43.83	47.94	37.14	50.87	168	130	44.6	
	4			88	103	2470	40.64	42.89	35.62	28.84	415	149	51.1	
	5			42	54	1983	26.64	17.83	14.98	17.25	1214	456	32.1	
	6			37	54	2642	25.51	13.42	16.18	12.29	847	1032	29.7	

* Expressed in basal area loss, only dominant trees considered.

than crown extension itself. Thus, maximum crown radius, which can be derived from stem diameter, has been used to estimate crown projection area [19, 51]. Because increasing stand density results in increasing overestimates an adjustment factor has been introduced that is generally derived from overlap estimates [13]. More recently, average crown radius and canopy cover in several types of conifer forests were successfully estimated with regression equations that have been derived from stem diameter, height, and/or crown length [17]. All of these methods are developed to give reliable results on the stand level, which is suitable for many of the purposes mentioned above. It is not sufficient, however, for analyses that account explicitly for the asymmetry of crowns. Information about asymmetric crown extension has been used e.g. for detailed ecosystem characterisation [47] or the simulation of wood quality [28, 45], radiation distribution [10, 11], susceptibility of trees to windthrow [46], crown biomass [22], and individual tree physiology [23]. Therefore, a method, which estimates crown radii in various cardinal directions for every tree in a given stand would be of great value for these research areas. In this paper, such an approach is presented that is based on the size of a tree and the size and position of surrounding competitors. Also, the sum of crown projection area and canopy cover (the total area covered by canopy) are both calculated based on the estimated radii and results are compared with those obtained with other methods.

2. MATERIALS AND METHODS

2.1. Stand description

In order to test the proposed method for crown radii estimation, a number of forest stands were selected that include the most important tree species and stand structure types in Germany. The stands consist of trees with a coniferous (*Picea abies* L. Karst.) and a broadleaved (*Fagus sylvatica* L.) tree species either in pure or mixed stands. All of them belong to the network of long-term investigation plots in Bavaria, South Germany and are maintained by the Chair for Forest Yield Science in Freising. Thus, tree position, stem diameter, height, height of crown base, and crown radii length had already been measured at many trees. The plots of pure spruce (Eurach, 4 plots) and beech (Starnberg, 5 plots) both represent different degrees of stand density. The mixed plots (Freising, 6 plots) represent different age classes. All plots of one site are located closely together to minimise differences in site conditions. For a more detailed description see Table I. The plots of pure spruce and the mixed plots are furthermore described in connection with other investigations [20, 42].

Diameter at breast height had been measured with a girth tape at all trees. Tree height and crown base height of each tree within one plot had been determined from height-diameter relations that are derived from a subset of approximately 40 measured heights at each plot. The visible crown extension in each of eight cardinal directions had been measured by vertically looking up as described by Röhle [43]. Calculations are carried out with all trees within the plots, but trees at the plot boundaries are omitted from the results. This is necessary because in these cases no competitors at the outward side are considered and crown radii would thus be overestimated.

2.2. Distance dependent approach

The suggested approach is based on two assumptions. The first is that the potential horizontal crown extension is a function of stem diameter, and the second is that the distance between the tree and its competitors determines the actual crown dimension within the limit of the potential crown extension. Following Arney [3], competitors are defined as trees with an overlap in potential crown extensions (Fig. 1A). Crown radius length in a particular direction is limited by the position of competitors within a certain angle on both sides of the radius (Figs. 1A and 1B) and by their crown width at the height where the maximum crown extension of a centre tree is assumed (Fig. 1C). The method is further on referred to as 'maximum radii estimation' (MRE).

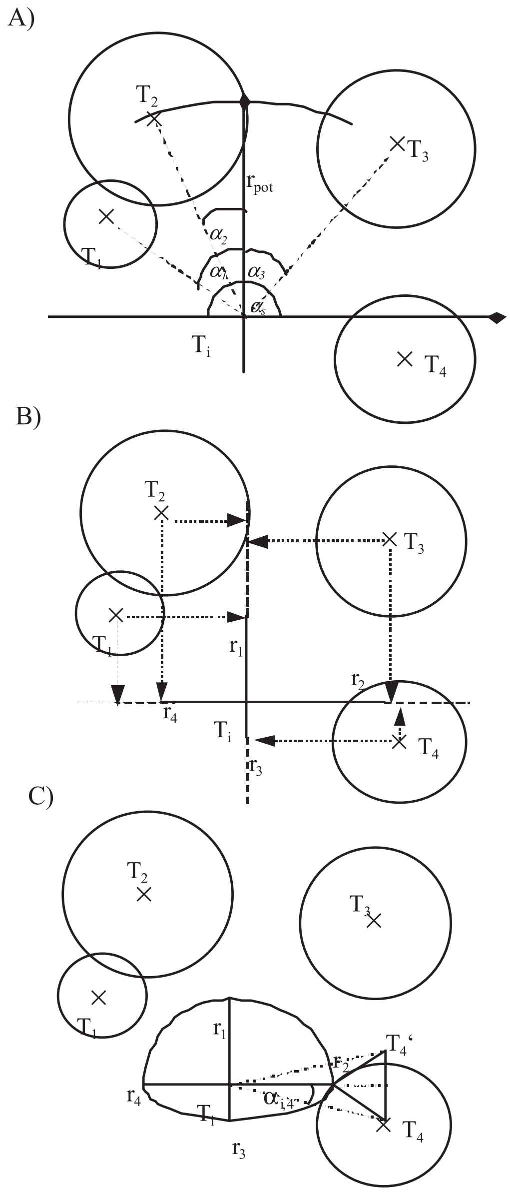

Figure 1. Determination of maximum crown radius per cardinal direction. (A) Selection of competitor trees that are in the range of the centre tree. (B) Radius limitation for r_{1-4} by competitor positions (stem position of a competitor tree is indicated by a cross). (C) Radius limitation by competitor crown extension (here only for r_2). T_i = centre tree, r_{pot} = potential radius of T_i, T_{1-4} = competitors with crown width at the height of maximum crown extension of T_i, α_s = angle between simulated radii (only 4 radii (r_{1-4}) are considered, whereas the calculations are based on 8 radii), α_{1-3} = angle between T_i and the competitors relevant for the determination of r_1, T_4'= virtual mirror tree for determination of radius length r_2.

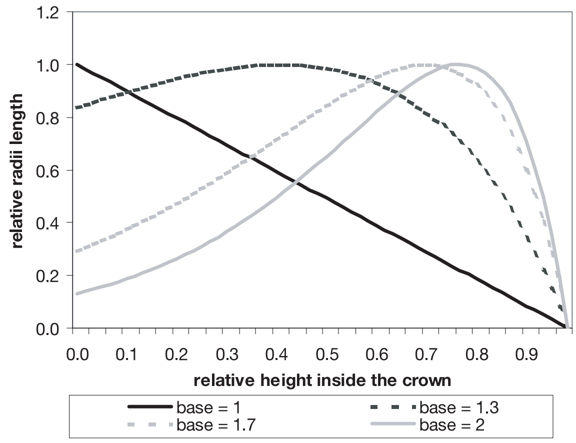

Figure 2. Effect of the '*base*'-variable in equation 1 on crown shape (inserting a crown length of 15 m for l_{cr}). 0 = crown base, 1 = tip of the tree.

Firstly, in order to determine the height where maximum crown width occurs, a crown shape function is required similar to those that have been suggested by several authors during the last decades (e.g. [8, 25, 26, 29, 35]). However, these equations require many parameters that are not directly measurable (e.g. [25]), assume a steady increase with canopy depth (e.g. [35]), or end with a zero-radius at crown base height (e.g. [29]). In the current context, these properties are considered as disadvantages. Thus, a new one-parameter equation is used that describes crown radius at every height h (r_h) as a function of crown base height (*hcr*), crown length (*lcr*), and the maximum radius in a particular cardinal direction (r_{max}). The term *relH* refers to the relative height within the crown, which is 0 at crown base and 1 at the tip of the tree.

$$r_h = r_{max} \cdot \frac{(1 - relH) \cdot f(h)}{\max[(1 - relH) \cdot f(h)]} \qquad \text{Eq. (1a)}$$

$$relH = \frac{h - hcr}{lcr} \qquad \text{Eq. (1b)}$$

$$f(h) = base^{\left(100 \frac{h - hcr}{lcr^2}\right)}. \qquad \text{Eq. (1c)}$$

The effect of the *base*-term in equation (1c) is demonstrated in Figure 2, with $r_{max} = 1$ and a crown length of 15 m. In a detailed analysis of 12 trees, values of *base* were found to be 1.23 ± 0.074 for spruce and 2.02 ± 0.71 for beech [21]. However, the standard deviation can be decreased if *base* is derived from crown length according to equation (1d) (1.23 ± 0.071 for spruce and 2.08 ± 0.345 for beech) with *ps* equal to 0.018 ($R^2 = 0.65$) and 0.0756 ($R^2 = 0.54$) for spruce and beech respectively.

$$base = 1 + ps \cdot lcr \qquad \text{Eq. (1d)}$$

ps: shape parameter.

To determine the maximum crown radii of one tree, the maximum crown extension for the competitor trees j are needed but generally not known. Thus, for a given competitor, $r_{max,j}$ is calculated from the distance to tree i (d_{ij}) and from diameter at breast height *(dbh)* of both trees according to equation 2. The distance between a tree and its competitor d_{ij} can easily be calculated from stem positions.

$$r_{max,j} = d_{ij} \cdot \frac{dbh_j}{dbh_j + dbh_i}. \qquad \text{Eq. (2)}$$

However, r_{max} of any tree is limited to its potential radius (r_{pot}), which describes the physical maximum is hardly affected by site conditions [24]. Since no open grown trees were available, r_{pot} is estimated from the 5% relative largest crown radii found at the trial plots.

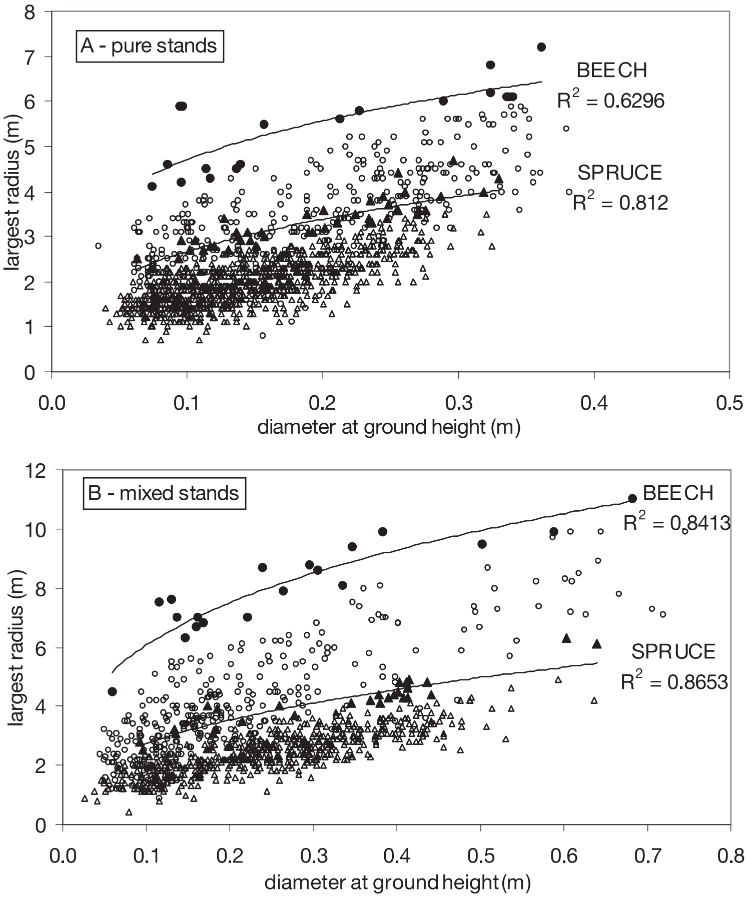

Figure 3. Measured crown radii in dependence on stem diameter at ground height. The lines indicate the potential radius r_{pot} for a given diameter separated for tree species (beech: circles, spruce: triangles) and stand type (A: pure stands, B: mixed stands). Larger points and triangles indicate the 5% of relative largest radii that are used to build the boundary function.

To determine these radii, firstly all radii (with 8 radii measured per tree) are exponentially fitted to the stem diameter at ground height *do* (MS Excel software package). The 5% selected radii are the ones with the largest positive deviation from this relation. Another exponential fit through these radii according to equation 3 derives the parameter pr_1 and pr_2. The diameter at ground height is derived from *dbh* by assuming a certain diameter decrease of the bole with increasing height (0.3 cm m^{-1}). It is used as independent variable instead of *dbh* because otherwise equation 3 would imply that small trees (< 1.3 m height) have no crowns at all, which would restrict the generality of the approach. Parameters are determined separately for each tree species and for pure and mixed stands although the differences between the relations for spruces in different stand structure types were not significant (Fig. 3). Values for pr_1 and pr_2 together with the number of radii that have been used to derive the functions are given in Table II.

$$r_{pot} = pr_1 \cdot do^{pr_2} \qquad \text{Eq. (3)}$$

(r_{pot} and *do* in m).

From $r_{\max,j}$ the potential crown extension of all competitor trees is calculated for every height according to equation 1 in height steps of 0.5 m. In this calculation, r_h of competing trees below the height of maximum crown diameter is set to $r_{\max}$ to better account for the influence of light competition in deeper canopy layers.

In the next step, the angle α_{ij} between the tree (*i*) and its competitor (*j*) is calculated from tree positions (Fig. 1A). Assuming that a branch will grow until it reaches the crown circumference of a competitor tree, the length of each crown radius is calculated as follows (Fig. 1C):

$$r_{h,\,i} = \min(\overline{T_iS}, r_{pot\ h,\,i}) \qquad \text{Eq. (4a)}$$

$$\overline{T_iS} = \cos\alpha_{ij} \cdot d_{ij} - l \qquad \text{Eq. (4b)}$$

$$l = r_{pot\ h,j} \cdot \overline{T_jT_j'} \qquad \text{Eq. (4c)}$$

$r_{h,i}$: actual radius of centre tree *i* at height *h*; $r_{poth,i}$: potential radius of centre tree *i* in height *h*; $r_{poth,j}$: potential radius of competitor tree *j* in height *h*; T_iS: distance between stem position and the point of intersection; *l*: help variable; $T_jT'_j$: distance between competitor tree j and a point, mirrored at the radius prolongation (T'_j is described as a 'virtual mirror tree' in Fig. 1C).

The actual radius of $r_{h,i}$ is calculated as the minimum radius determined by considering every competitor within angle α_s on both sides of the radius (see illustration in Fig. 1A). Based on former investigation results [33, 44] and test calculations with different angles, α_s is set to 45° (8 radii).

Since first calculations showed that the largest crown radii in one direction was too often equal to the potential radii, a further restriction was introduced to get more realistic results for $r_{\max}$. As illustrated in Figure 1B, the assumption is made that a radius can not grow beyond

Table II. Parameter, estimated for determination of radius length and potential crown cover (pr1 and pr2: maximum radii, alin1 and blin1: linear radii estimation, alog and blog: logarithmic crown area estimation, alin1 and blin2: linear crown area estimation, see text for equations and dimensions).

	Pure stands				Mixed stands			
	Spruce	*n*	Beech	*n*	Spruce	*n*	Beech	*n*
pr1	5.89	46	8.24	19	6.43	29	12.30	19
pr2	0.34		0.24		0.37		0.31	
alin1	5.24	4864	7.28	1819	7.09	3244	8.51	2712
blin1	0.66		0.86		0.44		0.73	
alog	–1.38	607	–0.97	231	–1.28	411	–0.91	342
blog	0.67		0.70		0.60		0.68	
alin2	–1.98	607	–4.44	231	1.13	411	–6.00	342
blin2	0.68		1.33		0.52		1.43	

Table III. Comparison of the distance dependent method and the dbh-based estimation of crown radii (MRE: distance dependent method with 8 radii based estimation, LIN: based on linear correlation to dbh; * = within 10% confidence interval, ** = within 5% confidence interval).

Location	Species	n_{radii}	Slope (MRE)	r^2 (MRE)	Slope (LIN)	r^2 (LIN)
Eurach	spruce	4864	0.957**	0.08	0.912*	–0.27
Starnberg	beech	1384	0.825*	0.27	0.878**	–0.34
Freising	spruce	1816	1.111*	0.26	0.907*	–0.41
Freising	beech	1808	0.762	0.42	0.809	–0.38
Freising	mixed	3624	0.898*	0.26	0.847	–0.28

the stem position of a competitor tree. Despite these limitations, it should be recognised that an overlap between crowns can result from the elliptical connection between two adjacent radii (see further down).

2.3. Other calculations

Currently, the most common estimation procedures of crown projection area are based on linear [17] or logarithmic [31, 52] relationships between stem and crown diameter. Thus, simple calculations are carried out using linear correlations between *dbh* and radius length (r_{max} in dm = $a_{lin1} + b_{lin1} \times dbh$), and *dbh* and crown projection area (A in m^2= $a_{lin2} + b_{lin2} \times dbh$ in cm) of individual trees. Crown projection area is also calculated with a logarithmic relation to stem cross-sectional area ($\ln A = a_{log} + b_{log} \times \ln(dbh^2 \times \pi \times 0.25)$). The parameter a_{log} and b_{log} are derived analytically from the same data set as pr_1 and pr_2 and are also presented in Table II for each tree species and for pure and mixed plots (not for each plot!). In order to derive crown projection area from measured and simulated crown radii, the area between the radii is considered as a fraction of an ellipse [44]. Canopy cover is calculated with a computer program that draws the crown projection area of every tree on a grid and counts the number of coloured pixels.

3. RESULTS

The relation between simulated and measured radii is shown in Figures 4A–4D. The coefficient of determination ranges from 0.2 for pure spruce to 0.45 for beech in mixed stands. A small bias is obvious in every figure, which indicates an overestimation of small radii and an underestimation of large radii. This is at least partly due to radii that had been measured with zero length, which can not be represented with the MRE method due to the assumption made in equation 2. Slope values with the regression line forced through the origin are presented in Table III separately for species and sites together with the respective R^2 values. The table shows that despite the bias positive correlation coefficients had been obtained with the MRE method in all cases, but not with the estimation based on the linear approach.

Figure 5 and Table IV show that MRE does not decrease the accuracy of crown projection area estimates compared with the fitted logarithmic (LOG) and the linear method (LIN). The slope values obtained with every method are similar (in average over all plots separated by species: MRE = 1.00, LOG = 0.91, LIN = 0.96) although the standard deviation of MRE is highest (MRE = 0.25, LOG = 0.12, LIN = 0.15). The R^2 values of MRE are similar to those obtained with the LOG approach and are higher than R^2 values obtained with the linear approach (MRE = 0.64 ± 0.15, LOG = 0.61 ± 0.16, LIN = 0.50 ± 0.23, with all negative values excluded from the average). However, crown projection area for spruce is somewhat overestimated, particularly in the mixed plots (+4 and +28% mean deviation from measurements for pure and mixed plots respectively), whereas for beech it is generally underestimated (–15 and –17%).

The goodness of fit apparently depends on the density of the plot and of the thinning intensity that the stand has been treated with (see Tab. I). In the plots Eurach 1 and Starnberg 2, which are the most dense for each species, the deviation from the 1:1 line is only marginal (spruce –4%, beech +1%) and the simulated values are closely correlated with measured crown projection area (R^2 = 0.7 and 0.8 for spruce and beech respectively). In spruce, overestimation increases in sparser plots (up to 23% in the sparsest plot Eurach 2), whereas for beech crown projection area is underestimated in thinned plots but no particular trend with the intensity of thinning is obvious.

The sum of crown projection areas within one plot is similar to that calculated from the measurements although an overestimation for spruce (+9%) and an underestimation for beech (–19%) is obtained (Tab. V). Again, the simulation of the densest plots for both species are closest to the measurements (Eurach 1: –6%, Starnberg 2: –4%).

Table V shows canopy cover values derived from either measured or simulated crown radii. Additionally, crown overlap is calculated from the difference between the sum of single tree crown projection areas and canopy cover. This demonstrates that the overlap derived with the MRE method is generally too small. In spruce stands, however, this underestimation is only slight (–3%), whereas it is in average –14% for beech stands. Mixed stands are in between (in average –6%).

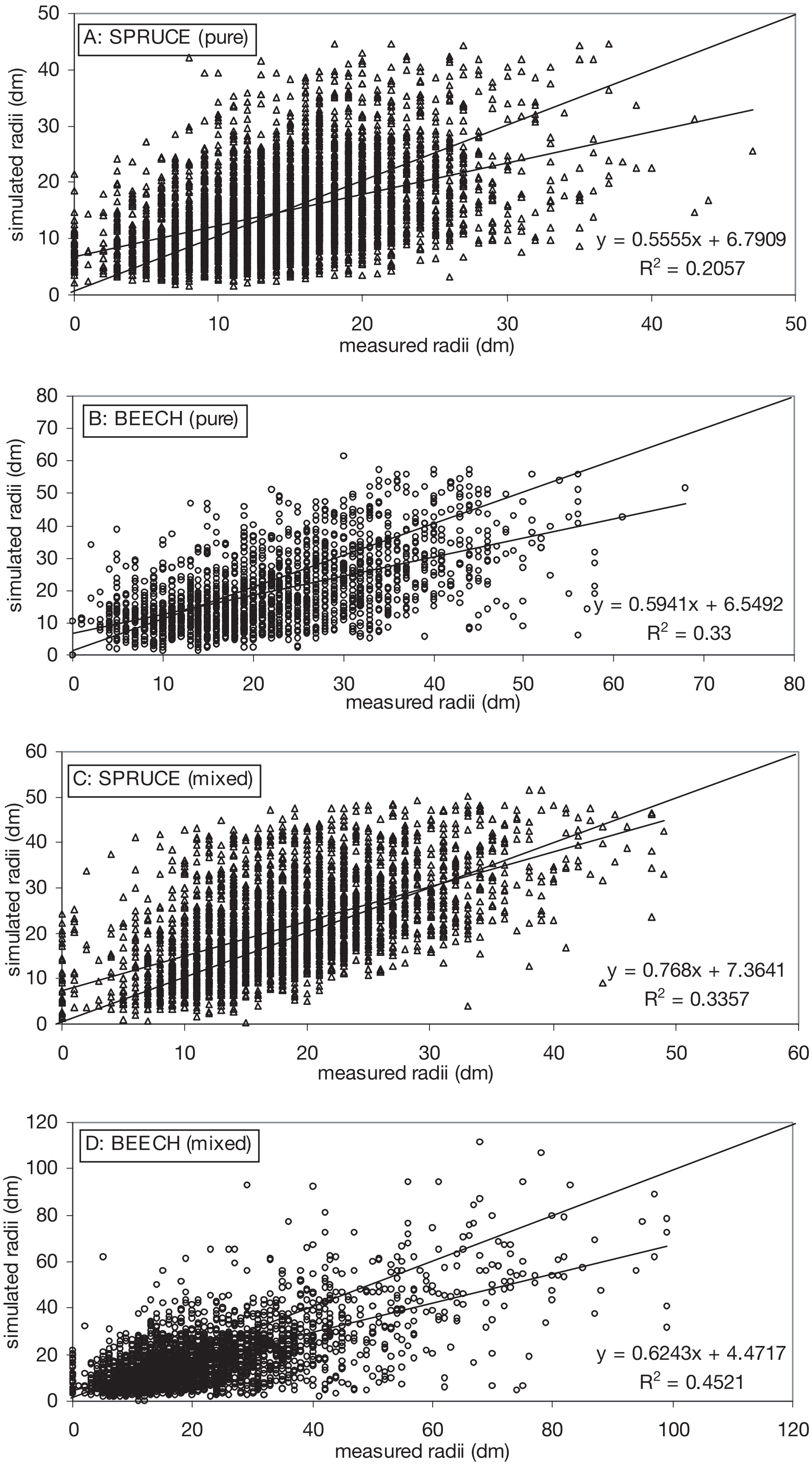

Figure 4. Simulated vs. measured crown radii in pure stands (A: spruce, B: beech) and mixed stands (C: spruce, D: beech).

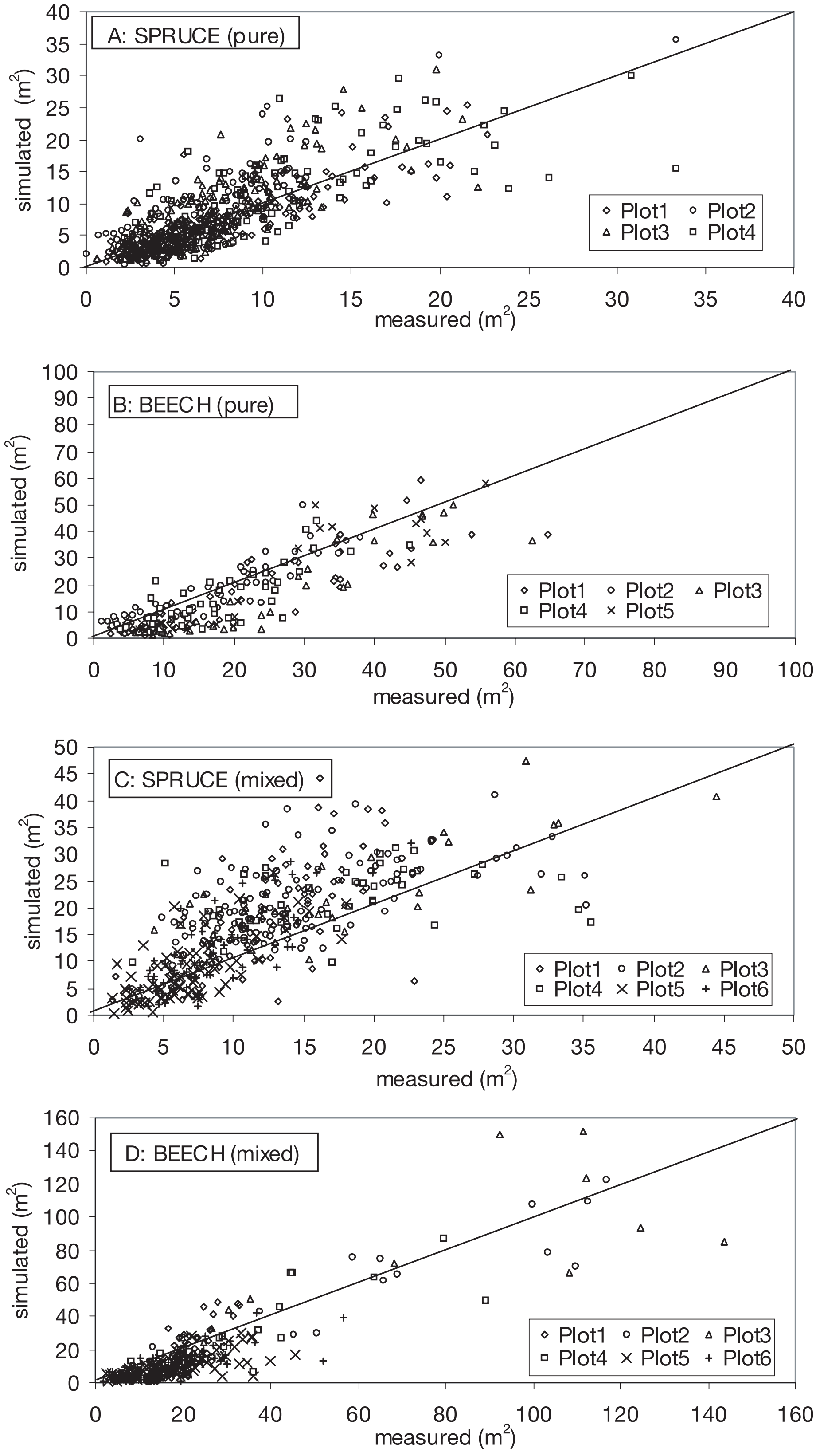

Figure 5. Comparison of crown projection areas calculated from simulated and measured crown radii in pure stands (A: spruce, B: beech) and mixed stands (C: spruce, D: beech).

Table IV. Slope and correlation coefficients of simulated against measurement-based crown cover calculations (*n*: number of trees that are considered for the calculations, MRE: distance dependent method, LOG: based on logarithmic correlation, LIN: based on linear correlation).

Location	Plot no.	Species	*n*	Slope (MRE)	r^2 (MRE)	Slope (LOG)	r^2 (LOG)	Slope (LIN)	r^2 (LIN)
Eurach	1	Spruce	174	0.96	0.70	0.99	0.73	0.97	0.69
	2		172	1.23	0.63	0.91	0.53	0.91	0.50
	3		154	1.17	0.62	0.94	0.53	0.94	0.48
	4		108	1.00	0.48	0.81	0.54	0.79	0.44
	Over all		**608**	**1.04**	**0.56**	**0.91**	**0.63**	**0.90**	**0.58**
Starnberg	1	Beech	60	0.80	0.78	0.87	0.85	0.86	0.82
	2		60	1.01	0.80	1.24	0.54	1.24	0.28
	3		38	0.76	0.79	0.77	0.85	0.75	0.86
	4		48	0.85	0.63	0.95	0.52	0.97	0.46
	5		27	0.92	0.81	0.85	0.86	0.83	0.87
	Over all		**173**	**0.85**	**0.76**	**0.91**	**0.68**	**0.90**	**0.61**
Freising	1	Spruce	65	1.50	0.43	0.86	0.50	1.03	0.38
	2		119	1.31	*–0.15*	0.98	*–0.24*	1.10	*–1.30*
	3		31	1.17	0.37	0.84	*–0.61*	0.93	*–1.88*
	4		44	1.10	*–1.25*	0.97	0.37	1.05	*–0.05*
	5		83	1.20	0.48	0.90	0.49	1.21	0.11
	6		69	1.41	0.67	0.79	0.69	1.05	0.31
	Over all		**227**	**1.28**	**0.46**	**0.92**	**0.60**	**1.06**	**0.37**
Freising	1	Beech	98	0.73	0.37	1.10	0.55	1.20	0.57
	2		18	0.93	0.87	0.98	0.77	0.89	0.53
	3		11	0.95	0.43	0.79	*–0.53*	0.72	*–1.56*
	4		24	0.88	0.64	0.96	0.33	0.96	0.15
	5		73	0.55	0.49	0.85	0.43	0.95	0.40
	6		118	0.61	0.69	0.68	0.68	0.75	0.68
	Over all		**226**	**0.83**	**0.77**	**0.89**	**0.77**	**0.88**	**0.69**
Freising	1	Total	162	0.92	0.19	1.04	0.59	1.16	0.61
	2		137	1.03	0.71	0.98	0.88	0.95	0.75
	3		42	0.98	0.73	0.80	0.75	0.75	0.63
	4		68	0.95	0.44	0.96	0.56	0.99	0.43
	5		156	0.64	0.22	0.86	0.69	0.98	0.56
	6		187	0.73	0.39	0.70	0.71	0.80	0.60
	Over all		**453**	**0.93**	**0.66**	**0.90**	**0.77**	**0.91**	**0.66**

4. DISCUSSION

Results indicate that the MRE method can be used to estimate crown radii for beech and spruce in dense stands but has to be applied cautiously. Although some of the variance may be due to the high inaccuracy of crown measurements [43], crown radii of trees from sparse plots or in recently thinned stands are generally overestimated. This is consistent with the underlying assumption of a balanced crown extension, which can not be expected in heavily thinned stands and which is more likely with morphological flexible tree species like beech than with spruce [4, 16].

Future tests and improvements of the MRE approach will focus on crown shape estimation, which is based on a quite small sample size of trees yet. Only a larger sample provides the possibility to establish dependencies of crown shape on spacing and competition that have been already found in other investigations [5, 12, 14, 32, 34]. Further improvements could be based on the finding that in mixed stands spruce radii are generally over and beech radii are underestimated. This would be mitigated if a species-specific weighing factor for the calculation of potential spruce and beech radii is introduced in equation 2. However, it is not clear from the limited set of test sites to which degree the effect is due to the stand structure rather than species-specific properties. Although they are older, most beeches of the mixed plots are smaller than the spruces. Thus, the assumption that crowns of small trees are restricted by the largest extension of competitor crowns rather than their actual extension may affect beeches more than the spruces at these particular plots. In this case, separate crown radii estimations for different crown layers may produce more favourable results but simulations of differently structured mixed stands are required to test this assumption.

Improvements in crown radii estimates will generally positively affect crown projection area and canopy cover estimates. Nevertheless, the good agreement of simulated and measured canopy cover despite the underestimation of crown projection area in beech stands shows that the estimation of

Table V. Comparison of total crown area and covered ground area, calculated from measured and estimated crown radii (MRE: distance dependent method, sd: standard deviation).

Location	Plot no.	Species	Sum of crown area					Sum of crown covered ground					Multiple coverage			
			Measured (m^2)	sd	MRE (m^2)	%	sd	Measured (m^2)	sd	MRE (m^2)	%	sd	Measured (m^2)	%	MRE (m^2)	%
Eurach	1	Spruce	1363		1288	94		879		956	109		484	36	331	26
	2		955		1174	123		727		881	121		228	24	293	25
	3		1095		1293	118		771		866	112		324	30	427	33
	4		1135		1217	107		754		899	119		380	34	318	26
	Average		**1137**	**146**	**1243**	**109**	**50**	**783**	**58**	**901**	**115**	**34**	**354**	**31**	**342**	**28**
Starnberg	1	Beech	1219		948	78		746		700	94		473	39	247	26
	2		980		941	96		639		668	105		340	35	273	29
	3		885		599	68		514		499	97		370	42	101	17
	4		839		676	81		494		602	122		345	41	74	11
	5		639		549	86		597		491	82		43	7	58	11
	Average		**912**	**189**	**743**	**81**	**169**	**598**	**91**	**592**	**99**	**86**	**314**	**34**	**151**	**20**
Freising	1	Mixed	2669		2457	92		1759		1818	103		910	34	639	26
	2		2747		3469	126		2266		2597	115		481	18	872	25
	3		1426		1597	112		1112		1213	109		315	22	384	24
	4		1541		1646	107		1125		1189	106		416	27	456	28
	5		1807		1387	77		992		960	97		815	45	426	31
	6		2242		1789	80		1215		1310	108		1027	46	479	27
	Average		**2072**	**518**	**2057**	**99**	**714**	**1411**	**454**	**1515**	**107**	**549**	**661**	**32**	**543**	**26**

crown overlap is also subjected to errors. Again, species-specific differences have to be considered since the predicted overlap for spruce trees is quite close to the measurement-based calculations. This finding strengthen the assumption that a separate calculation of different crown layers may be necessary.

The MRE method aims not preliminary on a precise estimate of crown projection area or canopy cover. Over all, the logarithmic approach, which is used here as an example for similar and sometimes more sophisticated procedures (e.g. [13, 17, 51]), produced slightly better results and would perform even better if parameters would have been fitted for each plot separately. Furthermore, the estimates produced with the MRE method seem to be more sensitive to stand density effects than established estimation methods [9] – at least for trees with inflexible crowns.

However, the author has found no other approach that estimates crown radii for different cardinal directions. Thus, the demand for crown asymmetry-information that has been formulated in various fields of research (scaling, light modelling, estimation of windthrow susceptibility, wood quality, and crown biomass) can currently only be fulfilled with actual measurements. Despite the scatter, the immanent bias, and the dependency of accuracy on species and stand density, the MRE method may thus be used as a substitute for measured crown radii in cases where these are not available but information about crown asymmetry is needed. While stem diameter, tree height, and crown length are often directly measured or can be estimated with suitable equations (e.g. [24, 36]), the acquisition of tree position data in the field may be more difficult and expensive. However, also tree positions can be generated based on stand inventory data (e.g. [39]), which may be sufficient for many of the purposes mentioned above.

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